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FACULTY OF HEALTH SCIENCES

Hip and Lower Limb Movement Screen: validity and reliability

of observational assessment in comparison to 3D motion analysis

by

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Abstract

Doctor of Philosophy

Hip and Lower Limb Movement Screen: validity and reliability of observational assessment in comparison to 3D motion analysis

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Movement screens are used widely to assess quality of movement by visual observation. However, there is a lack of research on the reliability and validity of the observation rating of the movement criteria that are assessed. The Hip and Lower Limb Movement Screen (HLLMS) is a new tool, specifically designed to focus on assessing control of hip movement, which is related to alignment of other joints in the lower limb. Good control of movement is thought to prevent injuries, particularly in sports, and in the longer-term, to protect the joints from developing osteoarthritis. If the HLLMS is to be used to inform exercise interventions to improve movement control, its reliability and validity need to be established to support its use as a robust tool.

The aims of the studies in this thesis were to examine the reliability and validity (criterion validity) using 3D motion analysis and sensitivity to change, of the observational rating of criteria from the HLLMS in male academy footballers, healthy young sedentary controls and professional golfers. Four experiments examined the reliability and validity of the HLLMS. Observational rating, video footage and 3D motion analysis data were collected while participants carried out the HLLMS. Motion analysis data were used to calculate kinematics corresponding to the movement criteria from the HLLMS.

Intra-rater reliability was assessed from video recordings, and between day and inter-rater observer rater agreement were examined in real-time, with mean AC1 values ranging from 0.6 to 0.8. However, individual criterion rater agreement ranged from -0.47 to 1.00 indicating poor to excellent agreement. Approximately 50% of the criteria assessed had criterion validity with significant differences between the kinematics for fault and no fault ratings. The majority of the ICC values for within day kinematic reliability were excellent (ICC>0.75) but between day kinematic reliability was lower with 10 of the 19 ICC values < 0.75. The validity to detect change of the observational rating of the criteria were assessed following a 12-week exercise intervention to improvement movement patterns in academy footballers. Four of the criteria had changes in their rating that consistently corresponded with a change in the kinematics.

The reliability and validity results from this thesis have demonstrated the potential for the HLLMS to be a robust tool in assessing movement patterns. Criteria that were found to be poor have either been revised or excluded from an updated HLLMS. Further research is needed to improve the accuracy of the criteria and establishing the validity and reliability of the revised criteria in the latest version of the HLLMS, in different populations. This thesis has advanced the field of movement screening by contributing to the development of a novel assessment tool that has the potential to inform exercise interventions to protect joints from injury and osteoarthritis.

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I, ... [please print name]

declare that this thesis and the work presented in it are my own and has been generated by me as the result of my own original research.

[title of thesis] ....

....

I confirm that:

1. This work was done wholly or mainly while in candidature for a research degree at this University;
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3. Where I have consulted the published work of others, this is always clearly attributed;
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Definitions

A

Anatomical markers – Markers attached to a rigid body whose positions have an anatomical relevance

Anatomical coordinate system – A set of axes with a point of origin which defines a rigid body and has an anatomical relevance

B

Bony landmark – A specific location on a rigid body that has anatomical relevance

C

Capture volume – Theoretical workspace in which data is captured

D

Degrees of freedom – The possible number of rotations and translations of a rigid body

E

Euler angles – A method for deconstructing the three rotations of a rigid body

G

Global coordinate system – A set of axes which define the origin and orientation of the capture volume

K

Kinematics – analysis of movement without regard to the forces acting on the body

Kinetics – analysis of movement with regards to the forces acting on the body

L

Local coordinate system – A set of axes defining the position and orientation of a rigid body

M

Motion capture system – Device used to track and reconstruct the movement of body in two or three dimensions.

O

Origin – The reference point of a global or local coordinate system, represented as (0,0,0)

P

Passive-marker – A sphere covered with reflective material that is attached to a body that can be tracked and its position recorded by a passive-marker motion capture system

Point – A position in space defined by its coordinates

R

Rigid body – A body segment which is assumed to remain solid and doesn't deform despite the application of a force

T

Technical marker set – A series of markers attached to a rigid body that have no anatomical relevance

V

Vector – A geometric object that has both direction and magnitude

List of abbreviations

2D	Two dimensional
3D	Three dimensional
ACL	Anterior cruciate ligament
ASIS	Anterior superior iliac spine
CI	Confidence interval
CMC	Coefficient of multiple correlations
DF	Dual fluoroscopy
FAI	Femoroacetabular impingement
FMS	Functional Movement Screen
HAGOS	The Copenhagen Hip and Groin Outcome Score
HLLMS	Hip and Lower Limb Movement Screen
ICC	Intra class correlation coefficient
IR	Internal rotation
OA	Osteoarthritis
OCST	Optimal common shape technique
MDC	Minimal detectable change
PPI	Patient and public involvement
PTPS	Patello femoral pain syndrome
PIS	Participant information sheet
PSIS	Posterior superior iliac spine
PROM	Passive range of motion

RCT	Randomised controlled trial
ROM	Range of motion
SARA	Symmetrical axis of rotation approximation
SCoRE	Symmetrical centre of rotation estimate
SD	Standard deviation
SDC	smallest detectable change
SEM	Standard error of measurement
SET	Semitendinosus
SKB Rot	Small knee bend with rotation
SKB	Small knee bend
STA	Soft tissue artefact

Chapter 1: **Introduction**

Participation in football has many health benefits, however it may impact on the health of hip and lower limb joints with an increased prevalence of osteoarthritis (OA) reported in ex-professional footballers (Shepard et al., 2003). The increased risk for developing hip OA may be due to low grade repetitive trauma (Manning and Hudson, 2009, Shepard et al., 2003). Gaining an understanding of the factors that lead to the deterioation of hip joint health would aid the development of effective intervention.

Maintaining joint health is not only beneficial to the individual but would also reduce direct and indirect healthcare costs related to work time losses and orthopaedic interventions (Barengo et al., 2014). There is a theory proposed by Bennell et al. (2012) that improving movement slows the progression of joint injury onto OA through reducing abnormal loading on joints. There is an increasing use of observation movement screens which are designed to identify people who may have movement patterns that increase the risk of injury and reduce joint health (Kiesel et al., 2007, Mottram and Comerford, 2008). However, research on the validity and reliability of the observational rating of movement patterns is limited and further research is needed to support the use of movement screens (Maclachlan et al., 2015, Whatman et al., 2015). The aim of this study is to examine the validity and reliability of the recently developed Hip and Lower Limb Movement Screen (HLLMS) (Botha, 2013). As part of the validation of the HLLMS the responsiveness to change following a specific exercise intervention will be examined. Measurement of any changes following the intervention will increase the understanding of the mechanisms.

1.1 Background

1.1.1 Football and hip osteoarthritis

It is generally accepted that physical activity has positive health benefits, yet more than half the adult population in the UK are not active enough (Department of Health, 2011). Football (soccer) is one of the most popular recreational activities in the UK and has many health benefits, possibly greater than running alone (Krustrup et al., 2010, Sport England, 2014). However, playing football may have some detrimental effects on joint health if joint loading is excessive or abnormal.

Encouraging the population to become more active through sports, such as football, needs to be balanced with developing prevention measures to reduce the risk of developing OA and limit the potential social and economic cost implications for the NHS.

There are many factors linked to developing OA including occupation, being overweight and previous injury (Richmond et al., 2013). Evidence also suggests that activity can affect joint health (Agricola et al., 2014). According to Shepard et al. (2003) various studies have shown an increased prevalence of OA in ex professional footballers. The hip is one of the main joints affected in footballers, with significantly increased radiographic signs of hip OA compared to age matched controls (Klünder et al., 1980). Shepard et al. (2003) reported significantly ($p<0.001$) increased hip OA, diagnosed by a doctor from a radiograph in ex professional football players, compared to age matched controls. A total of six of the 68 ex-football players had undergone eight total hip replacements, compared to none reported in the matched controls (Shepard et al., 2003). Similarly, in retired athletes total hip replacements are 2.5 times higher than controls (Tveit et al., 2012). The potentially high rate of hip OA in ex professional footballers highlights the need to identify factors that increase this risk, so that interventions can be implemented early on to prevent development. With large numbers of the public taking part in football, these prevention strategies are paramount to limit the potential cost implications for the National Health Service (NHS).

1.1.1.1 *Injuries in football*

The health benefits from participation in sports such as football needs to be balanced with any possible health risks. One area of concern is the increased risk of injury associated with participation in football which has been reported to be 1000 times higher than in other high risk occupations, such as construction and mining (Hawkins and Fuller, 1999). The injury rate of 27.5/1000 player hours during games was reported for the top professional European football clubs (Ekstrand et al., 2011). This is considerably higher than the 9.9/1000 hours for basketball in the National Collegiate Athletic Association (NCAA)(Dick et al., 2007).

Although most of the studies on football injuries are on professional players, the impact on recreational footballers also needs to be considered, as they form the majority of football players. There is some disagreement in injury rates in recreational footballers compared to professional players. Bollars et al. (2014) and van Beijsterveldt et al. (2014) both reported higher risk of injury for recreational vs. professional players. In contrast, Herrero et al. (2014) reported an injury rate of 1.15/1000 hours during games which is considerably lower than the 9.6/1000 hours reported by van Beijsterveldt et al. (2014). Methodological differences, such as the lack of exposure data

(Bollars et al., 2014) and retrospective, self-reporting (Herrero et al., 2014), means comparison of injury rates between recreational footballers and professional footballers is difficult. Nevertheless, there appears to be a need to reduce the injury risk at all levels of football players.

1.1.1.2 *Implications of injury*

The high injury rate in football has many implications, for example Woods et al. (2002) estimated costs to be £74.4 million over a season for the English professional football leagues based on wages of 10% of the squad being unable to train. In relation to the impact of injury on performance, a significant correlation was reported between lower injury burden (p=0.011), higher match availability (p=0.031) with a higher final league position and average points per match than the previous season in elite European football (Hägglund et al., 2013). Reducing injury rates in football is likely to have considerable financial and performance benefits.

1.1.1.3 *Short term injury implications*

An understanding of football injury epidemiology is an important step in reducing injuries with extensive, prospective studies having been carried out on elite European teams (Ekstrand et al., 2011). An injury is recorded if it resulted in a player being unable to fully participate in training or match play (Ekstrand et al., 2011). Injuries occur most commonly in the lower limbs with the hip and groin being the third most affected area (Table 1-1) (Ekstrand et al., 2011).

Table 1-1: Total number of injuries per area of the lower limb.

Lower limb area	Number of injury's
Thigh	1064
Knee	818
Ankle	625
Hip/groin	616
Lower leg/Achilles tendon	511
Foot/toe	268
Lower back/pelvis	237

adapted from Ekstrand et al. (2011)

Several authors reported hip and groin to be the second most common joint injury, accounting for 12% in European football (Waldén et al., 2005) and 14% in English football (Hawkins and Fuller, 1999). At a sub elite professional level in Spanish professional football, the hip and groin was the most injured joint, accounting for 17% of all injuries (Mallo et al., 2011). When comparing hip and groin injuries between recreational and professional footballers, no significant difference was seen (van Beijsterveldt et al., 2014). The findings outlined above suggest that hip and groin injuries are common in football and warrant focus in injury prevention.

1.1.2 Femoroacetabular impingement and development of OA

There are many possible causes of hip and groin pain including labral tears, adductor muscle strains and OA. One possible diagnosis with symptoms of hip and groin pain is femoroacetabular impingement (FAI), which is limited joint clearance between the femoral head-neck junction and the acetabular rim (Sankar et al., 2013, Loudon and Reiman, 2014). FAI can be associated with pain and linked to development of OA (Sankar et al., 2013, Loudon and Reiman, 2014). There are three types of FAI described; cam, pincer impingement and combined (mixed) (Figure 1-1).

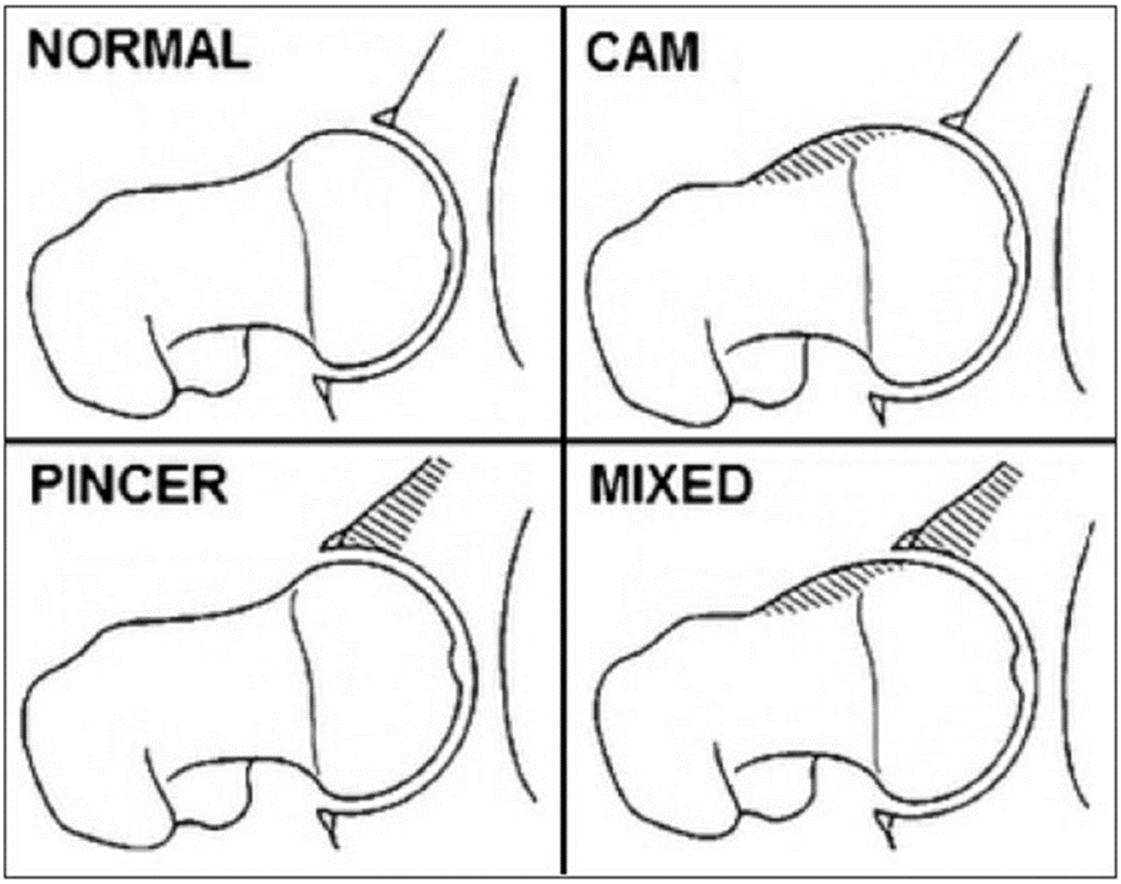


Figure 1-1: Structural changes at the hip joint centre that occur in FAI, permission gained from Algarni (2013)

Cam impingement is jamming of the abnormally large femoral head into the acetabulum during forceful motion (Ito et al., 2001). Cam impingement is commonly quantified using alpha (α) angle. The α angle is calculated by fitting a circle around the femoral head, a line is then drawn through the centre of the neck of femur and head with a second line drawn from the centre of the head to the point where the head-neck junction first departs from the circle (Nötzli et al., 2002) (Figure 1-2). Pincer impingement is the contact of the acetabular rim and femoral neck junction (Ito et al., 2001).

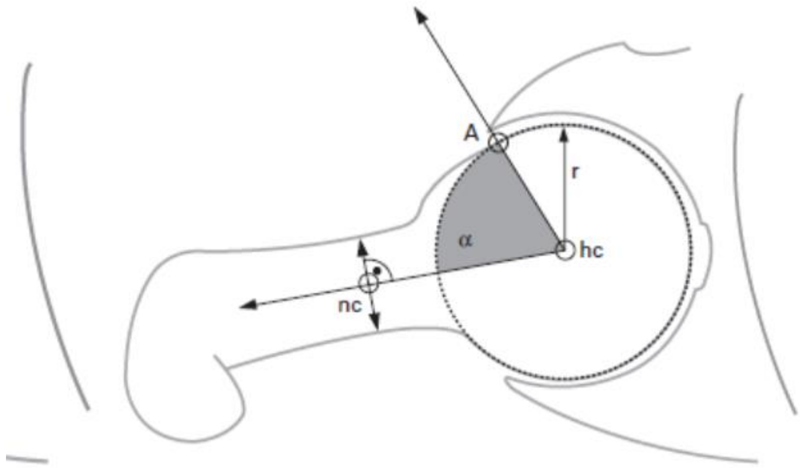


Figure 1-2: Calculation of the hip alpha angle for cam impingement, a type of FAI, permission gained from Notzli et al. (2002),

A high level of FAI was reported in elite soccer players, with 68% demonstrating radiographic evidence of cam impingement (Gerhardt et al., 2012). Similarly, a study on largely asymptomatic collegiate American Football by Kapron et al. (2011) reported 95% of hips had one sign of cam or pincer FAI. In contrast only 11% of a general population who had symptomatic hip or knee OA had signs of cam impingement (Agricola et al., 2013). The high levels of cam impingement reported by Kapron et al. (2011) needs to be balanced with their use of a low α angle of >50°, compared to the commonly used >60° (Agricola et al., 2013, Tak et al., 2015).

The diagnosis of FAI from radiographs alone has been challenged by the poor correlation between cam or pincer morphology and symptoms (Reiman and Thorborg, 2015). The high levels of morphological FAI in asymptomatic participants reported by Kapron et al. (2011) supports the need for clinical and radiographic diagnosis. Although there has been a focus on the structural diagnosis of FAI high rates of structural abnormality which are symptom free have been documented (Griffin et al., 2016). Therefore The 2016 Warwick Agreement on FAI syndrome introduced the FAI syndrome to reflect the central role of the patients symptoms where diagnosis of FAI was based on symptoms, positive clinical signs and image findings (Griffin et al., 2016). Additionally, reduced function needs to be considered in any diagnosis of FAI (Reiman and Thorborg, 2015, Sankar et al., 2013). The requirement for radiographic and clinical assessment of the hip is further supported by a prospective study that found 53% of participants developed end stage OA who had an α angle > 83° and internal hip rotation of ≤ 20°, compared to only 25% with only an α angle > 83° (Agricola et al., 2013). However, despite the variation in definition for cam impingement, FAI measured by cam deformity appears to be substantially more prevalent in footballers.

1.1.3 FAI aetiology

The presence of FAI has been shown to increase the risk for developing hip OA (Sankar et al., 2013, Loudon and Reiman, 2014, Ganz et al., 2003). As outlined above there are increased rates of FAI and hip OA in footballers. Therefore, understanding the cause of FAI may lead to reduction in hip OA. Reducing the risk of hip OA development in footballers requires understanding of the aetiology. While much is known about FAI with respect to the affected population, presentation, potential interventions and outcomes, the precise cause of the abnormal morphology and its relationship to sports participation in adolescents remains unclear (de Silva et al., 2016).

Young sporting people are especially at risk of FAI, as high physical demands placed on their joints during the critical stages of skeletal development may lead to morphological changes consistent with FAI (Agricola et al., 2014). There is some evidence that specifically playing football leads to the structural development of FAI, which appears to be gradually acquired during skeletal maturation. A prospective study by Agricola et al. (2014) reporting a significant rise ($p=0.002$) in cam deformity from 13.6% in footballers aged 12 years, compared to 50% in footballers aged 13 years. In addition, footballers who played ≥4 times per week before the age of 12 years had a significantly ($p=0.042$) higher risk of cam deformity, compared to those who started after the age of 12 years (Tak et al., 2015). However, the authors stated that the reported frequency of football played in their youth may have been affected by recall bias (Tak et al., 2015). Nevertheless, these results suggest that football activity at a young age increases the risk of developing morphological FAI in youth players.

The evidence outlined above suggests that playing football at a young age increases the risk of developing morphological changes associated with FAI, but there is also some evidence that playing other sports also leads to FAI (de Silva et al., 2016). In elite youth basketball players Siebenrock et al. (2013) reported significantly higher rates of cam-type deformity (a type of FAI-Section 1.1.2) compared to non-athletic participants. The authors suggested high level sports activity during growth may be a risk factor for a cam-type deformity, and a consequence of an alteration of the growth plate rather than reactive bone formation (Siebenrock et al., 2013). The risk of developing FAI in other sports was highlighted in a review of the literature by de Silva et al.

(2016). Adolescent males participating in ice-hockey, basketball and soccer training at least three times a week, were at greater risk than their non-athletic counterparts of developing the femoral head-neck deformity associated with FAI (de Silva et al., 2016). In support of the aforementioned review, a systematic review and meta-analysis by Nepple et al. (2015) determined that athletes participating in sports during adolescence, namely ice hockey, basketball and jumping sports, are at 1.9 to 8 times increased risk of developing a cam deformity during skeletal maturation. The evidence outlined above suggests that FAI is the result of the body adapting to chronic mechanical stress from taking part in high impact sports during growth, and not just from playing football (de Silva et al., 2016, Nepple et al., 2015). In addition de Silva et al. (2016) proposed that hip flexion and internal rotation movements, which are required in basketball, ice hockey and football are likely to contribute to cam development. The research outlined above suggest the link between mechanical loading, movement patterns in the development of FAI. With regard to the role of abnormal movement patterns, further research is required to examine if these can be altered and whether this leads to a reduction in FAI in athletic youth populations, and less OA in later life.

The development of hip OA in footballers has been proposed to be due to low grade repetitive trauma (Manning and Hudson, 2009, Shepard et al., 2003). The low grade trauma may be related to the high injury rate reported for the hip and groin area in professional footballers (Ekstrand et al., 2011, Hawkins and Fuller, 1999, Mallo et al., 2011, Waldén et al., 2005) and in amateur footballers (van Beijsterveldt et al., 2014). The high rate of hip and groin injuries in all levels of footballers with the potentially increased rate of hip OA has cost implications for the NHS. Playing football could increase the rate of hip arthroplasty and the associated costs to the NHS. The findings outlined above suggest that hip and groin injuries are common in footballers and warrant focus in injury prevention, which may lead to a reduced risk of developing hip OA and reduce the financial burden on the NHS. Additionally, injury prevention at academy level was fundamental in ensuring the health and wellbeing of the football players is maintained and allowing a player to pursue a career in the sport (Rusling et al., 2015).

With an increased rate of FAI in footballers, understanding the aetiology is important. However, currently more is known about FAI morphological abnormalities than the aetiology (Austin et al., 2008). FAI appears to begin during skeletal maturation and is related to activity and loading patterns (Agricola et al., 2014, Tak et al., 2015). Movement patterns, such as hip internal rotation and adduction, may contribute to symptoms of FAI (Austin et al., 2008, Loudon and Reiman, 2014, Wall et al., 2013, Emara et al., 2011). Altered movement patterns of increased hip flexion and poor hip medial rotation control were reported in symptomatic academy footballers diagnosed with FAI during a small knee bend movement control test (Botha et al., 2014). Additionally, participants with FAI demonstrated decreased squat depth and altered lumbar kinematics during the deep squat compared to healthy controls (Kivlan and Martin, 2012). However, it is not possible to determine if abnormal movement patterns are the cause or effect, but altering these patterns could be beneficial to joint health. Therefore, gaining greater understanding of FAI aetiology would help develop effective prevention and treatment.

1.1.3.1 *Limited hip range of movement in footballers*

Reduced internal rotation is linked with hip OA and has been suggested as an early sign of hip degeneration (Manning and Hudson, 2009). Significantly ($p<0.001$) lower hip internal rotation was reported in senior football players compared to senior controls, youth team footballers ($p<0.05$). Furthermore, youth team players had significantly ($p<0.001$) lower internal rotation than youth controls (Manning and Hudson, 2009). In addition, Manning and Hudson (2009) suggested that reduced hip range of movement (ROM) may increase the risk of injuries to other joints. Therefore, maintaining ROM at the hip may benefit the health of the whole lower limb.

As mentioned previously, there is some controversy in FAI diagnosis based on imaging alone, therefore there is a need to consider clinical signs (Reiman and Thorborg, 2015, Sankar et al., 2013, Griffin et al., 2016). However, there appears to be an increased rate of FAI in senior (Gerhardt et al., 2012) and youth footballers (Agricola et al., 2014) and altered hip ROM (Manning and Hudson, 2009) in all footballers. This suggests that taking part in sports such as football may cause hip structural abnormalities and lead to increased risk of OA. Therefore, encouraging participation in popular sports, such as football, for health benefits needs to be balanced with guidance on how to exercise safely to minimise the impact on joint health.

1.1.4 Treatment of FAI

Effective treatment of FAI could have both short-term benefits and longer-term implications, such as preventing the development of OA. The literature on FAI treatment mainly focuses on surgical interventions possibly due to FAI being classified as a mechanical disorder, leading to surgeons dismissing non-operative treatment (Wall et al., 2013). A rapid increase in the number of surgical procedures for FAI has been reported, despite a lack of evidence for surgery (Reiman and Thorborg, 2015), including no placebo randomised controlled trial (RCT) of FAI surgery on the development of OA (Agricola et al., 2013). In agreement Griffin et al. (2016) concluded that currently there is no evidence that the treatment of FAI syndrome alters the risk of subsequent

OA. The current evidence for FAI surgery appears limited, with non-surgical options needing to be investigated (Agricola et al., 2013, Reiman and Thorborg, 2015).

The evidence for conservative treatment for FAI is limited (Reiman and Thorborg, 2015, Griffin et al., 2016). A review by Wall et al. (2013) suggested the current evidence for FAI conservative management is restricted by a large variation in diagnostic criteria, a lack of treatment detail and no RCT's. Several authors advocate the importance of altering movement patterns to reduce FAI symptoms (Austin et al., 2008, Emara et al., 2011, Loudon and Reiman, 2014), although the research is currently only low level evidence case studies.

1.1.4.1 *Altered movement patterns with FAI*

Conservative treatment for FAI could reduce symptoms, prevent progression, allow healing and negate the need for surgery (Wall et al., 2013). A case study by Austin et al. (2008) reported the use of a SERF strap (Don Joy Orthopaedics, Inc, Vista, CA) decreased pain by two points on a visual analogue scale (VAS 0-10), peak hip adduction by 5.7° and hip IR by 7.3 ° during a step down in a female FAI participant with an α angle 84° (Austin et al., 2008). The SERF strap was designed to reduce internal rotation during movement (Austin et al., 2008). The decreased internal rotation through the use of the SERF strap may have reduced pain by stopping the FAI participant reaching end range of their possibly limited hip internal rotation, which is a clinical symptom of FAI. The authors proposed that abnormal movement patterns (increased internal rotation during functional task) needed to be combined with morphological changes in the hip to produce FAI symptoms, and possibly explain why a morphological FAI hip may be asymptomatic (Austin et al., 2008). In a review by Wall et al. (2013) current evidence for conservative management of FAI is limited by a large variation in diagnosis, use of low α angles, lack of treatment detail and no RCT. However, altering movement patterns warrants further research.

It is known that FAI is exacerbated with the combined movement of hip flexion and internal rotation (Ito et al., 2001, Ganz et al., 2003, Lavigne et al., 2004). Therefore, the combination of poor control of hip flexion and medial rotation reported by Botha et al. (2014) may lead to FAI symptoms by increasing the antero-medial contact stress (Yazbek et al., 2011). In addition poor control of hip medial rotation and adduction has been suggested to contribute to knee valgus (Zeller et al., 2003, McLean et al., 2004), which has been linked to anterior crucial ligament (ACL) injury risk (Hewett et al., 2005). However, the influence of this compensation as observed in academy footballers on hip and groin micro trauma, leading to pain and injuries are unknown.

The mechanisms behind how altering movement patterns may reduce stresses on joints and tissues was suggested by Austin et al. (2008) to be through altering the hip kinematics during dynamic activities, which off loads the anterior hip structures and decreases pain. The altered hip flexion and medial rotation movement patterns observed in academy footballers when performing the HLLMS, could indicate difficulty in controlling the hip muscles, especially the gluteus medius and maximus (Botha et al., 2014). When poor hip control is present, especially in the gluteus medius muscle, the hip tends to move into adduction when loaded, which leads to hip medial rotation and knee valgus (Zeller et al., 2003). The influence of hip muscle exercises on hip and lower limb alignment during weight bearing activities may have significant implications for movement control. Gluteus medius, gluteus maximus, and iliopsoas weakness can contribute to increased anterior hip forces (Yazbek et al., 2011). This weakness can also lead to abnormal lower extremity alignment associated with excessive hip adduction and medial rotation, leading to lower extremity dynamic valgus (Powers, 2010), as observed in academy footballers (Botha et al., 2014). Medial rotation of the hip increases when the iliopsoas force decreases and the tensor fascia latae (TFL) force increases, which causes an imbalance and increases anterior hip loading (Lewis et al., 2007). Kennedy et al. (2009) and Casartelli et al. (2011) argue alterations in movement control may be a result of strategies adopted to compensate for a hip muscle function deficiency.

MacIntyre et al. (2015) concluded that restoring the strength, endurance and dynamic control of the gluteal muscles through progressive exercises as demonstrated in their case study on an ice hockey player, patients can return to good hip function and lower limb kinematics (Pierce et al., 2013). As demonstrated in the case study above, the underlying hip morphological characteristics such as FAI can still be present. It also highlights the importance of soft tissue structures contributing to the source of hip pain and dysfunction, by addressing these biomechanical limitations with a patient centred approach, which may contribute to improved hip and lumbopelvic joint function. MacIntyre et al. (2015) suggest that conservative management utilising a multimodal approach, as described in their case study, should be the first line treatment. However, the study was a single case study, which is a limitation and further research is needed to determine if the clinical findings in the case study apply to larger groups.

Altering movement patterns of the hip may benefit other lower limb joint injuries in the kinetic chain. Landing with the hip further away from terminal internal rotation ROM could decrease loading on the anterior cruciate ligament (ACL) reducing the risk of ACL injury (Bedi et al., 2014). Therefore, identifying abnormal movement patterns of the hip could be important for reducing injuries and maintaining joint health in the lower limb. Altering movement patterns may also benefit the longer-term health of joints. Bennell et al. (2012) theorised that improving movement would slow the progression of joint injury onto OA through the reduction of abnormal loading on joints. Additionally, there could be reduced direct and indirect healthcare costs, such as reduced work time losses and need for orthopaedic interventions (Barengo et al., 2014).

1.1.4.2 *Altered movement patterns with lower limb injury*

Altered movement patterns, as well as potentially leading to FAI, may also increase the risk of other lower limb injuries and affect joint health. For example, there is evidence that greater severity of knee valgus alignment was associated with greater odds of lateral knee OA progression (adjusted odds ratio (OR) 1.47/1° valgus; 95% CI 1.30 to 1.65) (Sharma et al., 2010). Therefore, poor movement patterns of increased knee valgus (knee moving medially) may cause greater loading on the lateral compartment of the knee, causing micro trauma, increasing the risk of lateral knee compartment OA progression. Greater severity of knee varus at baseline was also associated with greater risk of medial knee OA progression (adjusted odds ratio (OR) 1.29/1° varus; 95% CI 1.22 to 1.37) (Sharma et al., 2010). In addition, Bennell et al. (2011) indicated higher dynamic medial knee loading predicts greater cartilage loss over 12 months in medial knee OA. There is also evidence that movement impairments at the hip and pelvis may trigger injuries such as anterior cruciate ligament tears (Hewett et al., 2005), iliotibial band syndrome (Noehren et al., 2007), and patellofemoral joint pain (Powers, 2003). There is increasing evidence that supports the link between poor movement quality and the increased risk of lower extremity overuse injuries (Chuter and de Jonge, 2012, Felson et al., 2013). Therefore, improvement in movement control at the hip and/or pelvis may help prevent injuries more distally in the kinetic chain.

1.1.5 Movement screening

Having suggested the link between abnormal movement FAI, and other lower limb injuries, the next section considers the use of observational movement screening which considers the quality of the movement for specific undesirable movement patterns. Traditionally measures of athleticism such as strength, ROM, power and speed have been the focus of athletic training with little attention paid to movement quality and control. A lack of movement quality could lead to a performance paradox, where athletes could perform at a high level but have poor movement patterns, that may increase their risk of injury (Teyhen et al., 2014) (Figure 1-3). There are different types of injury which can be split into trauma or progressive (micro trauma). This thesis will consider the progressive type of injury which could lead to OA. There have been movement screens that quantify performance such speed, distance or time to perform a certain task. These include tests such as the hop test and Star Excursion Balance Test (SEBT) which are outside of the remit of this thesis. For a more thorough review on the use of performance tests to predict injury refer to the systematic reviews by Hegedus et al. (2014) and Hegedus et al. (2015) . The focus of this thesis is on movement screening designed to identify abnormal movement patterns in terms of qualitative control.

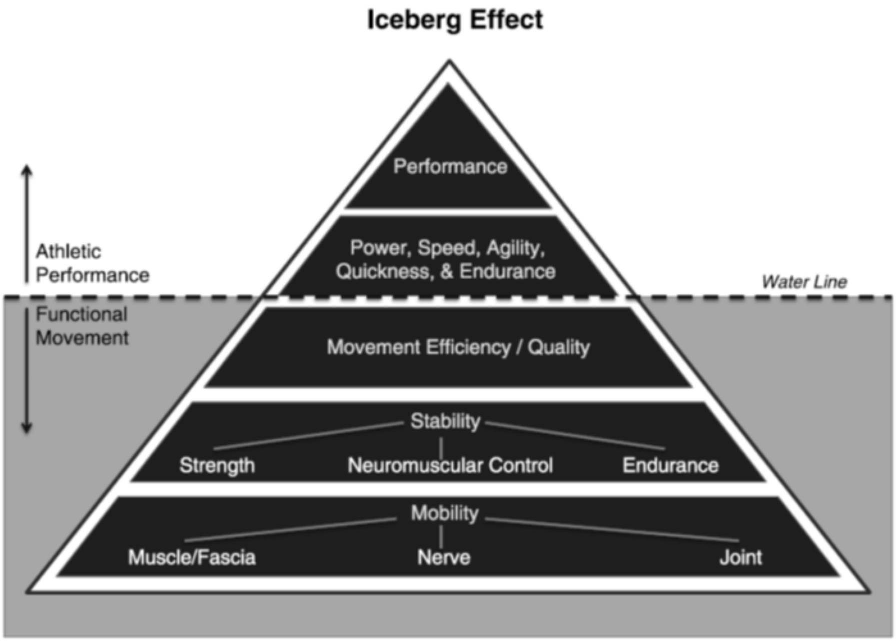


Figure 1-3: The relationship between functional movement and athletic performance, permission gained from Teyhen et al. (2014)

The use of whole body tasks to assess changes in motor control have been suggested to be superior than traditional measurements such as ROM and strength (Kiesel et al., 2011). The use of functional tests to evaluate movement control ("movement screening") is now highly recommended (Whatman et al., 2011). Movement screening tests challenge components of ROM, muscle strength, flexibility, coordination, proprioception and motor control of multiple body regions, which can be assessed at the same time by observing movement patterns (Cook et al., 2006, Kivlan and Martin, 2012). Movement screening is considered important to identify dysfunction or abnormal movement patterns (Frohm et al., 2012).

Observational movement screening could identify footballers with altered movement patterns that may impact on the health of the joint and increase the risk of developing FAI and OA. There is a growing consensus that movement patterns are significant and modifiable factor for injury (Rusling et al., 2015). The current emphasis on movement screening in English Premier League youth football was reported by Rusling et al. (2015) with the Elite Player Performance Plan stipulating that clubs' academies conduct movement screening of players.

Current movement screens in the literature include Functional Movement Screen (FMS) (Kiesel et al., 2007), nine test screening battery (Frohm et al., 2012), The Foundation Matrix (Mottram and Comerford, 2008) and Landing Error Scoring System (LESS) (Padua et al., 2009). The FMS scores performance of each of the seven tests from 0-3, with a total score of 21, with a lower score being predictive of increasing injury risk (Kiesel et al., 2007). The FMS is the most widely published movement screen, but evidence for its ability to predict injury is conflicting and thus limits the capacity to make definitive recommendations for its use (Chimera and Warren, 2016). In support Moran et al. (2017) concluded there is insufficient evidence to support the use of composite FMS scores as an injury prediction tool and clinicians should be cautious in using a single total FMS score or a specific cut off point for injury prediction (Chimera and Warren, 2016).

A systematic review reported the FMS to be the most commonly used movement screening tool in elite football, with 66% of clubs using it (McCall et al., 2014). Additionally, 16% of the clubs reported that a modified version of the FMS was used and investigation into how and why clubs altered the FMS would be beneficial (McCall et al., 2015). Furthermore, there was a non-significant relationship between total FMS score and injury prediction in a professional football academy over one season with 120 players aged 8-21 years (Rusling et al., 2015). Rusling et al. (2015) questioned the relative use of a test that had both feet on the ground when football injures rarely occur when this is occurring. In conclusion, Rusling et al. (2015) stated although the FMS is commonly used in football there may be no justification for its use.

1.1.5.1 *Limitations of the FMS to assess FAI movement patterns*

The previous section outlined some of the limitations of the FMS as a movement screening tool to predict injury, despite it being the most commonly used tool. Lower limb movement control has been linked to FAI and other injuries of the lower limb, suggesting there is a need to assess lower limb movement control. The use of the FMS to assess lower limb movement control may be limited, as it has no single leg weight-bearing tests, which is a common task assessed and needed in daily functions or sports (Bailey et al., 2009). The lack of a single leg squat or similar, which was used by Austin et al. (2008) in their case study on FAI, may be a reason for the limited use of the

FMS with hip movement screening. The Single Leg Squat or Small Knee Bend test has demonstrated evidence of validity in participants with suspected hip dysfunction (Kivlan and Martin, 2012); those who graded poorly exhibited weaker and slower muscle activation of the hip abductors than those graded as good (Crossley et al., 2011). The FMS test components appear to require contribution from the hip joint, with assistance from other joints. Where hip muscle weakness is present then compensation provided by other joints may enable apparently successful completion of the movement, therefore not isolating hip and pelvic movement and reducing the ability of the FMS to assess hip dysfunction (Samar and Bansal, 2013). Hip control needs to be tested in isolation and if it is found to be poor, then it may indicate that the hip joint is vulnerable to abnormal loading. Considering the limitations of current movement screening tools to identify movement dysfunction (Kivlan and Martin, 2012, Samar and Bansal, 2013) and the need to maintain hip joint health to prevent FAI and hip OA, the development of a specific movement screen to assess hip and lower limb movement patterns is warranted. Therefore, the development of a specific movement screen to assess movement patterns of the lower limb could provide a more useful tool than the FMS to maintain hip joint health. The development of a lower limb movement screen is not to predict injury but to identify poor movement control to indicate what exercises are needed to improve control and maintain joint health.

To identify young footballers who have poor movement patterns associated with FAI and other lower limb injuries, a movement screening tool has been developed (Botha et al., 2014, Botha, 2013). The movement screen is focused on identifying movement patterns that may affect joint health. Although the tool focuses on the hip, it also assesses other joints in the kinetic chain, so is termed the Hip and Lower Limb Movement Screen (HLLMS).

One key consideration in the development of any movement screen is the validity of the visual rating, highlighted by Frohm et al. (2012). One method of validation is to compare 3D motional analysis of the relevant kinematics to the observer rating (Whatman et al., 2015, Maclachlan et al., 2015).

There is increasing interest in the use of movement screening to detect poor movement patterns, which have been linked to reduced joint health in footballers and potential increased risk of OA. A HLLMS has been developed, but the kinematic validity of the observer ratings is yet to be assessed (Botha, 2013).

This PhD study aims to aid the development of the HLLMS through assessing the reliability and validity of the observer rating with the use of 3D motion analysis. Part of the study will assess the accuracy of 3D motion analysis as a tool to measure joint angles. Additionally, through measurement of muscle activity this study will try and gain an understanding of the mechanisms underlying any change in movement patterns.

Chapter 2: Literature Review – Validity and reliability of lower limb observational movement screening tools

2.1 Search Criteria

The use of observational movement screening tools has been outlined in the background section of the thesis. The use of these observational movement screening tools has to be based on their ability to correctly identify movements of interest, for example medial knee movement during the small knee bend. There is a need for the validation of these subjective observational movement screening tests compared to an objective measurement of movement (Ageberg et al., 2010). Without objective validation of these movement screens there may be little justification for their use with athletes and others to identify abnormal movement patterns that may increase the risk of injury.

The author of this thesis was one of the authors in a systematic review on the ability of movement screens to predict lower limb injuries (Whittaker et al., 2017) . This thesis will not consider the ability of movement screens to predict injury but focus on movement screening to identify movement patterns that could affect joint health.

The aim of this literature review was to analyse the research on the reliability and validity of lower limb observational movement screens with the use of objective measurement of the kinematics.

A search of the literature was performed using the terms below (Table 2-1). To generate the search terms assistance was sought from the Faculty of Health Sciences Librarian and further search terms were added from the keywords of prominent articles.

Table 2-1 Search terms used for literature review

Movement screening	**Validity**	**Lower limb**
"landing error scoring system"	valid*	"lower extremity"
"visual rating"	"three dimension*"	leg
squat	motion AND analysis	pelvis
"functional movement screen*"		hip
"movement screen*"		knee
movement AND quality		

*truncation

The literature search was conducted in SPORT Discus, MEDLINE, CINAHL Plus with Full Text and Science Citation Index. No limits were applied. The search was carried out for articles published before

The search produced 18 titles following removal of duplicates and any articles that were not relevant based on their title. Key article reference sections were also used to identify any further articles on interest (Figure 2-1).

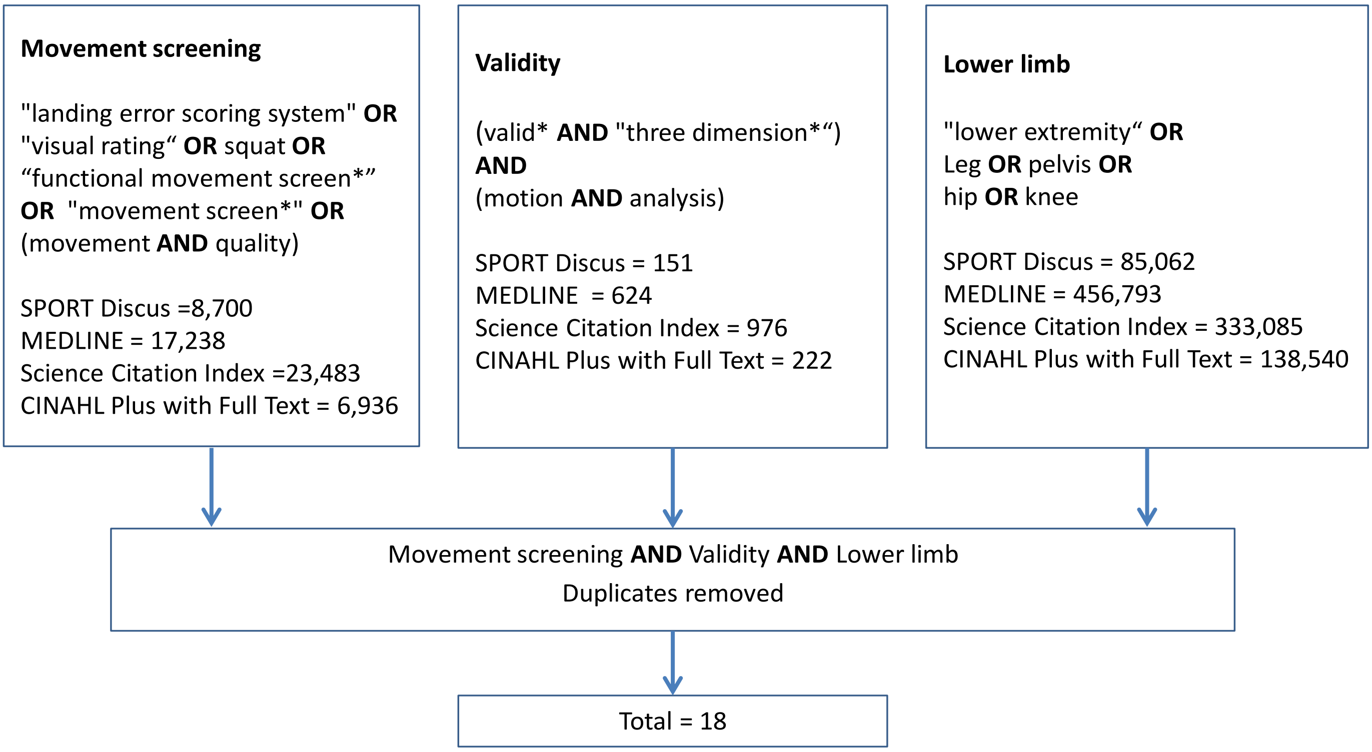


Figure 2-1: Flow diagram of literature search

2.2 Comparison of observational movement screening to 3D kinematics

Visual rating and assessment of dynamic alignment is commonly used in clinical practice to aid in diagnosis, prevention and management of musculoskeletal injuries, (Whatman et al., 2015). A lack of control or abnormal movement patterns is suggested to be a key risk factor for lower limb injuries (Whatman et al., 2015). The validity of the visual rating by the clinician is therefore key to inform the correct diagnosis, appropriate intervention and subsequent re-evaluation of any intervention. The use of movement screening as a tool for clinicians to assess dynamic movement has to be based on the ability of the clinician correctly identify through observation the kinematics of interest. There the need to compare the visual rating of dynamic movement to an objective measure.

Assessing movement patterns using 3D motion analysis can give accurate data however it requires expensive equipment, is very time consuming and may not be practical in clinical settings. The HLLMS requires no equipment, relatively simple, cheap and can be done quickly, so has substantial advantages over 3D motion analysis from a clinician's perspective. However, the validity of the HLLMS needs to be established as a tool to measure movement patterns.

According to Portney and Watkins (2009) validity is the extent to which an instrument or tool measures what it is intended to. Validity can be divided in to different types such as face, content, criterion (Portney and Watkins, 2009). Comparing one test such as the observational rating from the HLLMS to the kinematics calculated using 3D motion analysis is assessing the criterion validity. Criterion validity can be further divided into concurrent and predictive. Concurrent validity is when both tests are carried out at the same time, concurrently. This thesis will try to establish the criterion validity of the observational rating of the HLLMS using 3D motion analysis, as the tests measure movement at the same time.

A systematic review by Maclachlan et al. (2015) on observer rating versus 3D motion analysis of lower extremity kinematics during functional screening tests highlighted the lack of research in this area as only six papers were found. A possible reason why the literature search in this thesis found more articles than Maclachlan et al. (2015) could have been due to difference in the search terms they used compared to this literature review (Table 2-1). Maclachlan et al. (2015) did not include terms such as movement screen, movement and quality or squat that were used by the author of this thesis.

At present there is no specific research on the kinematic validity of the Functional Movement Screen (FMS) (Kiesel et al., 2007), 9 test screening battery (Frohm et al., 2012) The Foundation Matrix (Mottram and Comerford, 2008).

To measure the kinematic validity of the observational rating in movement screening Whatman et al. (2015) suggested that 3D motion analysis was the gold standard for assessing joint kinematics. The Landing Error Scoring System (LESS) has been developed to identify individuals with poor jump landing technique who may be at risk of ACL injuries with 17 specific movement criteria (Padua et al., 2009). Agreement from experienced observers with the 3D motion analysis demonstrated substantial variation from 10% agreement for lateral trunk flexion at initial contact to 100% agreement for toes at greater than 30 degrees at initial contact (Onate et al., 2010). The apparent low validity of lateral trunk flexion reported by Onate et al. (2010) was due to the 3D motion analysis scoring all 19 participants as having the fault with a mere 1.0 ±0.8cm lateral trunk flexion. The low values for mean trunk flexion reported by Onate et al. (2010) suggests that the criterion may be too sensitive as only people with perfect vertical alignment would not be rated as having lateral trunk flexion.

There was large variation in the agreement between 3D kinematics and clinical observation for the LESS which suggests certain criteria are not valid such as knee flexion > 30° at initial contact (21% agreement) (Onate et al., 2010). However, as the LESS was assessed with video which a low ICC (0.23) has been reported for real time compared to video rating (Mischiati et al., 2015). The use of video to rate movement could affect the results. Nonetheless, the results from Onate et al. (2010) suggest some criteria such as knee flexion > 30° at initial contact from the LESS are not valid.

There has been limited research comparing the visual rating to 3D motion analysis for specific movement from movement screens. Medial knee movement during the small knee bend test is a commonly used to assess for poor hip movement control (Frohm et al., 2012, Mottram and Comerford, 2008, Botha et al., 2014) and is a potential predisposing factor for knee injuries (Mauntel et al., 2014). High observational validity measured using 2D motion analysis of the medio-lateral knee movement during a single limb mini squat was reported by Ageberg et al. (2010). A significant ($p<0.001$) difference in peak knee valgus angle in 2D (only using frontal plane coordinates from the 3D data) between the group that were observed to have medio-lateral knee motion compared to the group that did not. However, the increased valgus angle seen with 2D was not reported for 3D. In 3D there was significantly higher ($p=0.049$) hip internal rotation in the knee medial to ankle group compared to the knee over foot group. There was a non-significant difference in knee valgus reported in 3D kinematics between the medial knee group and knee over foot group (Ageberg et al., 2010). The lack of validity using 3D motion analysis suggests the medial knee movement fault is not valid related to kinematics. Although, there was a significant difference between the groups for hip internal rotation in 3D motion analysis (Ageberg et al., 2010). The apparent knee valgus seen in 2D may be due to rotation of the hip rather than a true valgus, which is supported by the significant higher hip internal rotation in 3D in the knee medial to ankle group reported by Ageberg et al. (2010).

The lack of significant difference in medial knee movement measured as valgus angle in 3D reported by Ageberg et al. (2010) may have been due to trying to measure knee valgus. Using medio-lateral displacement of the knee joint Horan et al. (2014) reported significantly ($p=0.02$) greater displacement of the knee joint centre 53.7 [SD 16.8] mm in those rated as having poor performance compared to those rated as good 38.4 [SD 14.3] mm. Rating for good or poor performance by Horan et al. (2014) was calculated using a 1 to 10 ordinal rating scale of overall performance and with good calculated from the upper tertile of the raters scores for their clinical observation. In contrast, the raters in the study by Ageberg et al. (2010) were observing for medial knee movement when the knee was placed medial to the 2nd toe or not. The results from Horan et al. (2014) suggest that there are significant differences in medial knee movement between groups. However, the raters in the study by Horan et al. (2014) where not specifically rating medial knee movement so it is not possible to say if the observational rating of medial knee movement is valid related to kinematics. Specifically comparing the observational rating of medial knee movement with the kinematic values during the small knee bend task needs to be assessed.

The findings of Ageberg et al. (2010) and Horan et al. (2014) suggest the potential that observation of medial knee movement during the SKB is valid related to knee kinematics. However, caution is needed when applying the results of Ageberg et al. (2010) to commonly used movement screens. Firstly, as highlighted by Whatman et al. (2015) validity is only related to the exact protocol used by the authors such as the movement fault criteria, the raters used and how much training they had. The SKB task used in the HLLMS developed by Botha et al. (2014) has some key differences such as no fingertip support and not looking down compared to Ageberg et al. (2010). The use of fingertip support by Ageberg et al. (2010) is not common practice (Frohm et al., 2012, Horan et al., 2014, Botha et al., 2014). The use of fingertip support could increase the stability of the participant's movement and making it easier to observe knee medial movement due to smoother movement.

The 3D kinematic validity of other movement faults from the SKB in the HLLMS such as trunk flexion have yet to be established. Another important consideration in applying the results from Ageberg et al. (2010) to Botha et al. (2014) is the effect of rating multiple movement faults. Ageberg et al. (2010) only had to score medial knee movement over five trial compared to Botha et al. (2014) where raters have to observe for five different movement faults in three repetitions which includes one repetition viewed from the side of the participant. The need to rate multiple criteria at various body segments such as the hip, pelvis and trunk used by Botha et al. (2014) is commonly required (Frohm et al., 2012, Mottram and Comerford, 2008). In the development of the HLLMS (Botha, 2013) and related to the findings outlined above there is the need for 3D kinematic validation of observations of multiple movement faults of all the movement tasks including hip abduction.

2.2.1 Validity of 3D motion analysis

Having considered the need to validate the observational rating with objective kinematics, the validity of the methods used to generate the kinematics will be considered. Objective measurement of movement patterns with 3D motion analysis, with the use of skin mounted retro reflective markers, is a common non-invasive method to quantify lower limb kinematics. Three dimensional motion analysis is suggested to be the gold standard for measuring kinematics (Maclachlan et al., 2015). However, the accuracy of 3D motion analysis has been questioned. Sources of error with the use of 3D motion analysis have been suggested including soft tissue artefact, marker misplacement, marker drop out, assumptions and constraints of the kinematic model (Cappozzo et al., 2005, Chiari et al., 2005, Della Croce et al., 2005, Leardini et al., 2005). Errors in placing markers on anatomical landmarks was suggested to be one of the biggest source of error (McGinley et al. 2009). The commonly used method of identifying a joint centre through anatomical landmarks can lead to errors due to the relative motion of those skin markers over bone known as soft tissue artefact (Taylor et al. 2005).

Three-dimensional motion analysis, using skin mounted retro reflective markers, is an increasingly common non-invasive method to quantify knee kinematics and kinetics (Boeth et al., 2013, Tsai et al., 2011). However, soft tissue artefact (STA), which is the relative motion of the markers compared to the underlying bone, limits the accuracy of 3D motion analysis. Soft tissue artefact can be split into two categories, the collective movement of the skin marker set over the underlying bones and secondly the displacement of the individual markers relative to each other (Taylor et al., 2005). The STA is caused by factors such as segment inertia and muscle contraction

(Barre et al., 2013) and can be prominent when performing dynamic rather than static movement tasks. Methods for reducing STA have been developed including the use of bone pins (Fuller et al., 1997) and software algorithms (Andriacchi et al., 1998, Taylor et al., 2005). However, the use of bone pins is both highly invasive and has been shown to affect gait mechanics (Akbarshahi et al., 2010). Software approaches to model and account for the effects of soft tissue motion have shown promise for reducing the effects of STA. However, the in vivo validation of such algorithms remains limited and determination of whether their application enables accurate assessment of the 3D arthro-kinematics across a spectrum of activities is yet to be determined.

Several methods to reduce soft tissue artefact (STA) with 3D motion analysis have been proposed including the use of clusters of markers placed on each segment with anatomical landmarks defined relative to the clusters (Cappozzo et al., 1995). To reduce soft tissue artefact, the Optimal Common Shape Technique (OCST) has been developed to create a rigid marker configuration from the complete segment marker data (Taylor et al., 2005). The OCST removes any motion of the makers relative to one another, which can be caused by soft tissue artefact during muscle contractions; thereby maintain the rigid body assumption for adequate determination of joint kinematics. There are limitations in directly applying the results from the study by Taylor et al. (2005) to the current study. The use of OSCT resulted in better prediction of bone kinematics but there was still a large average error in predicting the femoral head location of 15.9mm (Taylor et al., 2005). Additionally the study by Taylor et al. (2005) was carried out on sheep and during gait which may limit the application of the results to humans when performing other tasks than gait.

To further reduce potential error from variation in individual marker placement the use of a "functional approach" to defining joint centres and axes of rotation has been suggested (McGinley et al., 2009). The use of functional joint centres reduces measurement error through not relying on accurate identification of anatomical landmarks (McGinley et al., 2009) and identifies joint centres and axes from the trajectories of a larger number of markers attached to the articulating segments captured during dedicated movements. One method, the Symmetrical Centre of Rotation Estimate (SCoRE) has been reported to be the most accurate when both segments are moving (Ehrig et al., 2006). The SCoRE method has been shown as reliable in identification of the hip joint centre and insensitive to marker placement (Taylor et al., 2010, Heller et al., 2011, Kratzenstein et al., 2012). Defining the flexion axis of the knee is also a source of error as skin mounted markers might fail to reliably and accurately identify the medial and lateral femoral epicondyles, key anatomical landmarks thought to approximate a flexion-extension axis at the knee (Churchill et al., 1998). Moreover, whether a static axis defined by these landmarks can accurately represent the complex sliding hinge nature of the knee joint remains controversial

(Hancock et al., 2013). The Symmetrical Axis of Rotation Approximation (SARA) has been reported to produce the smallest errors in the estimation of joint axes. Combining OCST, SCoRE and SARA has been reported to be a reliable method for identification of joint centres and axes which increases the precision of lower limb kinematics compared to motion analysis systems that rely on identification of anatomical landmarks (Taylor et al., 2005).

There have been limitations reported in the use of 3D motion analysis related to soft tissue artefact and marker placement. The use of a functional approach outlined above have yet to be assessed in calculating the kinematics related to movement screen.

2.2.2 Validity of assessing responsiveness to change

Having considered the need to assess the criterion validity of the observational rating of movement patterns there is an obvious need to try and improve the movement patterns to reduce injury and the potential decline in joint health. Increased rates of OA in footballers, particularly in the hip warrant research on ways to reduce the impact on joint health. At present the main treatment for OA is to replace the joint. However, trying to treat the causes of OA at an early stage such as improving abnormal movement patterns could prevent the need for joint replacement. In relation to improving movement patterns in football the Fédération Internationale de Football Association (FIFA) FIFA 11+ a specific football warm up injury prevention programme has been developed and in a recent systematic review has been shown to significantly reduced injury incidence (Barengo et al., 2014). Despite the positive impact on injury incidence from the FIFA 11+, if a programme is intended to improve movement patterns it would be useful to see if these movement tools such as the HLLMS and 3D motion analysis can detect a change and are responsive to change.

An important consideration of the HLLMS is the ability to assess responsiveness to change. The HLLMS could be used as an outcome measure, but its validity and reliability are not yet proven. Developing a valid and reliable movement screen would assist in increasing the knowledge on how movement patterns may affect injury risk and joint health. There is some evidence that exercise programmes can change movement patterns and reduce symptoms in the shoulder (Worsley et al. 2013).

There is some conflicting research on exercise programmes changing lower limb movement. Knee valgus during the SKB is commonly assessed in movement screening. A six week neuromuscular training programme reported no significant change in peak knee valgus kinematics during the drop or stop jump task in female college athletes (Chappell and Limpisvasti, 2008). In contrast Herrington (2010) reported significant reduction in knee valgus (left leg reduced by 9.8°, p = 0.002, right leg reduced by 12.3°,p = 0.0001) in female basketball players following a four week training programme. It is difficult to state the specific cause of the differences between the two studies due to different methodologies used to measure knee valgus, Chappell and Livingstone (2008) used 3D motion analysis and Herrington (2010) used a digital video camera. A possible cause of the differences in the results could have been due to Herrington (2010) using a progressing jump training programme where correct technique was emphasised. In contrast Chappell and Livingstone (2008) used and intervention similar to the FIFA 11+. These results suggest that knee valgus can be changed with an exercise programme. Furthermore, Olson et al. (2011) reported a four week neuromuscular training programme significantly increased anterior tilt and contralateral pelvic drop during a step down in 20 females. In applying the results of the above studies in female athletes to males caution needs to be applied as Noyes et al. (2005) reported females had different knee kinematics to males and warrants investigation. Additionally the measurement of movement by the studies outlined above used time consuming and expensive equipment which Barker-Davis et al. (2018) commented limits its use in a clinical setting where funding may be limited and immediate clinical information is required. Movement screens such as the HLLMS are cheap and quick to administer, however it is not known if observational rating is valid in detecting the changes in movement that they assess.

To improve the lower limb movement patterns, a warm up exercise programme has been developed as part of Nadine Booysen's PhD, specifically addressing hip movement faults. There is a need to measure the effects of the exercise programme objectively by measuring kinematics. Providing evidence of changes in movement, similar to the shoulder study mentioned above (Worsley et al 2013), will increase the understanding of how movement may affect joint health and also help validate the HLLMS.

2.3 Reliability of observational rating and kinematics from movement screening

2.3.1 Movement kinematics

In developing a valid and reliable movement screen several areas need to be considered. The reliability of the kinematics and observational rating both need to be assessed and will be considered in the sections below. The kinematic reliability will be considered in the next section.

Whatman et al. (2015) suggested that the day-to-day reliability of the 3D kinematics needs to be measured to see if any change over time for example after an intervention is a true change not just due to natural variability. It is possible that the amount of medial knee movement in the study by (Horan et al., 2014) may not have had the same if measured several days later. There has been a lack of day-to-day reliability of the kinematics reported by Whatman et al. (2015). A between day (a week between sessions) ICC of 0.88 (95% CI 0.64 to 0.96, mean 93.06° SEM 2.16°) was reported for the variability in knee flexion during a small knee bend (Alenezi et al., 2014). However, the amount of knee flexion is not generally used as a criterion in movement screening. The medial knee displacement during the small knee bend task is commonly used to assess a movement fault. The day-to-day variability of peak medial knee displacement during a SKB was reported to be high with a mean difference of 1.0cm (range 0.0-2.0) with and ICC range of 0.59-0.93 for three trials (Whatman et al., 2011). In comparison within day variability was substantially lower for peak medial knee displacement mean 0.5cm (range 0.2-0.7) and ICC 0.94-0.98 (Whatman et al., 2011).

The reliability values for within and between day-to-day for knee kinematics reported above suggest a high level of reliability. Though the generalisability of the values reported by Alenezi et al. (2014) are suggested to be limited as protocol conditions may affect them (Whatman et al., 2015). Additionally the values outlined for variability in peak knee medial knee displacement by Whatman et al. (2011) may not reflect true variability due to use of a marker pen to aid placement of the markers in repeat testing. Variation in marker placement (discussed later in this literature review, Section 2.4) could lead to differences in kinematics above natural variation and needs to be considered when measuring day to day variability in kinematics. While there are limitations in the studies by Alenezi et al. (2014) and by Whatman et al. (2011) they highlight the need to measure within and between day variation in kinematics.

2.3.2 Observational rating reliability

The inter-rater reliability is an important part of validating any measurement tool. There are various measures of inter-rater reliability used with movement screening including ICC for total score, percentage agreement and kappa values for specific criteria (Frohm et al. 2012; Whatman et al. 2012; Mischiati et al. 2015). For raters to reliably classify a person's movement pattern there needs to agreement at each criterion suggesting agreement of these is more important than total score of a movement screen.

2.3.3 Within session intra-rater

There was limited research on the within session intra-rater agreement using multi segment and multiple criteria. One study by Mischiati et al. (2015) used multi segments and multiple criterion rating, and reported overall intra-rater agreement using video footage for the two raters of 97.5% (range 87.5-100%) and 93.9% (range 75-100%). However, the agreement is only relevant to the methodology used and the movements assessed. The movements and criteria rated in the study by Mischiati et al. (2015) are considerably different from those in the HLLMS and highlight the need to establish the within session intra-rater agreement using video footage.

2.3.4 Between day intra-rater

The between day intra-rater agreement is important to measure the natural variation in both the raters scoring and participants performance of a movement screen. With a measure of the between day variation it can be compared to the change in ratings from pre to post intervention to see if a true change has occurred that is above the natural day to day variation.

There has been some research on the between day reliability of the rating of movement screens. A range of ICC values have been reported for intra-rater between day agreement for the FMS composite score from ICC = 0.76 (95% CI: 0.63, 0.85) by Teyhen et al. (2012) to ICC = 0.6 (95% CI: 0.35, 0.77) reported by Schultz et al. (2013). These results suggest that even for a composite score there was some variation in the rating for the FMS. The intra-rater between day agreement for individual tests that assessed movement quality including the single leg squat was reported by Tarara et al. (2014) with weighted Kappa scores ranging from -0.09 to 0.81. The study by Tarara et al. (2014) assessed between day agreement of movement quality using a scale of 0 to 5, with the higher the score the less errors. However, the results of Tarara et al. (2014) do not assess the between day agreement of specific movement patterns such as trunk flexion that are rated in the HLLLMS. The studies outlined above highlight the need to assess between day intra-rater agreement for specific movement patterns from the HLLMS.

2.3.5 Inter-rater agreement

One key consideration of a movement screen is the inter-rater reliability, so that independent of rater the score is consistent. A range of slight to excellent inter-rater agreement for movement screening has been reported in the literature (Whatman et al., 2015). However, it is important to consider exactly what inter-rater agreement was measured for example total score or specific faults. A high ICC (0.81) was reported for total score between the eight raters, in contrast a wide range in ICC (0.3 to 0.85) was reported for individual test scores within the 9 test battery (Frohm et al., 2012). For a reliable movement screen, it should have high agreement on each fault not just the total score for all the tests. For example, two raters may have the same total scores but markedly different scores for each fault. For specific movement faults a high inter-rater agreement for the medial movement of the knee during a single limb mini squat (96% agreement, Kappa 0.92 (95% CI, 0.75 to 1.08) was reported by Ageberg et al. (2010). However, Ageberg et al. (2010) only had one fault to rate and when multiple faults are rated the inter-rater agreement may be reduced. In regards to the inter-rater agreement of rating multiple movement criterion of different segments of the body Mischiati et al. (2015) reported high levels of percentage agreement (86.5%, range 67.5-100%). In contrast lower ranges of inter-rater percentage agreement were reported by Whatman et al. (2012) of 45-79% and 32-82% by Chmielewski et al. (2007). The low inter-rater percent agreement reported by Whatman et al. (2012) and Chmielewski et al. (2007) may have been due to them using video recordings to rate agreement or rating of different movements to those in the HLLMS. The low inter-rater agreement using video footage may be due to raters not being able to get a clear view of the fault compared to real time. In support of the effect on rating of using video footage or rating in real time Mischiati et al. (2015) reported a mean agreement between using video footage and real time of 74.5% (range 30.8-100%) for the movement criteria from The Foundation Matrix. The results above highlight the variation and potentially low inter-rater agreement of some of the movement criterion assessed in movement screening. As the HLLMS is new movement screen with no published data on the inter-rater agreement, there is a need to establish the inter-rater agreement for the individual criterion to develop a reliable screen.

2.4 Summary

Altered movement patterns may affect joint health and be related to hip conditions such as FAI. There is a need to establish the validity of an effective hip screening tool to identify modifiable movement faults that could be addressed by an intervention. Currently there is a lack of research validating the observational rating of movements

Observational movement screens could be low cost and easily accessible method to screen a large number of people. Movement screening with 3D motion analysis technology in the laboratory is difficult on a large scale due to both expense and practicality. However, the observational HLLMS needs to be shown to be valid and reliable tool.

One of the issues identified when undertaking this literature search is the wide array of terms used in relation to movement screening and consistency on defining movement screening which makes collating the research difficult. This is highlighted by conflicting terms used by different authors such as functional screening tests by Whatman et al. (2015) and movement control tests used by Mischiati et al. (2015). Part of the PhD is to be involved in the setup of an international group on movement screening to try and reach consensus on definitions in this field of research. One of the early tasks is to identify all the terms used in movement screening to try to ascertain all the researchers working in the area. Additionally, there is clearly a need to define and encourage the use of a consistent terminology.

2.5 Aims of the present study

2.5.1 Overall aim

To examine the validity and reliability of the HLLMS

2.5.2 Specific aims

2.5.2.1 *To assess the criterion validity using 3D motion analysis of the observed faults from the HLLMS in young males.*

2.5.2.2 *To assess the inter-rater and intra-rater reliability of the HLLMS.*

2.5.2.3 *To assess the change in movement patterns and muscle activation post exercise intervention in adolescent male footballers to test sensitivity to change in the screen and 3D motion analysis.*

Chapter 3: **General Methodology**

3.1 Introduction

This chapter describes the procedures utilised commonly for data collection for the Hip and Lower Limb Movement Screen (HLLMS) in the laboratory. Any changes from the methodology reported below are detailed in the relevant chapters.

3.2 Participant recruitment

Several studies were carried out to collect the data for this thesis. The general methodology section provides details of the studies on the male academy footballers and controls (young male students) only as data from these studies are used in several chapters. Methodological details of other studies in this thesis are presented within the relevant individual chapters.

3.2.1 Footballers

Suitable football clubs in the South Central region were identified by Nadine Booysen (NB) through discussion with the coach patient and public involvement (PPI) representative (Lee Peacock) to assist in selecting clubs with similar level of football skills and training. All male footballers aged 15-19 years from appropriate local semi-professional football clubs were invited to take part.

Before the start of the investigation the purpose of the study and data collection procedure was fully explained to all participants (ages 15-19) and to the guardian/parents of the participants aged 15-17 years. A participant information sheet (PIS) was given to all the participants and parents of the participants aged 15-17 years. The consent procedure for the different age categories are described below:

Age 15-17: Parents/guardian signed an informed consent form prior to data collection. In addition, each child gave verbal assent with the researcher and the participant signing a form as evidence that assent had been given.

Age 18-19: Participants signed informed consent form document. It was emphasised that participation in the project was voluntary.

Participants who were interested in taking part signed consent forms and their parent/guardian signed consent forms if they were under 18 years old. Completed consent forms were given to the coaches and passed on to the lead researcher David Wilson.

3.2.1.1 *Player exclusion criteria*

Potential participants were included or excluded based on specific criteria which was devised to screen potential participants and ensure validity and generalisation of results (Table 3-1).

Table 3-1 Intervention study inclusion and exclusion criteria

Player Inclusion criteria	**Football Club Inclusion criteria**
• Young male amateur footballers aged 15-19 years	• Clubs practice two to five times a week and play between 15-30 matches during season
Player Exclusion criteria	
• Professional footballers	
• Injured and unable to take part in football training and/ or matches	
• Systemic disease (e.g. cancer, arthritis, heart disease)	
• Lumbar spine pathology (disc problems, nerve root pain)	
• Neurological disorders (e.g. head injury)	
• Bone or joint problems (e.g. osteomyelitis, osteitis pubis, perthes' disease)	
• Any conditions preventing full participation in all organised football activities	
• Allergies to tape	

3.2.2 Controls

The sample size for the control study was based on the formula by (Bonett, 2002) using an ICC of 0.8 and a desired width of 95% CI of 0.35 for the kinematics from the HLLMS. The ICC values were selected based on aiming to attain an excellent ICC, above 0.75. This was similar to the combined day-to-day ICC of 0.81 for the single leg squat kinematics reported by Alenezi et al. (2014). The 95% CI of 0.35 was selected to keep the lower end of the ICC within the range of a good correlation and to set a realistic sample size for data collection. The sample size for this study was similar to that of Alenezi et al. (2014) (15 participants) and Whatman et al. (2013) (23 participants) who analysed reliability of single leg squat kinematics.

3.2.2.1 *Method of recruitment and achieving informed consent.*

Participants were recruited through posters displayed at the University of Southampton and an advert placed on the University of Southampton website (SUSSED). Participants interested in taking part in the study were provided with a Participant Information Sheet (Appendix D) with details of what the study involves and highlighting any potential risks. Participants that agreed to take part contacted the lead researcher, DW and a time was agreed for data collection in the laboratory. Participants signed a consent form (Appendix E) instructing that they agree to take part in the study prior to commencement of data collection.

3.2.2.2 *Exclusion criteria*

Participants were excluded if they had any lower limb pain, diagnosed with lower limb pathology, any musculoskeletal, neurological or systemic diseases, skin diseases (allergies), lower limb or spinal fractures and not between the ages of 18 to 30 years old.

3.3 Hip and Lower Limb Movement Screening tool

The HLLMS, developed by Botha et al. (2013), was carried out in a standardised manner outlined below. The screen consists of seven tests, small knee bend (SKB) (Figure 3-1), SKB with trunk rotation (SKB Rot) (Figure 3-2), standing hip flexion (Figure 3-3), deep squat (Figure 3-4), sitting hip flexion (Figure 3-5), hip abductor rotation stabiliser test with medial and lateral rotation (Figure 3-6, Figure 3-7). The participants were given three to six practice attempts and given guidance if required to correct movements, such as keeping the trunk upright during the SKB, which was similar to the methodology used by Mischiati et al. (2015). The tests from the HLLMS evaluate the performance of an unfamiliar movement and not a natural functional movement. It is important that a person was judged to fail a test because of poor active cognitive control of movement, not because they were unsure of what the control task required. Additionally, coaching prior to assessment should reduce the trial to trial variability. The tests were performed in the same order and the raters stood either in front or to the side of the participant that was being rated. Right and left sides were assessed and rated for each participant. The side rated first was noted to assess if a learning affect was present.

During the Movement Control tests for 'SKB' and 'SKB with trunk rotation' outlined below, the participant stood on one leg which was placed in a position with the 2nd metatarsal aligned along the 10° neutral line of weight transfer. Placing the foot in this orientation ensures a correct and neutral foot position according to Comerford and Mottram (2012) . Participants were instructed to maintain a level pelvis and the trunk positioned vertical. The individual stands on one leg by flexing the unsupported knee to 90°, hip at 0° with the thigh aligned in neutral, so the foot is behind the body (Chmielewski et al., 2007). The participant was instructed to perform a small knee bend, by flexing the knee and dorsi-flexing the ankle of the supporting leg whilst aiming to keep the heel on the floor. The individual is then asked to bend the knee, without bending forward from the hips, until he/she can no longer see the top bar of the T-shape along the toes (corresponding to more than 2 cm over the 2nd metatarsal or approximately 50° of knee flexion) (Ageberg et al., 2010, Bremander et al., 2007). For each trial the participant was given several practice trials where feedback was given to try and correct any movement faults. Feedback was given as the test is designed to see if the participant can correct movement faults, a test of their ability to control certain movements not how they naturally perform the task.

3.3.1 Small Knee Bend (SKB) test

The SKB test was included in the HLLMS as it is commonly used movement to assess the ability to maintain balance, postural control, and lower body alignment (Crossley et al., 2011). Furthermore, the SKB test is used in single leg stance and drop down landing studies, where poor control of hip and knee alignment (in particular uncontrolled hip medial rotation and knee valgus) along with poor control of pelvic tilt and rotation increases lower extremity injury risk (Dingenen et al., 2014; Dingenen et al., 2015; Dingenen et al., 2016). Additionally, Crossley et al. (2011) demonstrated weaker and slower muscle activation of the hip abductors of those who had poor control, which included medial knee movement.

During the SKB test the body weight was kept on the heel rather than the ball of the foot. The knee should be guided over the 2nd metatarsal and move 2 cm past the toes.

Verbal instructions

- Stand on one leg with your foot pointing forward.
- Place the unsupported foot behind you by bending your knee.
- While keeping upright, keeping your pelvis and heel in position, bend your knee so that your knee keeps inline and moves over your 2nd toe.

- Do you understand the instructions?

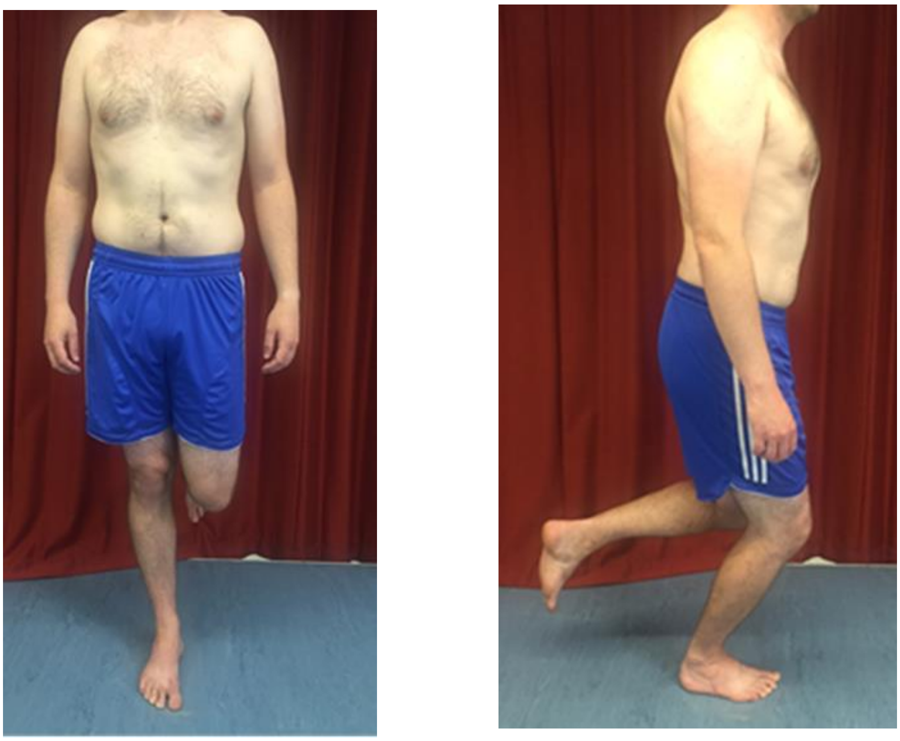


Figure 3-1: Start position (right image) and bottom of knee flexion (left image) for small knee bend test on right leg

3.3.2 SKB with trunk rotation test (SKB Rot)

The reasons for the inclusion of the SKB Rot test in the HLLMS are similar to the above outlined for the SKB. Additionally the SKB Rot test assesses relative stiffness (restrictions) of thoracolumbar rotation, while maintaining pelvic control (Comerford and Mottram, 2012). Sports such as football, involving actions like tackling, kicking, sprinting and change of direction require trunk rotation to facilitate the required movement task. Holding the SKB and then rotating the trunk assesses stability and control of the trunk while maintaining pelvic control. The test assesses ability to actively dissociate and control hip medial and lateral rotation independently of trunk rotation (Comerford and Mottram, 2012).

Participants perform movement as for SKB with the addition of rotating the upper trunk approximately 30° whilst keeping the pelvis facing forwards. The SKB Rot test is designed to assess control of hip rotation when other parts of the body move, a key concept of movement screening. The participants rotates towards the side of the weight bearing leg initially then to the opposite side.

Verbal instructions

- Stand on one leg with your foot pointing forward.
- Arms placed across your chest.
- Place the unsupported foot behind you by bending your knee.
- While maintaining an upright torso, keeping your pelvis and heel in position, bend your knee so that your knee aligns along your 2nd toe.
- While holding this position turn your upper body to the left and right looking over your shoulder
- Do you understand the instructions?

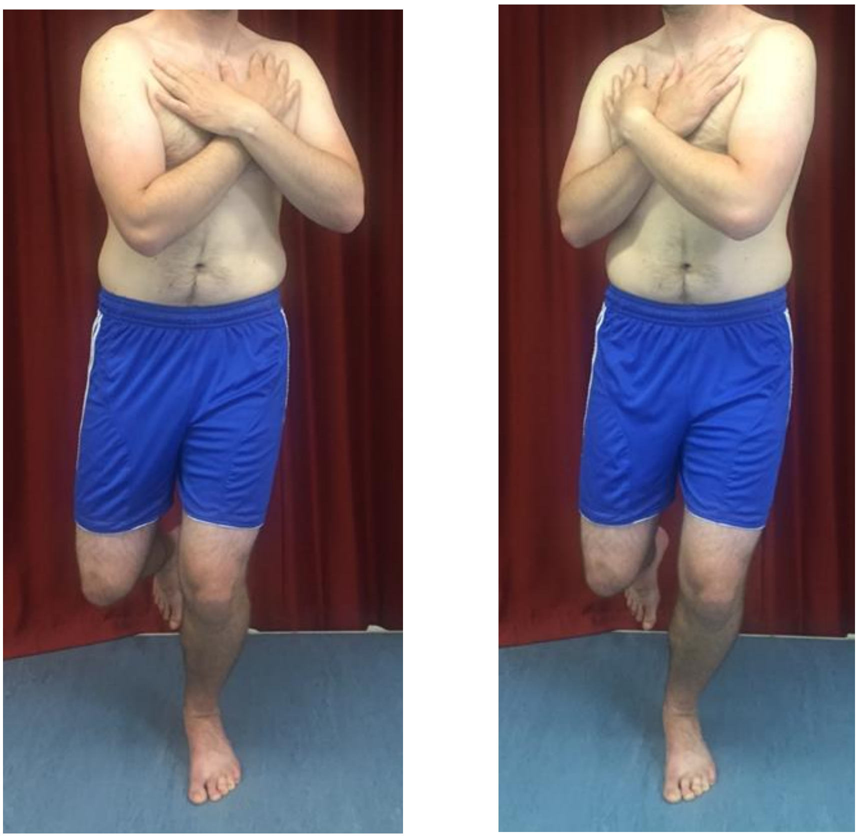


Figure 3-2: Small knee bent test with rotation showing trunk rotation to right and left with left leg being rated

3.3.3 Standing hip flexion test (Hip flex 0-110°)

The standing hip flexion test assesses the specific muscle recruitment of the hip flexor stabilisers (iliacus/pectineus) (Hislop and Montgomery, 2007) which poor control is associated with dysfunction of hip abductor muscles (Morrissey et al., 2012). The test assesses ability to actively dissociate and control hip lateral rotation/abduction (Comerford and Mottram, 2012).

The participant stands with the pelvis maintained level and the trunk vertical. The participant is instructed to lift the non-weight bearing leg so that the hip flexes to 110°, with knee flexion.

Verbal instructions

- Stand with your feet approximately pelvis width apart and the toes pointing forward.
- Place your arms across your chest.
- While maintaining an upright torso, keeping your pelvis steady and knee locked on the standing leg, raise the opposite leg, flexing your hip to 110°.
- Do you understand the instructions?

Figure 3-3: Anterior view and lateral view of standing hip flexion test with right leg being rated

3.3.4 Deep squat test.

The deep squat test assess the major joints of the lower body (i.e. ankle, knee and hip) and the lumbar and thoracic spine requiring adequate stability and mobility to ensure a competent squat pattern (Sahrmann, 2002). In addition it assesses pelvic stability and function of the rectus femoris, hamstrings, hip abductor and adductor muscles (Sahrmann, 2002, Claiborne et al., 2006). Inability to perform a bodyweight squat at or below 90 degrees of knee flexion with balance, symmetry, and control may imply generalised body stiffness or restricted joint mobility and/or stability within the kinetic chain (Cook, 2003, Cook et al., 2006). Patients with FAI, demonstrated less squat depth and altered lumbo-pelvic kinematics (Lamontagne et al., 2009, Bagwell et al., 2016). The reasons outlined above support the inclusion of the deep squat within the HLLMS.

The starting positon for the deep squat involves is the participant standing with the pelvis maintained level, the trunk vertical and arms horizontal in front of the shoulders.

Verbal instructions

- Stand with your feet approximately shoulder width apart and the toes pointing forward.
- Place your arms forward.
- While maintaining an upright torso, keeping your heels in position and your weight equal, move down as deep as possible aligning your knee to your 2nd toe.
- Do you understand the instructions?

Figure 3-4: Deep squat test at lowest point of squat

3.3.5 Sitting hip flexion test (flex 90°-110°)

The sitting hip flexion test is similar to the standing hip flexion test in that it assesses specific muscle recruitment of the hip flexor stabilisers (iliacus/pectineus) (Hislop and Montgomery, 2007). The test also places additional stress on the ability to actively dissociate and control hip rotation and lumbo-pelvic alignment, due to offloading of the muscles that anteriorly tilt the pelvis that are used in standing (Comerford and Mottram, 2012).

The participant sits with hip and knee flexed to 90°. The pelvis is maintained level and the trunk positioned vertical while the feet were not touching the floor.

Verbal instructions

- Sit with your arms across your chest.
- While maintaining an upright torso, keeping your pelvis steady raise the opposite leg, flexing your hip to 110°, making sure to maintain your foot aligns with the ankle, knee and hip.
- Do you understand the instructions?

Figure 3-5: Sitting hip flexion test with left leg being rated at peak hip flexion

3.3.6 Hip abductor rotation stabilisers test.

The hip abductor rotation stabiliser tests assess trunk and pelvic control during active lower limb movement from an unstable position (Nelson-Wong et al., 2009), and assesses the maintenance of neutral trunk and pelvic alignment in the frontal plane (Davis et al., 2011). Poor control may be associated with reduced stabilising ability of the gluteal lateral rotators, especially deep posterior gluteus medius and maximus (Comerford and Mottram, 2012). Additionally, hip abduction with medial rotation assesses the function of medial rotator stabilisers which include gluteus minimis and deep anterior gluteus medius (Hislop and Montgomery, 2007). The lack of hip medial and lateral rotation have been associated with poor lower limb movement control including knee valgus (Crossley et al., 2011).

In tests for hip abductor lateral and medial rotator stabilisers the participant is in side lying with the pelvis and spine in neutral alignment and the bottom leg flexed for support. The uppermost leg was kept straight and rested on the lower leg, with the hip extended as far as no lumbar extension or anterior pelvic tilt occurs. The participant was instructed to lift the upper leg towards the ceiling (into hip abduction).

3.3.6.1 *Hip abductor lateral rotator stabilisers test (deep posterior Gluteus Medius and deep intrinsic Lateral Rotators) - The uppermost leg, the hip is laterally rotated.*

Verbal Instructions

- Lie on your side with your bottom leg flexed for support.
- While maintaining leg extension, a straight back and your leg turned outward, lift your leg towards the ceiling (approximately 45° while keeping your pelvis steady.
- Do you understand the instructions?

Figure 3-6: Hip abductor lateral rotator stabiliser task, starting position (top image) and peak hip abduction (bottom image)

3.3.6.2 *Hip abductor medial rotator stabilisers test (Gluteus Minimis and deep anterior Gluteus Medius) - The uppermost leg, the hip is medially rotated.*

Verbal Instructions

- Lie on your side with your bottom leg flexed for support.
- While maintaining leg extension, a straight back and your leg turned downward, lift your leg towards the ceiling (approximately 30°) while keeping your pelvis steady.
- Do you understand the instructions?

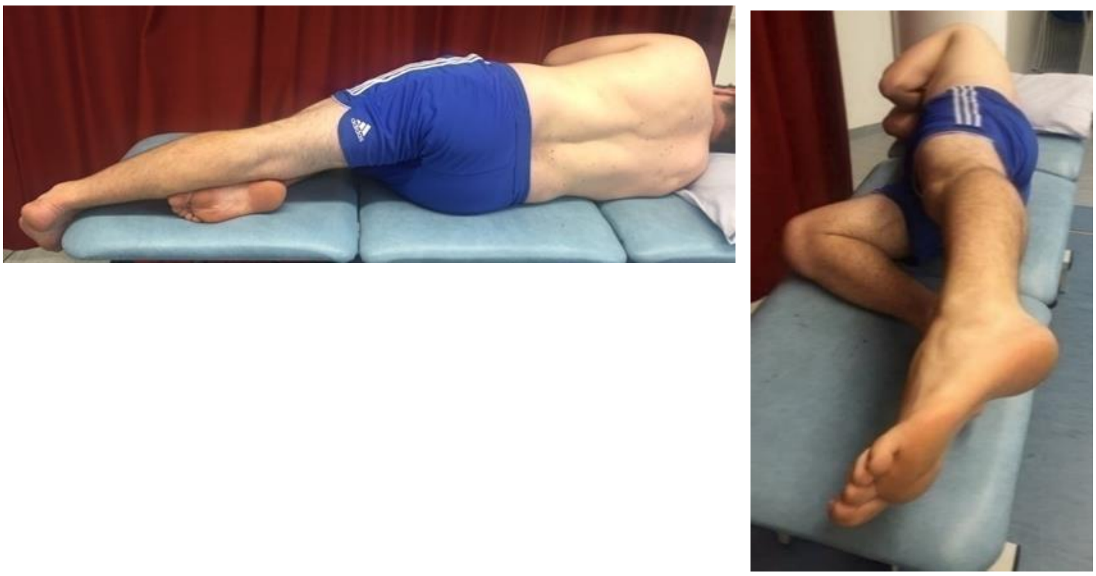


Figure 3-7: Hip abductor medial rotator stabiliser task, starting position (left image) and peak hip abduction (right image)

Participants performed the HLLMS and were rated in a standardised manner. Scoring of the movement faults were recorded on the HLMMS scoring sheet (Table 3-2). Movement control was assessed as either demonstrating control or no control. Participants were permitted three practice trials with verbal prompting to correct any faults by the rater. The participants then carried out the seven tests whilst data were recorded for three trials.

Table 3-2: HLLMS scoring sheet, version 3, permission gained from Botha (2013)

Movement Control Test				
Test	**Verbal Instruction**	**Outcome**		
SKB Test	• Stand on one leg with your foot pointing forward. • Place the unsupported foot behind you by bending your knee 90°. • While keeping your body upright, keeping your pelvis and heel in position, bend your knee so that your knee is in line with your 2nd toe and moves past it until you can no longer see the tape line. • Do you understand the instructions?		Right	Left
		Does the knee move inward from the 2nd toe?	Y=1 N=0	Y=1 N=0
		Does the pelvis drop (hitch) on the weight bearing side?	Y=1 N=0	Y=1 N=0
		Does the knee fail to move 2cm past the toes?	Y=1 N=0	Y=1 N=0
		Does the trunk lean forwards (flex)?	Y=1 N=0	Y=1 N=0
		Does the pelvis tilt forwards (anterior)?	Y=1 N=0	Y=1 N=0
		Total Score		
SKB with Trunk Rotation Test	• Stand on one leg with your foot pointing forward. • Place the unsupported foot behind you by bending your knee 90°. • While keeping your body upright, keeping your pelvis and heel in position, bend your knee so that your knee aligns along your 2nd toe. • While holding this position turn your upper body to the left and right looking over your shoulder 30° • Do you understand the instructions?		Right	Left
		Does the hip and pelvis follow the trunk?	Y=1 N=0	Y=1 N=0
		Does the trunk side-bend?	Y=1 N=0	Y=1 N=0
		Does the pelvis drop (hitch) on the weight bearing side?	Y=1 N=0	Y=1 N=0
		Does the trunk rotate less than 30°?	Y=1 N=0	Y=1 N=0
		Do the toes claw or any loss of balance?	Y=1 N=0	Y=1 N=0
		Does the trunk lean forwards (flex)?	Y=1 N=0	Y=1 N=0
		Total Score		
Standing Hip Flexion Test	• Stand with your feet approximately hip width apart and the toes pointing forward. • Place your arms across your chest. • While keeping your body upright, keeping your pelvis steady and knee locked. Raise the opposite leg, bending your hip up to 110°. •Do you understand the instructions? **Rating the weight bearing leg**		Right	Left
		Does the pelvis drop (hitch)?	Y=1 N=0	Y=1 N=0
		Does the pelvis tilt backwards (posteriorly)?	Y=1 N=0	Y=1 N=0
		Does the hip fail to bend (flex) just beyond 90 degrees (approximate 110 degrees)?	Y=1 N=0	Y=1 N=0
		Does the trunk lean backwards (extend)?	Y=1 N=0	Y=1 N=0
		Does the weight bearing knee bend (flex)?	Y=1 N=0	Y=1 N=0
		Total Score		

Deep Squat	• Stand with your feet approximately shoulder width apart and the toes pointing forward. •Place your arms forward. •While keeping your body upright, keeping your heels in position and your weight equal, move down as deep as possible aligning your knee to your 2nd toe. Your upper thigh needs to be horizontal with the floor. •Do you understand the instructions?	Does the trunk fail to stay parallel with the shin (tibia)? Does the thigh (femur) fail to be horizontal with the floor? Does the pelvis tilt forwards (anteriorly)? Does the bodyweight shift to one side?	Y=1 N=0 Y=1 N=0 Y=1 N=0 Y=1 N=0	
		Total Score		
Sitting Hip Flexion Test	• Sit with your arms across your chest. • While keeping your body upright, keeping your pelvis steady raise the opposite leg, bending your hip to 110°, making sure to maintain your foot alignment with the ankle, knee and hip. • Do you understand the instructions?	Is there axial rotation of the pelvis? Does the pelvis hitch? Does the foot fail to align with the ankle, knee and hip? Does the pelvis tilt backwards (posteriorly)? Does the hip fail to bend (flex) just beyond 90 degrees (approximate 110 degrees)? Does the trunk lean backwards (extend)?	Right Y=1 N=0 Y=1 N=0 Y=1 N=0 Y=1 N=0 Y=1 N=0 Y=1 N=0	Left Y=1 N=0 Y=1 N=0 Y=1 N=0 Y=1 N=0 Y=1 N=0 Y=1 N=0
		Total Score		
Hip Abduction lateral rotators Test	•Lie on your side with your bottom leg bent for support. •While maintaining the leg straight, with the upper body straight and your leg turned outward, lift your leg towards the ceiling 45° while keeping your pelvis steady. •Do you understand the instructions?	Does the leg lose outwards (lateral) rotation? Does the hip/knee (leg) move forwards(flexion)? Does the pelvis rotate backwards (not stay vertical)? Does the pelvis hitch?	Right Y=1 N=0 Y=1 N=0 Y=1 N=0 Y=1 N=0	Left Y=1 N=0 Y=1 N=0 Y=1 N=0 Y=1 N=0
		Total Score		
Hip Abduction medial rotators Test	• Lie on your side with your bottom leg flexed for support. • While maintaining leg extension, a straight back and your leg turned downward, lift your leg towards the ceiling while keeping your pelvis steady. •Do you understand the instructions?	Does the leg lose downwards (medial) rotation? Does the hip/knee (leg) move forward(flex)? Does the pelvis move backward (not stay vertical)? Does the pelvis hitch?	Right Y=1 N=0 Y=1 N=0 Y=1 N=0 Y=1 N=0	Left Y=1 N=0 Y=1 N=0 Y=1 N=0 Y=1 N=0
		Total Score		

3.4 Motion Analysis

3.4.1 Motion capture system

A Vicon Motion Capture System with 12 cameras (6 x T40 and 6 x T160) recording at 100Hz was used to capture marker locations in order to determine kinematics. The cameras were fixed to the ceiling around the walkway at approximately 2.5m above the floor. The capture volume of approximately 2.5m height, 9m length and 3m width.

3.4.2 System calibration

Before each testing session the motion capture system was calibrated in two stages, dynamic and static. The dynamic calibration determines the position of the cameras in relation to each other. The system calibration active T frame (Figure 3-8) was moved around the capture volume in different orientations ensuring the wand was visible to as many cameras as possible. Dynamic calibration was complete once all the cameras had captured 2400 frames. The system provided a residual error score for each camera and was deemed as acceptable if the mean residual error was 1 mm or less. Calibration was repeated if the error was deemed unacceptable.

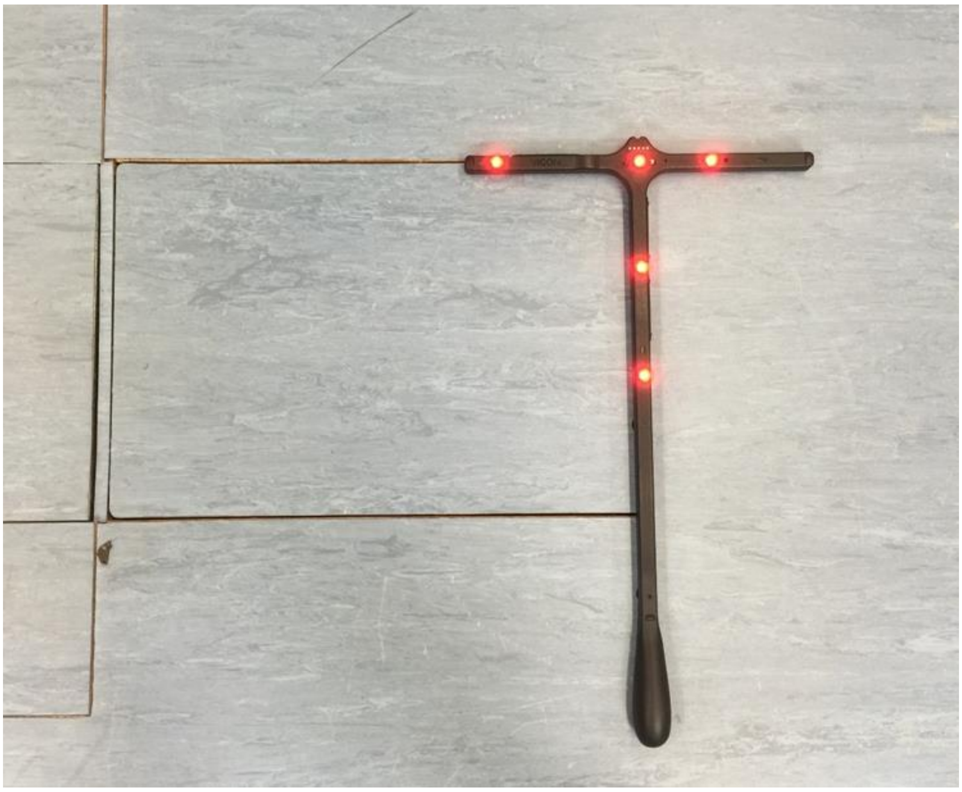


Figure 3-8: Active marker T frame used for calibration in position on force platform to identify the origin.

Following completion of dynamic calibration, the active marker T frame was aligned with the force platform (Kistler AG, Switzerland) embedded within the walkway and positioned so that X axes was pointing forward, Y pointing left and Z upwards and could be obtained for the global coordinate system.

3.4.3 Participant Preparation

Participants wore shorts, removed clothing from their upper body to allow attachment by DW of retro reflective markers to the participant's skin with double sided tape. Markers were placed in accordance with the requirements for functional gait analysis (Kratzenstein et al. 2012; Boeth et al. 2013; Trepczynski et al. 2014). Markers measuring 14mm diameter were placed on the thorax and pelvis and 6.5mm markers on the legs and feet. In total 48 markers were placed on the participant. Marker placement was based on the work by Heller et al. (2011) and Kratzenstein et al. (2012) and discussion with supervisors (Figure 3-9 and Table 3-3).

Figure 3-9: View of anterior location of reflective markers.

Thorax marker placement

Markers were placed on the sternal notch, xiphoid process, C7 and T8 spinous processes, four in total.

Pelvis marker placement

Markers were placed on the anterior superior iliac spine (ASIS), posterior superior iliac spine (PSIS), iliac crest bilaterally, six in total.

Thigh marker placement

Marker were placed on the anterior superior thigh midway between the patella and ASIS and inferior thigh half way between the superior marker and patella. Markers were placed on the lateral and posterior thigh level with the superior and inferior anterior markers. Markers were placed on the lateral and femoral condyle which was located by palpation during knee flexion on the non-weight bearing leg. Markers were attached bilaterally with 16 in total on the thighs.

Shank marker placement

The superior tibial marker was placed on the tibial tuberosity and anterior inferior tibial marker was placed halfway between the superior marker and the ankle. The lateral and posterior shank markers were placed at the same levels as the anterior markers. Markers were also placed on the lateral malleolus and medial malleolus. Markers were attached bilaterally on the shank with 16 markers in total.

Foot marker placement

Markers of the foot were placed on the heel (posterior calcaneus), dorsal aspect of 5th metatarsal head and the dorsal aspect of 1st metatarsal head. Markers were placed bilaterally on the feet with 6 in total.

Table 3-3: Marker name and placement location, R(L) – bilateral placement, 48 in total.

Name	Placement location
C7	Spinous process of 7th cervical vertebrae
T8	Spinous process of the 8th thoracic vertebrae
IJ	Deepest point of the Incisura Jugularis (suprasternal notch)
PX	Xiphoid process
R(L)ASI	Anterior superior iliac spine (ASIS)
R(L)PSI	Posterior superior iliac spine (PSIS)
R(L)ILC	Iliac crest
R(L)AntSupThi **R(L)LatSupThi** **R(L)Pasiphae**	Superior thigh marker - midpoint ASIS to patella on anterior/lateral and posterior thigh
R(L)AntInfThi **R(L)LatInfThi** **R(L)PosInfThi**	Inferior thigh marker - midpoint between superior thigh marker and patella on anterior/lateral/posterior thigh
R(L)LatKne	lateral femoral condyle
R(L)MedKne	medial femoral condyle
R(L)AntSupTib **R(L)LatSupTib** **R(L)PosSupTib**	Superior tibia marker – level with tibial tuberosity on anterior/lateral/posterior shank
R(L)AntInfTib **R(L)LatInfTib** **R(L)PosInfTib**	Inferior tibia marker midpoint between superior tibia marker and ankle on anterior/lateral/posterior tibia
R(L)LatAnk	lateral malleolus
R(L)MedAnk	medial malleolus
R(L)Heel	heel (posterior calcaneus)
R(L)5thMet	dorsal aspect of 5th metatarsal head
R(L)Toe	dorsal aspect of 1st metatarsal head.

Pilot work revealed substantial marker drop out during the side lying hip abduction test during the HLLMS. To improve identification of the retroreflective markers the lower supporting leg markers, which were not of interest, were obscured from the cameras by a blanket.

3.4.4 Calibration movements

A static trial was recorded where the participant was asked to stand still whilst a five second recording was taken.

Participants performed the Star movements of the hip to determine functional hip joint centres (Camomilla et al., 2006). The Star was performed on the non-weight bearing leg with the knee extended and consisted of hip flexion, extension and abduction to around 30°. The hip was abducted at 45°, 90° and 135° in the sagittal plane. Three repetitions of each movement were performed on each leg. Knee flexion from 0° to 90° was performed on the non-weight bearing leg on the right and left sides to determine knee functional axes. The final calibration movement was a single repetition of a small squat which was used for auto labelling in Nexus.

3.4.5 HLLMS data collection

Kinematic data were collected whilst the participants were rated performing three separate trials on the right and left side of each test movement from the HLLMS.

3.5 Data processing

3.5.1 HLLMS observational rating

3.5.1.1 *Data management*

Observational ratings for the faults from the HLLMS were inputted into Microsoft Excel 2013.

3.5.2 Three-dimensional motion analysis

3.5.2.1 *Data management – pre-processing*

All data management was carried out by DW. Motion Analysis data were recorded via Vicon Nexus software (Version 2.3). Following data collection marker data were post-processed using Nexus, which includes labelling markers and ‘gap-filling’ using the rigid body algorithm available within the Nexus software. The rigid body gap filling option takes a number of marker trajectories and assumes these move as a rigid body. The gaps in the trajectory of the marker are filled as if the trajectory is part of the same body. To gap fill a marker, three markers were selected that were surrounding the marker with a gap. The markers used to gap fill needed to have no gaps, be in different planes (i.e. not in a straight line) and not have been gap filled themselves.

3.5.2.2 *Data management – estimating kinematics*

The Optimal Common Shape Technique (OCST) was used to reduce the effect of soft tissue artefact using a local optimisation method during the Star movement (Taylor et al., 2005). The OCST, using a generalised Procrustes analysis (GPA) technique generated an average shape for the markers for a given segment. During the Star movement on the right side a right pelvis and right thigh average shape was determined using a GPA and the same for the left side. During the knee flexion cycles from 0-90° a right thigh and shank average shape was determined using a GPA and the same for the left side. A functional joint centre for the hips were determined using the Symmetrical Centre of Rotation Estimation (SCoRE) technique (Ehrig et al., 2006) using the right pelvis and right thigh average shapes and the same for the left pelvis and left thigh. A functional knee flexion axis was determined from non-weight bearing knee flexion cycles from 0-90 ° using the Symmetrical Axis of Rotation (SARA) technique (Ehrig et al., 2007). During the knee flexion cycles the SARA technique used a GPA to generate a right knee axis from the right thigh and shank average shapes and the same for the left side. During the dynamic trials from the HLLMS an ordinary Procrustes analysis technique was used to fit the shapes from the Star movement and knee flexion cycles for each segment to the dynamic trial. The hip joint centres from the parent (proximal) and child (distal) segments were imported to get an average hip joint centre. For the knee during the dynamic trials the axis was imported for the parent and child segments. The medial and lateral knee markers were projected onto the axis and the midpoint of the markers was the knee joint centre. A local coordinate system was used to define each segment using X to the right, Y forward and Z up as outlined in Table 3-4.

Table 3-4: Definitions of local coordinate orientation for thorax, pelvis, femur and tibia segments.

Segment	X	Y	Z
Thorax	Perpendicular to Z and Y axes pointing to the right	Line between C7 and IJ that is perpendicular to the Z axis pointing forwards	Line between midpoint of IJ and C7 and midpoint of PX to T8 pointing upwards
Pelvis	Line through right to left ASIS markers and perpendicular the Y axis pointing right	Line from midpoint between left and right ASIS and midpoint between left and right PSIS markers pointing forwards	Perpendicular to X and Y axes pointing upwards
Femur	Line between medial and lateral femoral condyle markers projected on functional knee axis and perpendicular to the Z axis pointing to the right	Perpendicular to Z and X axes pointing forwards	Line between hip joint centre and knee joint centre (midpoint of line between medial and lateral femoral condyles projected onto functional knee axis in the femur frame).
Tibia	Line between medial and lateral femoral condyle markers and perpendicular to the Z axis pointing to the right	Perpendicular to Z and X axes pointing forwards	Line between knee joint centre (midpoint of line between medial and lateral femoral condyles projected onto functional knee axis in the tibia frame and ankle joint centre (midpoint of line between medial and lateral malleoli)

The location of the resulting hip joint centre was determined with respect to the pelvis local coordinate system (Ehrig et al., 2006). The orientation of the of the knee flexion axis as determined by the tibia moving relative to the femur and was located within a femur local coordinate system. The orientation of the of the knee flexion axis as determined by the femur moving relative to the tibia was located within a tibia local coordinate system. The knee joint centre was determined as the mid-point between the medial and lateral femoral condyles and mapped on the two knee flexion axes. The ankle joint centre was determined as the mid-point between the lateral and medial malleoli. During the dynamic trials the joint centres and knee flexion axes were mapped into the global system based on their known location within their respective local coordinate systems. Anatomical local coordinate systems were then defined in order to determine joint kinematics. Euler angle decomposition was then performed to obtain joint kinematics in an X (flexion/extension), Y (abduction/adduction) and Z (internal/external rotation) order between proximal to distal segments, pelvis to femur, femur to tibia in local coordinate system. Thorax and pelvis kinematics were relative to global coordinate system.

3.5.2.3 *Data analysis*

Marker data were processed using custom code written in Matlab (The Math-Works, Natick, USA) which was used to describe joint rotations. In both models a rigid body approach was adopted to define the trunk, pelvis, femur, tibia and foot segments.

Event identification

Kinematic data for the HLLMS was normalised with respect to time through interpolation of the data to 1001 points from the start (0%) to end (100%) of each test movement, meaning that each data point represents 0.1% of the movement. An automated method was developed to identify the start and end and significant events during the movement of each movement for the HLLMS. This method was developed with the supervisors and other PhD students utilising the HLLMS tool and based on kinematic and kinematic parameters (e.g. angular velocity for knee flexion exceeding a predetermined threshold). Details of specific timings related to calculation of relevant kinematics for the movement faults from the HLLMS are detailed below.

The purpose of this PhD was to validate the observational ratings through the use of kinematic variables. There has been little research done of the validity of observational rating of movement, therefore, this study was exploratory. Consequently, it was decided that it was too early in the research process to set a kinematic threshold for how much movement was deemed a fault. Rather than to stipulate a threshold for good or poor movement, the study aimed to see if the dichotomous grading of good and poor movement were associated with an objective, quantitative, measure of kinematics. Due to the reasons outlined above, peak kinematic values were used as the main method to validate the observational rating for the tests from the HLLMS. Details of the event timings and kinematic criteria used to calculate the relevant kinematics related to the movement faults from the SKB test are shown in Table 3-5.

Table 3-5: Small knee bend test from the HLLMS tool, with movement faults and the specific joint kinematics to be used to calculate the reliability

Event timings to be identify	Kinematic criteria
1. End of bilateral stance	1. When non-weight bearing knee angular velocity > 10% of maximum angular velocity
2. Start weight bearing knee flexion	2. Angular velocity weight bearing knee > 10% of maximum knee angular velocity and non-weight bearing knee flex >60 degrees or event 1 if unsupported knee flexion not reach 60 degrees
3. End weight bearing knee flexion	3. Angular velocity weight bearing knee < 10% of maximum angular velocity
4. Peak weight bearing knee flexion	4. Maximum weight bearing knee flexion
5. Start weight bearing knee extension	5. Angular velocity weight bearing knee < 10% of minimum supported knee angular velocity and after event 4
6. End weight bearing knee extension	6. Angular velocity weight bearing knee < 10% of minimum supported knee angular velocity and after event 5
7. End- return to bilateral stance	7. When non-weight bearing knee angular velocity > 10% of minimum angular velocity

Plots of the event timings in relation to criteria for each test from the HLMMS outlined above were visually checked to ensure the correct sequence and appropriate location. Event timings were manually adjusted if, for example start of knee flexion was due to a small movement of the knee prior to the start of knee flexion movement for the SKB test. An example of the plots of knee flexion to check event timings for the SKB test are shown below (Figure 3-10).

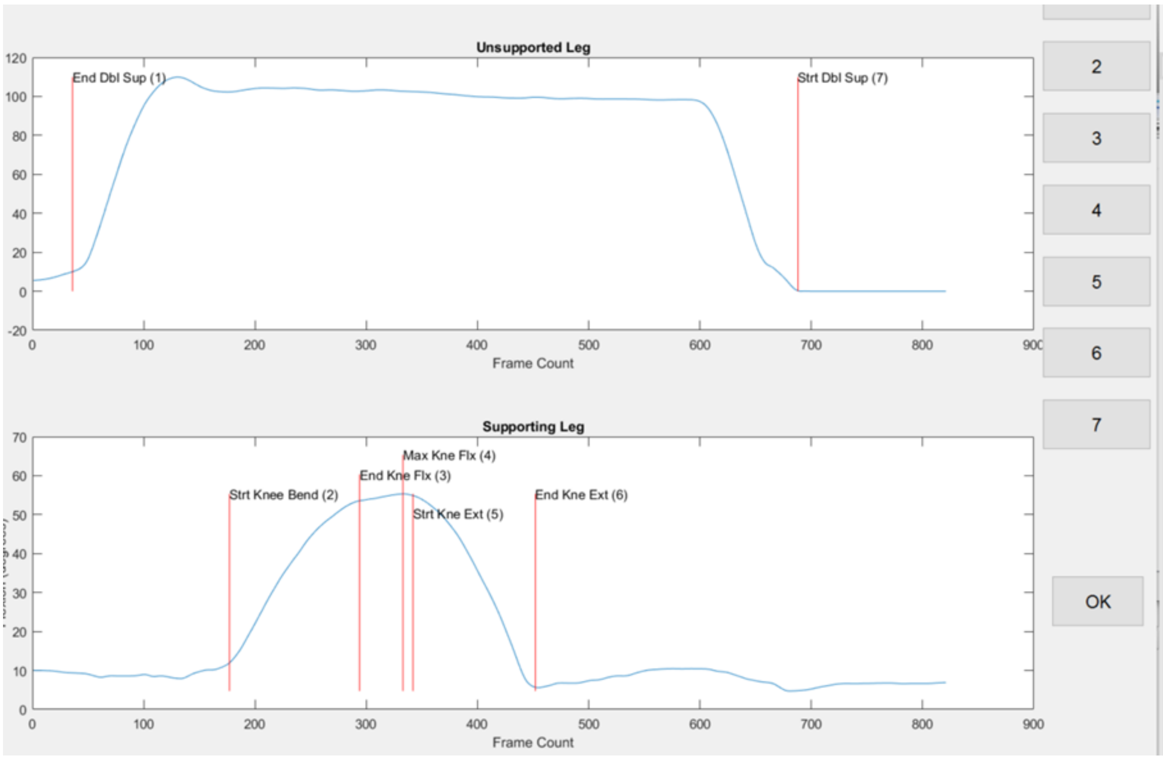


Figure 3-10: Example of timing of events in relation to knee flexion angle of un-supporting (top graph) and supporting leg (bottom graph) during SKB

Details of the criteria used to calculate the relevant joint kinematics for each movement fault from the SKB test are shown in Table 3-6. Due to other researchers using a variety of kinematics to assess the validity of the knee moving medially, several kinematic criteria were assessed. Knee medial displacement excursion at peak knee flexion and knee valgus were used by Ageberg et al. (2010). In discussion with supervisors it was deemed not practical to accurately measure if the knee failed to move 2cm past the toes, therefore peak knee flexion was calculated to assess depth of the SKB.

Table 3-6: Joint kinematics related to the movement fault from the small knee bend test in the HLLMS tool

Movement Fault	Joint Kinematic criteria
Does the knee move inward from the 2nd toe?	peak excursion of medial displacement of the knee joint centre with respect to mid-point of fore foot (event 2 to 6)
	peak excursion of medial displacement of the knee joint centre with respect to mid-point of fore foot at peak knee flexion (event 4)
	peak excursion knee valgus (event 2 to 6)
Does the pelvis hitch?	peak excursion pelvis lateral rotation (event 1 to 7)
Does the knee fail to move 2cm past the toes?	maximum knee flexion angle (event 1 to 7)
Does the trunk lean forwards?	peak excursion thorax flexion (event 1 to 7)
Does the pelvis tilt anterior?	peak excursion anterior tilt (event 1 to 7)

Events 1-7 are defined in Table 3-5

3.5.2.4 *SKB with rotation*

Details of the how the event timings and kinematic criteria are calculated to calculate the kinematics related to the observed movement faults for the SKB Rot test Table 3-7. The outcome parameter for the ‘does the pelvis follow the trunk?’ criterion/question from the SKB Rot test was the coupling angle derived from an angle-angle plot between the axial rotation of the trunk and pelvis (Seay et al., 2011). Four unique coordination patterns were identified from this coupling angle: in-phase coordination between pelvis and trunk (both segments moving simultaneously in the same direction); antiphase coordination between pelvis and trunk (both segments moving simultaneously in opposite direction); trunk-only motion; and pelvis-only motion. Pelvis and trunk segment rotation in global coordinate system was used.

Table 3-7: Event timing and kinematic criteria for the SKB Rot to be used to calculate kinematics related to the movement faults the reliability from the HLLMS.

Event timings to be identify	Kinematic criteria
1. End of bilateral stance	1. When non-weight bearing knee angular velocity > 10% of maximum angular velocity
2. Start weight bearing knee flexion	2. Angular velocity weight bearing knee > 10% of maximum knee angular velocity and non-weight bearing knee flex >60 degrees or event 1 if unsupported knee flexion not reach 60 degrees
3. Peak weight bearing knee flexion	3. Maximum weight bearing knee flexion Angular velocity weight bearing knee < 10% of maximum angular velocity
4. Start trunk rotation	4. Angular velocity trunk rotation > 10% of maximum trunk angular velocity
5. End trunk rotation	5. Angular velocity trunk rotation < 10% of minimum trunk angular velocity
6. End weight bearing knee extension	6. Angular velocity weight bearing knee < 10% of minimum supported knee angular velocity and after event 5
7. End- return to bilateral stance	7. When non-weight bearing knee angular velocity > 10% of minimum angular velocity

Details of how the kinematics were calculated related to the observational movement faults for the SKB Rot test are shown in Table 3-8.

Table 3-8: Joint kinematics related to the movement fault for the SKB Rot test from the HLLMS.

Movement Fault	Joint Kinematic criteria
Does the hip and pelvis follow the trunk?	Percentage of time pelvis and trunk segment's axial rotation were in-phase from the start to end of trunk rotation (event 4 to 5)
Does the trunk side-bend?	thorax (global) lateral rotation maximum excursion for right and left combined (event 1 to 7)
Does the pelvis hitch?	peak excursion pelvis lateral rotation (event 1 to 7)
Does the trunk fail to rotate more than 30°?	peak trunk axial rotation clockwise and anticlockwise (event 1 to 7)
Do the toes claw or any loss of balance?	not possible to measure
Does the trunk lean forwards?	peak trunk flexion excursion from start of knee flexion (event 1 to 7)

Details of event times and kinematic criteria used to calculate the kinematics values for the standing hip flexion test from the HLLMS as shown in Table 3-9.

Table 3-9: Event timings and kinematic criteria for the standing hip flexion test to be used to calculate kinematics for the movement faults.

Event timings to be identify	Kinematic criteria
1. Start hip flexion	1. When non-weight bearing hip angular velocity > 10% of maximum angular velocity
2. Peak hip flexion	2. Maximum non-weight bearing hip flexion
3. End hip extension	3. When non-weight bearing hip angular velocity > 10% of minimum angular velocity

Following discussion with other researchers using the HLLMS and supervisors the criteria for the fault of the hip failing to flex to 110° was the femur flexion in the global coordinate system was used. The raters agreed that although the fault was hip flexion, they were rating the femur rather than true hip flexion which is calculated on the angle between the femur and pelvis segments. Details of the joint kinematic criteria related to the movement faults from the standing hip flexion test are shown in Table 3-10.

Table 3-10: Joint kinematics related to the movement fault for the standing hip flexion test from the HLLMS.

Movement Fault	Joint Kinematic criteria
Does the pelvis hitch?	peak excursion pelvis lateral rotation (events 1-3)
Does the pelvis tilt posterior?	peak excursion pelvic anterior tilt (events 1-3)
Does the hip fail to bend (flex) > 90° (approx. 110°)?	peak femur flexion in global coordinate system (events 1-3)
Does the trunk lean backwards?	peak excursion trunk extension (events 1-3)
Does the weight bearing knee flex?	peak excursion weight bearing knee flexion (events 1-3)

3.5.2.5 *Deep Squat*

Left side kinematics were chosen due to this being the side that the lateral view for the fault ratings was used in the laboratory. Event timings and their kinematic criteria for the Deep squat are defined in Table 3-11.

Table 3-11: Events to be identified and related kinematic criteria from the deep squat from the HLLMS to be used to calculate kinematics related to the observed movement faults.

Event timings to be identify	Kinematic criteria
1. Start weight bearing knee flexion	1. Angular velocity left knee > 10% of maximum knee angular velocity
2. Peak weight bearing knee flexion	2. Maximum left knee flexion
3. End weight bearing knee extension	3. Angular velocity weight bearing knee > 10% of minimum left knee angular velocity

During data collection it was noticed that the force platforms were not working correctly due to a firmware issue with the Vicon system, which was not solved during the data collection period. Therefore, the fault of the bodyweight shifting to one side was not able to be validated by an objective measure. Details of the how the joint kinematics related to movement faults from the deep squat are shown in Table 3-12.

Table 3-12: Joint kinematics related to the movement fault from the deep squat test from the HLLMS.

Movement Fault	Joint Kinematics
Does the trunk fail to stay parallel with the tibia?	Segment angle of the tibia vs. the segment angle of the thorax and the difference between the two (event 2)
Does the femur fail to be horizontal with the floor?	Segment angle of femur at peak knee flexion (event 2)
Does the pelvis anterior tilt?	Peak anterior pelvis tilt excursion (event 1 to 3)
Does the bodyweight shift to one side?	Peak difference in ground reaction force, 1 foot on each platform (event 1 to 3)

3.5.2.6 *Sitting hip flexion test*

During data processing for the sitting hip flexion there was substantial marker drop out on the lower limbs. Marker drop out was due to participants sitting on the posterior thigh markers and the plinth which occluded the markers. Despite trying to optimise the orientation of the participant in the laboratory marker drop out was still substantial. Following discussion with supervisors it was concluded that due to the substantial marker drop out the validity of the kinematics would be limited. Therefore, the kinematics were not calculated for the sitting hip flexion test.

3.5.2.7 *Hip abduction with medial and lateral rotation test*

Similar to the sitting hip flexion, during data processing of the 3D motion analysis data for the hip abduction tests substantial marker drop out was identified. Additionally, there was large variation between how many markers were visible during each trial and between participants. An attempt was made to replace the missing markers using the OCST method. Using a trial that had all six pelvic markers present comparisons were made between the marker location and where the OCST placed the marker. However, there were extensive differences in marker location between the captured markers and the replaced markers using the OSCT, tested on a trial where all markers were visible, which would subsequently affect the pelvic segment location and orientation. Given that the movement faults from the hip abduction test are largely based on the pelvis movement, following discussion with supervisors it was decided that kinematic data would have limited accuracy and was not calculated. All the laboratory setup, calibration, data collection and analysis were carried out by the lead investigator.

Chapter 4: **Reliability of the HLLMS: Observational rating**

4.1 Introduction

There is a need for data to be accurate so that conclusions in clinical practice and research are based on reliable data. According to Portney and Watkins (2009) reliability is the first prerequisite of measurement and is defined as the extent to which a measurement is consistent and free from error. However, a measurement may be reliable but not valid which is defined as not measuring what it is supposed to. Validity of the HLLMS will be covered in later chapters of this thesis. This chapter will consider reliability of the HLLMS in relation to the observational rating. Kinematic reliability well be assessed in the following chapter.

4.1.1 Observational reliability of the HLLMS

It may be virtually impossible to remove all measurement error when carrying out measurement, but possibly of more importance is measuring or estimating the size of the error. Measurement error has been defined as the difference between the true value and observed value (Portney and Watkins, 2009). Sources of measurement error are suggested to be 1) due to the rater, 2) measuring instrument and 3) variability of the characteristics being measured (Portney and Watkins, 2009). To reduce measurement errors, it is important to know where they occur and then address them. Identifying where errors exist is needed, for example if substantial error is due to the rater, greater training and standardisation of protocols could reduce this error. Another source of error could be due to a large variation in performance by the participant performing the tests, in this case the HLLMS, which could be reduced by increasing the practice trials or may need to be taken into account when interpreting the results.

In relation to measurement errors due to the rater, factors such as training on how to use the tool correctly including agreeing protocols, clarifying fault criteria and standardisation of the procedure need to be addressed. To try to minimise measurement error for the HLLMS by the rater, a standardised protocol was used, described in section 3.4.5 of this thesis.

Having outlined the need to measure reliability, how reliability is measured will now be considered. If repeated measures are taken and not expected to obtain the same measures each time, this is called variance. Variance is related to the true difference and other random sources or error such as measurement error. Reliability measures how much true score variance contributes to the total variance. The ratio is a reliability coefficient, with no error the score would be 1, and 0 indicating no reliability. Reliability coefficients for nominal data can be calculated using kappa and percentage agreement (Portney and Watkins, 2009).

4.1.1.1 *Types of reliability*

To calculate reliability for the HLLMS a range of statics could be used to estimate the test re test reliability. Percentage agreement was chosen due to it being used by several authors to assess rater reliability with movement screening, (Ageberg et al., 2010, Whatman et al., 2012, Mischiati et al., 2015). However, a limitation of percentage agreement is that it does not consider the potential for chance agreement (Gwet, 2001).

To try and calculate the test re-test agreement considering the effect of chance agreement, Cohen's Kappa is a commonly reported measure of rater agreement. According to Gwet (2001) Kappa values of ≤0.2 poor, 0.21-0.4 fair, 0.41-0.6 moderate, 0.61-0.80, good and 0.81-1.0 almost perfect/excellent agreement. However, according to Viera and Garrett (2005) low Kappa values may not suggest low rates of overall agreement as agreement is affected by small numbers of observations leading to the paradox of Kappa. Gwet (2001) supported this view and suggested that Kappa only gives a reasonable measure when prevalence is close to approximately 50% and its ability to predict agreement diminishes when prevalence gets closer to 0 or 100%. Whatman et al. (2012) suggested there was a potential for a high prevalence of fault or not fault with movement screening, therefore the paradox of Kappa would be a problem.

To attempt to adjust overall percentage agreement for chance agreement and avoid the paradox of Kappa, the AC1 was used (Whatman et al., 2012). AC1 is suggested to give an estimate of true agreement and is thought to be more stable and consistent with percentage agreement than Kappa (Whatman et al., 2013b). The interpretation for AC1 values can be similar to that used for kappa (Gwet, 2001).

Use of a single value for rater agreement such as percentage agreement or AC1 may not give enough detail. Positive and negative agreement allows analysis for raters' agreement when a movement fault is present or absent. For example, a moderate overall percentage agreement may be due to a high level of raters agreeing on a movement fault being present, but low rater agreement on a movement fault being absent or vice versa.

4.1.1.2 *What reliability will be measured?*

Having considered how reliability will be measured for the HLLMS the next section will consider what types of test re test reliability will be assessed.

Intra-rater reliability

As outlined previously there are several measures of reliability that need to be established for the HLLMS. Intra-rater reliability is commonly assessed by using video footage to ensure there is no difference in the movement patterns between the repeated ratings made by the same observer and remove the variability of the characteristics being measured (Whatman et al., 2013b, Mischiati et al., 2015). A range of 75-100% intra-rater percentage agreement using video footage has been reported for a movement control screen (Mischiati et al., 2015). Similarly, the average intra-rater percentage agreement for medial knee movement during a single leg squat was 83% agreement (range 70-96%) and 84% agreement (range 70-100%) for the pelvis remaining neutral in the frontal plane movement during the SKB (Whatman et al., 2013b). Values for AC1 for medial knee movement during a single leg squat was 0.71 (range 0.41-0.95) and the pelvis remaining neutral in the frontal plane during the SKB was AC1 0.73 (range 0.48-1.00), as was reported by Whatman et al. (2013b). With the development of the new movement screen, the HLLMS, it was important to establish the intra-rater reliability using video footage of the current author before examining reliability at the next level, during real-time observations.

4.1.1.3 *Intra-rater between session*

Another important consideration is the reliability of participants to perform movement screening between days defined as intra-rater between day, which has received little research. If trying to detect if a true change has occurred, then it is important to know to natural variability of participant's ability to perform a movement screen. Several authors have examined between day intra-rater agreement but have only reported ICC values for the composite score agreement from the FMS (Teyhen et al., 2012, Shultz et al., 2013). There is a lack of research on individual movement criterion from movement screens intra-rater between day agreement and currently there is no research for the between day intra-rater agreement for HLLMS.

4.1.1.4 *Inter-rater reliability*

Inter-rater reliability is important to ascertain the potential variation between raters. Usefulness of the HLLMS as a tool for clinical practice and research may be limited if it has poor inter-rater reliability. Additionally, assessing inter-rater reliability would identify movement faults that may require further training of the raters.

Inter-rater reliability where two raters independently rate movement faults have been assessed by several authors (Ageberg et al., 2010, Whatman et al., 2012, Mischiati et al., 2015). A high level of mean inter-rater agreement was reported by both studies, with 96% reported by Ageberg et al. (2010) and Mischiati et al. (2015) 86.5% (range 67.5-100%). In contrast lower ranges of inter-rater percentage agreement were reported by Whatman et al. (2012) of 45-79% and 32-82% by Chmielewski et al. (2007). The low inter-rater percent agreement reported by Whatman et al. (2012) and Chmielewski et al. (2007) may have been due to them using video recordings to rate agreement or rating of different movements to those in the HLLMS. The low inter-rater agreement using video footage may be due to raters not being able to get a clear view of the fault compared to real time. In support of the difference between video and real time inter-rater agreement Mischiati et al. (2015) reported a mean 74.5% (range 30.8-100%) agreement between video and real time rating of the same participants. The findings above suggest that video can under estimate inter-rater agreement. Additionally, the use of video footage to rate the HLLMS clinically is not practical due to time and financial cost. Therefore, there is a need to assess the inter-rater agreement of the HLLMS in real time.

Despite the limitations of measuring inter-rater agreement with video footage outlined above, currently only video footage has been used to calculate AC1 with movement screening (Whatman et al., 2012). An inter-rater reliability range of AC1 of 0.22 to 0.71 for movement faults related to trunk, pelvis, knee, foot and overall during a small knee bend was reported by Whatman et al. (2012). Similar inter-rater AC1 values of 0.37- 0.61 were reported for 66 physiotherapist rating pelvis and knee alignment during a SKB in athletes aged 11 (SD 1) years (Whatman et al., 2013a). Both Whatman et al. (2012) and Whatman (2013b) rated multiple segment movement faults but only on the SKB and using video footage, for which limitations have been outlined above. The lack of current literature on inter-rater reliability on a range of movement tasks, in real time, highlight the need for this to be assessed with the HLLMS. Also measuring inter-rater agreement for each individual movement fault would highlight the criteria that may need refinement during the development of the HLLMS, rather than just considering the total score for all tests in the movement screen.

4.1.1.1 *Inter-rater reliability in golfers*

Assessing the inter-rater reliably of the HLLMS on a range of athletes would support its use and aid in the development of a reliable tool to be used with a range of athletes. The HLLMS was originally developed to be used on footballers (Botha, 2013), yet it may be of use in other sports.

Golf is a popular sport with an estimated four million players in the UK (Farrally et al., 2003). A range of incidences of hip injury have been suggested with recent systematic review by Cabri et al. (2009) reporting the prevalence of hip injuries in golfers ranging from 2-18%. Batt, (1992) reporting the hip to be the third most reported location of injury in male amateur golfers. The cause of hip injuries could be related to the high rotational velocities, especially in the lead hip (Gulgin et al., 2009). The studies outlined above suggest golf may place the hip at risk of injury and warrant further research on the aetiology to aid prevention.

As highlighted by Dickenson et al. (2016) there is little research on the predictors of hip pain in golfers. Assessing movement control in the kinetic chain is recognised as a useful way of identifying athletes at risk of injury. Abnormal movement patterns have been linked with other hip injuries such as FAI (Austin et al., 2008). The link between abnormal movement patterns and FAI has been discussed previously in this thesis (section 1.1.3 and 1.1.4). It could be possible that abnormal movement patterns increase the risk of hip injury due to the high rotation loading that golf places on the hip and suggests movement screening is worth investigating in this population.

As highlighted above, playing golf could lead to players developing abnormal movement patterns and subsequently increased risk of hip injury. Therefore, golfers would be a suitable athletic population to use the HLLMS on. Ascertaining the inter-rater reliability in golfers would also potentially increase the generalisability of the HLLMS to be used on different athletes other than footballers.

4.1.1.2 *Outline of reliability chapter*

Having considered the different types of reliability to be assessed for the HLLMS, an outline of the reliability assessed in this chapter is shown in Figure 4-1.

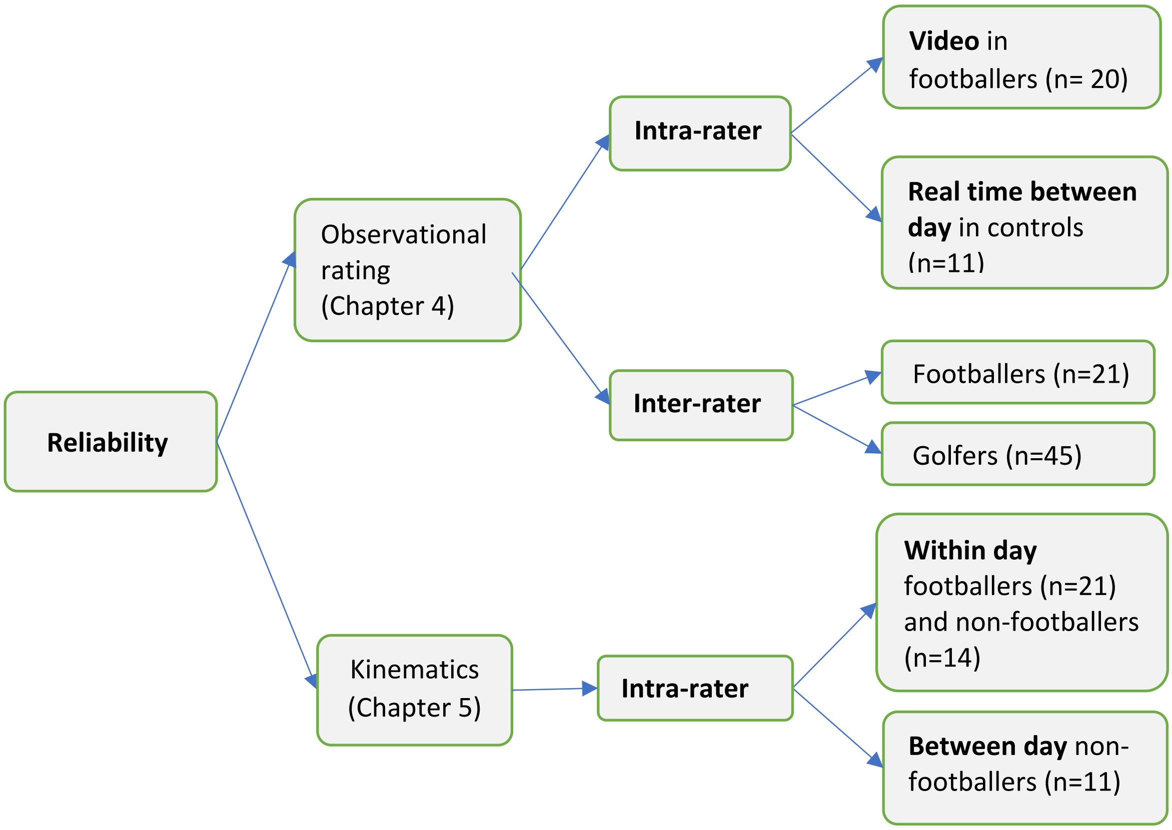


Figure 4-1. Outline of types of reliability from the HLLMS to be measured in this thesis

4.1.2 Overall aim of the chapter

Investigate the reliability of the observational rating of the HLLMS.

The objectives were to quantify the observational rating reliability of the HLLMS in relation to:

- intra-rater reliability using video footage in male academy footballers
- intra-rater reliability between days using real time rating in young male student controls
- inter-rater reliability in male academy footballers
- inter-rater reliability in male professional golfers during five tests from the HLLMS.

4.2 Methodology

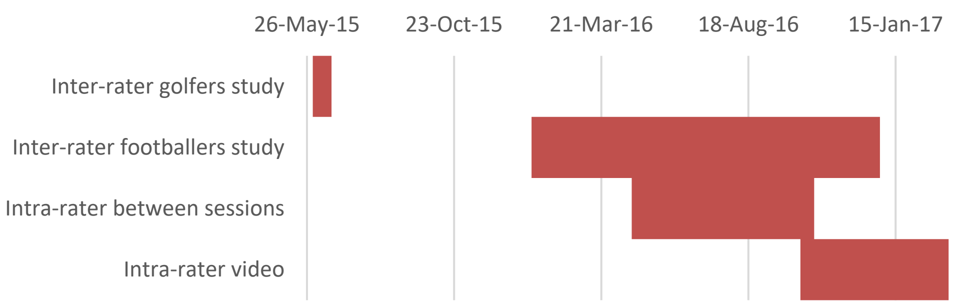
4.2.1 Ethics

Three separate studies were carried out to gather the data for this reliability chapter. Ethical approval was granted for male academy footballers and male students as controls (Ethics approval numbers 23370 and 27322) by the Faculty of Health Sciences, University of Southampton Ethics Committee. For the study on male professional golfers, ethical approval was granted by the 'Biomedical and Scientific Research Ethics Sub-Committee, Warwick Medical School, The University of Warwick' (ethics approval number 'REGO-2015-1570'). Figure 4-1 outlines which participants groups were involved in the studies to measure the different types of reliability.

4.2.2 Rater characteristics

The current author (DW) had five years of musculoskeletal physiotherapy experience, three months experience of movement control assessment and attended a movement screening course (The Performance Matrix: Movement and Performance Screening course) prior to the start of data collection. The second therapist Nadine Booysen (NB) had 10 years musculoskeletal experience, three years movement control assessment and had attended The Performance Matrix: Movement and Performance Screening course. The order of data collection for the studies included in this thesis are shown in Table 4-1

Table 4-1: Author of thesis rater's experience (over a 24-month period) for each of the studies



4.2.3 Rater training

The HLLMS was designed by NB and there was no formal training for rating the HLLMS to standardise the specific criteria for fault or no fault. Each fault was described against an optimal benchmark on the screening questionnaire. One of the purposes of the study on male professional golfers was to aid with the training for DW to rate the HLLMS. Training consisted of demonstrating the tests and discussion of the faults that DW was not clear on.

4.2.4 Participant recruitment

4.2.4.1 *Participants for intra-rater reliability using video*

Twenty male academy football players (mean 16.8 years, SD 0.6, range 16-18 years) old were recruited from South Central community football club academies for the study. Further details of footballer recruitment and consent are outlined in section 3.2. The sample size was the same as that used by Mischiati et al. (2015) to measure intra-rater reliability. Details for participant recruitment are described in section 3.2 of Chapter 3. Participants received a participant information sheet (Appendix A) and gave their written informed consent (Appendix B) prior to commencement of data collection. Data collection took 15 minutes per participant.

4.2.4.2 *Participants for intra-rater between day reliability real time*

An original sample size was calculated of 18 healthy male students between the ages of 18 – 30 years. Due to difficulty recruiting participants, complete data were only collected on 11 participants (mean 26.3 years, SD 1.4, range 24-28 years). Details of participant recruitment and consent are outlined in section 3.2.2.

4.2.4.3 *Participants for inter-rater footballer reliability*

Footballers for the inter-rater study were recruited in the same way as for the intra-rater video study, see above. See section 3.2.1 for details of participant's recruitment, inclusion and exclusion criteria. Twenty footballers were recruited for the study (mean 17.6 years, SD 0.5, range 17-18 years).

4.2.4.4 *Participants for inter-rater golfer reliability*

Participants were recruited during three practice days before a tournament on the European Change Tour with all golfers present during the practice days being invited to take part. A total of 155 golfers took part in the tournament. Due to time pressures the players had from other commitments the raters completed the screen as soon as the players became available. In total 73 golfers were screened and of those 45 were screened by both raters at the same time.

Inclusion criteria

a. European Challenge Tour Golfers attending the Aviemore event 2015

b. Able to give informed consent

Exclusion criteria

Inability to read and complete questionnaires written in English

4.2.5 Data collection

The standardised protocol for carrying out the HLLMS is outlined in section 3.3. Specific details for variation in the methods are outlined below.

4.2.5.1 *Intra-rater video*

Participants were recorded during the HLLMS using a digital video camera (Sony handycam HDR CX280E, 8.9 megapixels, 1080 Full HD, MP4) mounted on a tripod. The camera was framed to capture the whole body of the participant during the movement. The participant was recorded from both the anterior and lateral view to give the best views for all the movement faults. All participants wore only shorts to allow observations of movement. Video footage was edited so that every movement test had one anterior and lateral view using Microsoft Movie Maker 2016. The rater could view as many repetitions of the trials needed to score the movement fault. A minimum of a week between the ratings was used to minimise the potential for the rater to remember scores.

4.2.5.2 *Inter-rater male academy footballers*

The HLLMS was carried out as detailed in section 3.3. Two raters independently scored the participants movement live and at the same time.

4.2.5.3 *Inter-rater male professional golfers*

Due to limited time to complete the assessment of the golfers, five tests of seven from the HLLMS were used. The tests to be used were discussed with NB and thought to be the most clinically relevant. The screen was carried out as per the instructions and scoring in section 3.2. The HLLMS used was an earlier version (Appendix E) than the current version (Table 3-2). The golfers were rated at the same time by both raters independently. Right and left scores were compared separately.

4.2.6 Data Analysis

4.2.6.1 *Observational rating*

Scores from the HLLMS were inputted into Microsoft Excel 2013 and AC1, percentage agreement, positive and negative agreement were calculated as outlined above (section 4.1.1). As discussed previously in, with low prevalence, Kappa values may not accurately represent agreement through the kappa paradox (Whatman et al., 2013b). Initial use of kappa to measure inter-rater agreement with male professional golfers demonstrated the Kappa paradox due to low prevalence of fault or no fault (Appendix G). Based to the literature and initial results from the present study kappa was not used to measure agreement. Right and left side faults were considered separately, so there was a total of 64 movement faults rated in HLLMS.

4.2.6.2 *Statistical analysis*

Percentage agreement was calculated by number of observed agreements divided by the maximum number of possible agreements, multiplied by 100 (Whatman et al., 2013b). A limitation of percentage agreement suggested by McHugh (2012) is that it may overestimate agreement as it does not take into account the possibility of guessing. As discussed earlier there are limitations of using kappa and therefor AC1 was used. AC1 was calculated using Gwet's AC1 formula (Table 4-2 and Figure 4-2). Confidence intervals (CI) were not reported for AC1 as McHugh (2012) suggested that small sample sizes create larger CI and therefore should not be calculated on samples below 30. Based on the values used by Gwet (2001), Portney and Watkins (2009) and Mischiati et al. (2015) an AC1 values of > 0.8 was considered excellent, 0.6-0.8 acceptable and < 0.6 poor agreement.

Gwet's AC1 = $\frac{p-e(\gamma)}{1-e(\gamma)}$

$p = \frac{A+D}{N}$

$e(\gamma)$= the chance agreement probability = 2q (1-q), $q = \frac{A1+B1}{2N}$

Figure 4-2: Formula for calculating AC1 from (Wongpakaran et al., 2013)

Table 4-2: Table used to show how rater's scoring is entered to calculate values for Gwet's AC1 formula from (Wongpakaran et al., 2013)

	Rater 1		
Rater 2	**Category 1**	**Category 2**	**Total**
Category 1	A	B	B1 (A+B)
Category 2	C	D	B2 (C+D)
	A1 (A+C)	A2 (B+D)	N

4.2.6.3 *Positive and negative agreement*

The formulae used to calculate positive agreement (PA) were PA = 2A/(2A+B+C) and negative agreement (NA) NA = 2D/(2D+B+C) (Cicchetti and Feinstein, 1990). Calculation of A, B, C, D is outlined in Table 4-3.

Table 4-3: Table used to show how raters' scoring was entered to calculate values of positive and negative agreement (Cicchetti and Feinstein, 1990)

	Rater 2		
Rater 1	**Positive (fault)**	**Negative (no fault)**	**Total**
Positive (fault)	A	B	(A+B)
Negative (no fault)	C	D	(C+D)
Total	(A+C)	(B+D)	N

Positive and negative agreement values are reported with 95% CI. To calculate 95% CI for percentage agreement = PA +/- 1.96 x SE (PA) and for negative agreement = NA +/- 1.96 x SE (NA) (Table 4-4). However, the method used to calculate the CI were based on an approximation, commonly used with proportions and percentages. The disadvantage with using approximation, the results can fall below zero or above one especially when the proportions are close to zero or one. Therefore, in the present study the values were capped at zero and one.

Table 4-4: Formulas used to calculate standard error values for positive (PA) and negative agreement (NA) using data from Table 4-3 (Graham and Bull, 1998)

Standard error positive agreement [SE (PA)] = $\frac{\sqrt{4A[(C+B)(A+C+B)]}}{(2A+B+C)^2}$

Standard error negative agreement [SE (NA)] = $\frac{\sqrt{4D[(C+B)(D+C+B)]}}{(2D+B+C)^2}$

4.3 Results

As the HLLMS was still in the developmental stages, criteria found to have poor reliability were amended to clarify ambiguity with the aim of improving reliability. These changes are indicated where relevant in the results presented below.

4.3.1 Intra-rater reliability video

The overall mean intra-rater video AC1 was 0.80 (range 0.36-1.00) and mean percentage agreement was 88% (range 60-100%) for the 64 movement criteria from the HLLMS in 20 male youth academy footballers (Table 4-5). Only 7 of the movement criteria were below the acceptable cut off 0.6 for the AC1 and 38 could be considered to have excellent agreement as they were above an AC1 of 0.8.

Table 4-5. Summary of intra-rater video agreement for observational rating from the HLLMS (n=20)

Test	**AC1 mean (range)**	**Percent agreement mean (range)**
Small knee bend	0.81 (0.55-1.00)	89 (75-100)
Small knee bend with rotation	0.83 (0.56-0.95)	89 (70-95)
Standing hip flexion	0.82 (0.60-1.00)	89 (80-100)
Deep squat	0.77 (0.36-1.00)	86 (60-100)
Sitting hip flexion	0.77 (0.50-1.00)	87 (65-100)
Hip abduction with lateral rotation	0.88 (0.71-1.00)	92 (85-100)
Hip abduction with medial rotation	0.71 (0.45-0.95)	83 (75-95)
Overall mean	0.80 (0.36 – 1.00)	88 (60-100)

4.3.1.1 *SKB test*

Overall intra-rater video AC1 was 0.81 and 89% agreement for the SKB test Table 4-6. Only the pelvis tilting forward on the right side was below the acceptable cut off of <0.6 for the AC1 (Table 4-6).

Table 4-6. Intra-rater video percentage agreement, AC1, positive and negative agreement for the SKB test in adolescent footballers (n=20). Updated movement criteria in italics. Shaded criteria indicate ones that remain unchanged in the updated HLLMS.

Movement criteria	**Side**	**AC1**	**Negative agreement (95% CI)**	**Positive agreement (95% CI)**	**% Agree**
Does the knee move inward from the 2nd toe? *Is there an increase in dynamic valgus from the start position?*	Right	0.60	0.80 (0.61-0.99)	0.80 (0.61-0.99)	80
	Left	0.80	0.90 (0.76-1.00)	0.90 (0.76-1.00)	90
Does the pelvis hitch/drop? *Does the pelvis fail to stay level?*	Right	0.85	0.75 (0.41-1.00)	0.94 (0.85-1.00)	90
	Left	0.93	0.86 (0.58-1.00)	0.97 (0.91-1.00)	95
Does the knee fail to move 2cm past the toes?	Right	0.95	0.97 (0.92-1.00)	0.00 (0.00-0.00)	95
	Left	0.89	0.95 (0.87-1.00)	0.00 (0.00-0.00)	90
Does the trunk lean forwards?	Right	1.00	1.00 (1.00-1.00)	1.00 (1.00-1.00)	100
	Left	0.91	0.93 (0.80-1.00)	0.96 (0.88-1.00)	95
Does the pelvis tilt forwards? *Does the pelvis begin in, or tilt forwards (anterior)?*	Right	0.55	0.62 (0.30-0.93)	0.81 (0.66-0.97)	75
	Left	0.66	0.67 (0.36-0.97)	0.86 (0.72-1.00)	80
Mean agreement (n=5)		0.81			89
Mean agreement of unchanged criteria (n=2)		0.94			95

The score of 0.00 positive agreement for the criterion ‘Does the knee fail to move 2cm past the toes?’ for the SKB test (Table 4-6) was due to there being no participant being rated fault in both sessions (Table 4-7). To get a positive or negative agreement score there must be at least one participant rated as fault/not fault for both sessions. Further details of how positive and negative agreement is outlined in Table 4-3 and Table 4-4.

Table 4-7. Scoring for calculation for intra-rater video reliability for the criterion ‘Does the knee move 2cm past the toes?’ on the right side from the SKB test in adolescent footballers (n=20).

		First rating	
		Fault (positive)	**No Fault (negative)**
Second Rating	Fault (positive)	0	0
	No Fault (negative)	1	19

4.3.1.2 *SKB Rot test*

intra-rater video AC1 was 0.83 and 89% agreement for the SKB with rotation test (Table 4-9). Only the criterion, ‘Do the toes claw or any loss of balance?’ (left) scored below 0.6 for the AC1 suggesting that it was not reliable (Table 4-8). Due to the low AC1, the criterion was removed from the updated HLLMS. Due to poor reliability reported by fellow researches using the HLLMS, the criterion ’Does the trunk side bend?’ was also removed from the HLLMS. Overall AC1 agreement for the remaining criteria is 0.92.

Table 4-8: Intra-rater video percentage agreement, AC1, positive and negative agreement for the SKB with rotation test in adolescent footballers (n=20). Updated movement criteria in italics. Shaded criteria indicate ones that remain unchanged in the updated HLLMS.

Movement criteria	Side	AC1	Negative agreement	Positive agreement	% Agree
Does the pelvis follow the trunk?	Right	0.87	0.67 (0.23-1.10)	0.94 (0.86-1.00)	90
	Left	0.93	0.86 (0.58-1.00)	0.97 (0.91-1.00)	95
Does the trunk side-bend? *	Right	0.94	0.97 (0.92-1.00)	0.57 (0.13-1.00)	95
	Left	0.79	0.91 (0.81-1.00)	0.57 (0.13-1.00)	85
Does the pelvis hitch/drop? *Does the pelvis stay level?*	Right	0.73	0.77 (0.52-1.00)	0.89 (0.76-1.00)	85
	Left	0.92	0.91 (0.73-1.00)	0.97 (0.90-1.00)	95
Does the trunk rotate less than 30°?	Right	0.95	0.97 (0.92-1.00)	0.00 (0.00-0.00)	95
	Left	0.95	0.97 (0.92-1.00)	0.00 (0.00-0.00)	95
Do the toes claw or any loss of balance? *	Right	0.71	0.50 (0.08-0.92)	0.88 (0.75-1.00)	80
	Left	0.56	0.25 (-0.15-0.65)	0.81 (0.67-0.96)	70
Does the trunk lean forwards?	Right	0.70	0.86 (0.70-1.00)	0.84 (0.67-1.00)	85
	Left	0.90	0.96 (0.87-1.00)	0.94 (0.83-1.00)	95
Mean agreement (n=6)		0.83			89
Mean agreement of unchanged criteria (n=3)		0.92			93

*criteria removed from the latest version of the HLLMS

4.3.1.3 *Standing hip flexion test*

Overall intra-rater video AC1 was 0.82 and 89% agreement for the standing hip flexion test (Table 4-9). No criteria were considered to have poor reliability as all scored AC1 values above 0.6 (Table 4-9). However, due to poor reliability in other studies in this thesis of criteria relating to the pelvis dropping and tilting backwards, these criteria were reworded (Table 4-9). Overall AC1 agreement for the remaining criteria in the updated HLLMS decreased to 0.78 and percentage agreement increased to 90%.

Table 4-9 Intra-rater video percentage agreement, AC1, positive and negative agreement for the standing hip flexion test in adolescent footballers (n=20). Updated movement criteria in italics. Shaded criteria indicate ones that remain unchanged in the updated HLLMS.

Movement criteria - Stand Hip Flex	**Side**	**AC1**	**Negative agreement**	**Positive agreement**	**% Agree**
Does the pelvis drop (hitch)?	Right	0.81	0.40 (0.14-0.94)	0.91 (0.82-1.00)	85
Does the pelvis fail to stay level?	Left	0.89	0.00 (0.00-0.00)	0.95 (0.87-1.00)	90
Does the pelvis tilt backwards (posteriorly)?	Right	0.93	0.86 (0.58-1.00)	0.97 (0.91-1.00)	95
Does the pelvis begin in, or move backwards (posteriorly)?	Left	0.87	0.67 (0.23-1.00)	0.94 (0.86-1.00)	90
Does the hip fail to bend (flex) just beyond 90 degrees (approximate 110 degrees)?	Right	1.00	1.00 (1.00-1.00)	1.00 (1.00-1.00)	100
	Left	1.00	1.00 (1.00-1.00)	1.00 (1.00-1.00)	100
Does the trunk lean backwards (extend)?	Right	0.66	0.86 (0.72-1.00)	0.67 (0.36-0.97)	80
	Left	0.73	0.89 (0.76-1.00)	0.77 (0.52-1.00)	85
Does the weight bearing knee bend (flex)?	Right	0.71	0.87 (0.72-1.00)	0.82 (0.63-1.00)	85
	Left	0.60	0.82 (0.64-0.99)	0.78 (0.57-0.99)	80
Mean agreement (n=5)	0.82				89
Mean agreement of unchanged criteria (n=2)	0.78				90

4.3.1.4 *Deep squat test*

Overall intra-rater video AC1 was 0.77, with 86% agreement for the deep squat test (Table 4-10). 'Does the pelvis tilt forwards?' criterion was the only test with a poor intra-rater reliability using video, with an AC1 of 0.36, which is below the 0.60 cut off and has been re-worded in the latest version of the HLLMS (Table 4-10). Removing the scores for the anterior tilt increased the overall AC1 agreement for the remaining criteria to 0.91.

Table 4-10: Intra-rater video percentage agreement, AC1, positive and negative agreement for deep squat in adolescent footballers (n=20). Updated movement criteria in italics. Shaded criteria indicate ones that remain unchanged in the updated HLLMS.

Movement criteria	**AC1**	**Negative agreement**	**Positive agreement**	**% Agree**
Does the trunk fail to stay parallel with the shin (tibia)?	1.00	1.00 (1.00-1.00)	1.00 (1.00-1.00)	100
Does the thigh (femur) fail to be horizontal with the floor?	0.83	0.93 (0.83-1.00)	0.83 (0.61-1.00)	90
Does the pelvis tilt forwards (anteriorly)? *Does the pelvis begin in, or move forwards (anteriorly)?*	0.36	0.73 (0.56-0.91)	0.20 (0.00-0.53)	60
Does the bodyweight shift to one side?	0.90	0.96 (0.87-1.00)	0.94 (0.83-1.00)	95
Mean agreement (n=4)	0.77			86
Mean agreement of unchanged criteria (n=3)	0.91			95

4.3.1.5 *Sitting hip flexion test*

Overall intra-rater video AC1 was 0.77, with 86% agreement for the sitting hip flexion test (Table 4-11). Due to poor reliability for axial rotation of the pelvis (right) and 'Does the pelvis hitch?' (left), the criteria were combined for the updated HLLMS. The score of N/A for positive agreement for the criterion 'Does the hip fail to bend (flex) just beyond 90 degrees (approximate 110 degrees)?' was due to all participants being rated as no fault, therefore it was not possible to score for positive agreement as there were no ratings of fault (Table 4-11). Overall AC1 agreement for the remaining criteria included in the updated HLLMS increased to 0.87.

Table 4-11: Intra-rater video percentage agreement, AC1, positive and negative agreement for the sitting hip flexion test in adolescent footballers (n=20). Updated movement criteria in italics. Shaded criteria indicates those that remain unchanged in the updated HLLMS.

Movement criteria - Sit Hip Flex	**Side**	**AC1**	**Negative agreement**	**Positive agreement**	**% Agree**
*Does the pelvis rotate (axial plane) or hitch/hike (frontal plane)? **					
Is there axial rotation of the pelvis? ¥	Right	0.50	0.74 (0.51-0.96)	0.76 (0.56-0.96)	75
	Left	0.70	0.84 (0.67-1.00)	0.86 (0.70-1.00)	85
Does the pelvis hitch? #	Right	0.94	0.67 (0.05-1.00)	0.79 (0.63-0.94)	95
	Left	0.51	0.00 (0.00-0.00)	0.79 (0.63-0.94)	65
Does the foot fail to align with the ankle, knee and hip?	Right	0.87	0.67 (0.23-1.10)	0.94 (0.86-1.00)	90
Does the foot fail to align with the ankle, knee and hip? (rate both legs)	Left	0.84	0.80 (0.53-1.00)	0.93 (0.84-1.00)	90
Does the pelvis tilt backwards (posteriorly)?	Right	0.60	0.78 (0.57-0.99)	0.82 (0.64-0.99)	80
Does the pelvis begin in, or move backwards (posteriorly)?	Left	0.70	0.84 (0.67-1.00)	0.86 (0.70-1.00)	85
Does the hip fail to bend (flex) just beyond 90 degrees (approximate 110 degrees)?	Right	1.00	1.00 (1.00-1.00)	N/A	100
	Left	1.00	1.00 (1.00-1.00)	N/A	100
Does the trunk lean backwards (extend)?	Right	0.80	0.89 (0.74-1.00)	0.91 (0.78-1.00)	90
	Left	0.72	0.88 (0.75-1.00)	0.80 (0.58-1.00)	85
Mean agreement (n=6)	0.77				86
Mean agreement of unchanged criteria (n=3)	0.87				93

*criterion created by combining criteria ¥ and #

4.3.1.6 *Hip abduction with lateral rotation test*

The overall intra-rater video agreement was excellent with an AC1 score of 0.88 and 92% for the hip abduction with lateral rotation test (Table 4-12). Both the pelvic movement criteria were reworded to 'fail to stay vertical' and the criteria of the hip reaching 45 degrees were added (Table 4-12). Overall AC1 agreement for the remaining criteria increased to 0.93.

Table 4-12: Intra-rater video percentage agreement, AC1, positive and negative agreement for the hip abduction with lateral rotation in adolescent footballers (n=20). Updated movement criteria in italics. Shaded criteria indicate ones that remain unchanged in the updated HLLMS.

Movement criteria	Side	AC1	Negative agreement	Positive agreement	% Agree
Does the hip fail to abduct to 45 degrees?	Right				
	Left				
Does the leg lose lateral rotation?	Right	1.00	1.00 (1.00-1.00)	N/A	100
	Left	0.95	0.97 (0.92-1.00)	0.00 (0.00-0.00)	95
Does the hip/knee (leg) move into flexion?	Right	0.94	0.80 (0.42-1.00)	0.97 (0.92-1.00)	95
	Left	0.81	0.40 (-0.14-0.94)	0.91 (0.82-1.00)	85
Does the pelvis move backward?	Right	0.71	0.82 (0.63-1.00)	0.87 (0.72-1.00)	85
Does the pelvis fail to stay vertical (rotate backwards or forwards)?	Left	0.84	0.80 (0.53-1.00)	0.93 (0.84-1.00)	90
Does the pelvis hitch/drop?	Right	0.88	0.50 (0.00-1.00)	0.94 (0.87-1.00)	90
Does the pelvis fail to stay vertical (rotate up or down)?	Left	0.94	0.67 (0.05-1.00)	0.97 (0.92-1.00)	95
Mean agreement (n=4)		0.88			92
Mean agreement of unchanged criteria (n=2)		0.93			94

4.3.1.7 *Hip abduction with medial rotation test*

The overall intra-rater video AC1 of 0.71 and 83% agreement were lower for the medial rotation test compared to lateral rotation test, which showed 0.88 and 92% respectively (Table 4-12, Table 4-13). Low agreement was due to ‘Does the leg lose medial rotation?’ (left) which remained in the latest HLLMS. The pelvis hitch/drop criterion, which had an AC1 of 0.58 on the left, has been re-worded in the latest HLLMS (Table 4-13). For the criteria that remain in the updated HLLMS, overall AC1 agreement was above the acceptable level at 0.66.

Table 4-13: Intra-rater video percentage agreement, AC1, positive and negative agreement for the hip abduction with medial rotation in adolescent footballers (n=20). Updated movement criteria in italics. Shaded criteria indicate ones that remain unchanged in the updated HLLMS.

Movement criteria	Side	AC1	Negative agreement	Positive agreement	% Agree
Does the hip fail to abduct to 35 degrees?	Right				
	Left				
Does the leg lose medial rotation?	Right	0.66	0.67 (0.36-0.97)	0.86 (0.72-1.00)	80
	Left	0.45	0.57 (0.26-0.88)	0.77 (0.59-0.95)	70
Does the hip/knee (leg) move into flexion?	Right	0.63	0.85 (0.70-1.00)	0.71 (0.45-0.98)	80
	Left	0.68	0.87 (0.74-1.00)	0.60 (0.24-0.96)	80
Does the pelvis move backward?	Right	0.89	0.95 (0.87-1.00)	0.00 (0.00-0.00)	90
Does the pelvis fail to stay vertical (rotate backwards or forwards)?	Left	0.95	0.97 (0.92-1.00)	0.00 (0.00-0.00)	95
Does the pelvis hitch/drop?	Right	0.85	0.75 (0.41-1.00)	0.94 (0.85-1.00)	90
Does the pelvis fail to stay vertical (rotate up or down)?	Left	0.58	0.55 (0.19-0.90)	0.83 (0.68-0.98)	75
Mean agreement (n=4)		0.71			83
Mean agreement of unchanged criteria (n=2)		0.66			78

Re-calculating the overall mean intra-rater video for the criteria that have not been changed in latest version of the HLLMS increased to 0.84 (range 0.45-1.00) for the AC1 and to 91% (range 70-100%) for the percentage agreement (Table 4-14).

Table 4-14. Summary of intra-rater video agreement for observational rating from the HLLMS (n=20) for the updated HLLMS.

Test	**Mean AC1 (range)**	**Mean percent agreement (range)**
Small knee bend	0.94 (0.89-1.00)	95 (90-100)
Small knee bend with rotation	0.92 (0.70-0.95)	93 (85-95)
Standing hip flexion	0.78 (0.60-1.00)	90 (80-100)
Deep squat	0.91 (0.83-1.00)	95 (90-100)
Sitting hip flexion	0.87 (0.72-1.00)	93 (85-100)
Hip abduction with lateral rotation	0.93 (0.40-1.00)	94 (85-100)
Hip abduction with medial rotation	0.66 (0.45-0.68)	78 (70-80)
Overall mean	0.84 (0.40-1.00)	91 (70-100)

4.3.2 Intra-rater reliability in real time in controls

The overall mean intra-rater reliability between days was lower than intra-rater reliability using video, with mean AC1 of 0.63 (0.20-1.00) and mean percentage agreement was 78% (45-100%) for the HLLMS in 11 young male students (Table 4-15).

Table 4-15. Summary of intra-rater between days in real time agreement for the observational rating from the HLLMS in controls (n=11)

Test	Mean AC1 (range)	Mean percent agreement (range)
Small knee bend	0.70 (0.32-1.00)	82 (64-100)
Small knee bend with rotation	0.63 (0.20-1.00)	78 (55-100)
Standing hip flexion	0.80 (0.45-1.00)	88 (73-100)
Deep squat	0.58 (0.30-0.74)	73 (55-82)
Sitting hip flexion	0.58 (-0.08-1.00)	77 (45-100)
Hip abduction with lateral rotation	0.65 (0.20-0.90)	76 (55-91)
Hip abduction with medial rotation	0.44 (0.20-0.86)	68 (55-91)
Overall mean	0.63 (0.20-1.00)	78 (45-100)

4.3.2.1 *SKB test*

Overall intra-rater video AC1 was 0.70, with 82% agreement for the SKB test (Table 4-16). 'Does the knee move inwards?' on left side, trunk lean forwards left side and pelvic tilt forwards on the left side had and AC1 below the acceptable cut off of 0.6. However, on the right side the values for the criteria with low reliability above were all rated as acceptable or excellent (>0.8 AC1) (Table 4-16).

Table 4-16. Intra-rater between days in real time percentage agreement, AC1, positive and negative agreement for the SKB test in controls (n=11). Shaded criteria indicate ones that remain unchanged in the updated HLLMS.

Movement criteria	Side	AC1	Negative agreement (95% CI)	Positive agreement (95% CI)	% Agree
Does the knee move inward from the 2nd toe?	Right	0.88	0.95 (0.84-1.05)	0.67 (0.05-1.28)	91
Is there an increase in dynamic valgus from the start position?	Left	0.32	0.71 (0.45-0.98)	0.50 (0.08-0.92)	64
Does the pelvis hitch/drop?	Right	0.86	0.80 (0.42-1.00)	0.94 (0.83-1.00)	91
Does the pelvis fail to stay level?	Left	0.74	0.50 (0.00-1.00)	0.89 (0.74-1.00)	82
Does the knee fail to move 2cm past the toes?	Right	0.90	0.95 (0.86-1.00)	0.00 (0.00-0.00)	91
	Left	1.00	1.00 (1.00-1.00)	1.00 (1.00-1.00)	100
Does the trunk lean forwards?	Right	0.32	0.50 (0.08-0.92)	0.71 (0.45-0.98)	64
	Left	0.74	0.50 (0.00-1.00)	0.89 (0.74-1.00)	82
Does the pelvis tilt forwards?	Right	0.70	0.67 (0.23-1.10)	0.88 (0.70-1.00)	82
Does the pelvis begin in, or tilt forwards (anterior)?	Left	0.52	0.57 (0.13-1.00)	0.80 (0.58-1.00)	73
Mean agreement (n=5)		0.70			82
Mean agreement of unchanged criteria (n=2)		0.74			82

4.3.2.2 *SKB rotation test*

Mean overall agreement for the criteria that remained in the HLLMS had an AC1 score of 0.79. However, trunk lean forwards had below acceptable AC1 agreement scores of 0.20 and 0.32 on the right and left respectively (Table 4-17).

Table 4-17: Intra-rater between days in real time percentage agreement, AC1, positive and negative agreement for the SKB with rotation test in male controls (n=11). Shaded criteria indicate ones that remain unchanged in the updated HLLMS.

Movement criteria	**Side**	**AC1**	**Negative agreement**	**Positive agreement**	**% Agree**
Does the pelvis follow the trunk?	Right	0.74	0.50 (-0.10-1.10)	0.89 (0.74-1.00)	82
	Left	1.00	1.00 (1.00-1.00)	1.00 (1.00-1.00)	100
Does the trunk side-bend? *	Right	0.70	0.88 (0.70-1.00)	0.00 (0.00-0.00)	82
	Left	0.64	0.84 (0.67-1.00)	0.00 (0.00-0.00)	73
Does the pelvis hitch/drop? *Does the pelvis stay level?*	Right	0.47	0.67 (0.31-1.00)	0.77 (0.52-1.00)	73
	Left	0.20	0.29 (0.00-0.72)	0.67 (0.39-0.94)	55
Does the trunk rotate less than 30°?	Right	1.00	1.00 (1.00-1.00)	N/A	100
	Left	1.00	1.00 (1.00-1.00)	1.00 (1.00-1.00)	100
Do the toes claw or any loss of balance? *	Right	0.48	0.00 (0.00-0.00)	0.78 (0.57-0.99)	64
	Left	0.86	0.80 (0.42-1.00)	0.94 (0.83-1.00)	91
Does the trunk lean forwards?	Right	0.20	0.29 (0.00-0.72)	0.67 (0.39-0.94)	55
	Left	0.32	0.50 (0.08-0.92)	0.71 (0.45-0.98)	64
Mean agreement (n=6)		0.63			78
Mean agreement of unchanged criteria (n=3)		0.79			87

*criteria removed from the latest version of the HLLMS

4.3.2.3 *Standing hip flexion test*

Reliability of the ratings was generally high for this test, with only two criterial showing poor results. The criterion 'Does the weight bearing knee bend?' had poor agreement with low AC1 scores on both sides (0.45, 0.52) and 'Does the trunk lean backwards?' on the left (0.58) was below 0.6 (Table 4-18).

Table 4-18 Intra-rater between days in real time percentage agreement, AC1, positive and negative agreement for the standing hip flexion test in male controls (n=11). Shaded criteria indicate ones that remain unchanged in the updated HLLMS.

Movement criteria	Side	AC1	Negative agreement	Positive agreement	% Agree
Does the pelvis drop (hitch)? *Does the pelvis fail to stay level?*	Right	0.86	0.94 (0.83-1.00)	0.80 (0.42-1.00)	91
	Left	0.86	0.94 (0.83-1.00)	0.80 (0.42-1.00)	91
Does the pelvis tilt backwards (posteriorly)? *Does the pelvis begin in, or move backwards (posteriorly)?*	Right	1.00	1.00 (1.00-1.00)	1.00 (1.00-1.00)	100
	Left	0.86	0.80 (0.42-1.00)	0.94 (0.83-1.00)	91
Does the hip fail to bend (flex) just beyond 90 degrees (approximate 110 degrees)?	Right	1.00	1.00 (1.00-1.00)	N/A	100
	Left	1.00	1.00 (1.00-1.00)	N/A	100
Does the trunk lean backwards (extend)?	Right	0.86	0.94 (0.83-1.00)	0.80 (0.42-1.00)	91
	Left	0.58	0.82 (0.63-1.00)	0.40 (0.00-0.94)	73
Does the weight bearing knee bend (flex)?	Right	0.45	0.73 (0.43-1.00)	0.73 (0.43-1.00)	73
	Left	0.52	0.80 (0.58-1.00)	0.57 (0.13-1.00)	73
Mean agreement (n=5)		0.80			88
Mean agreement of unchanged criteria (n=3)		0.74			85

4.3.2.4 *Deep Squat test*

Overall agreement AC1 scores of 0.58 for both all the criteria and without revised criteria had poor agreement (Table 4-19). The criteria that remained unchanged in the updated HLLMS had higher AC1 values apart from 'Does the bodyweight shift to one side?' which had a low AC1 score of 0.3.

Table 4-19: Intra-rater between days in real time percentage agreement, AC1, positive and negative agreement for the deep squat test in male controls (n=11). Shaded criteria indicate ones that remain unchanged in the updated HLLMS.

Movement criteria	**AC1**	**Negative agreement**	**Positive agreement**	**% Agree**
Does the trunk fail to stay parallel with the shin (tibia)?	0.70	0.67 (0.23-1.00)	0.88 (0.70-1.00)	82
Does the thigh (femur) fail to be horizontal with the floor?	0.74	0.89 (0.74-1.00)	0.50 (-0.10-1.00)	82
Does the pelvis tilt forwards (anteriorly)? *Does the pelvis begin in, or move forwards (anteriorly)?*	0.58	0.82 (0.63-1.00)	0.40 (-0.14-0.94)	73
Does the bodyweight shift to one side?	0.30	0.71 (0.46-0.95)	0.00 (0.00-0.00)	55
Mean agreement (n=4)	0.58			73
Mean agreement of unchanged criteria (n=3)	0.58			73

4.3.2.5 *Sitting hip flexion test*

With the criteria of 'Is there axial rotation of the pelvis?' and 'Does the pelvis hitch?' combined in the latest version of the HLLMS, the overall agreement AC1 score increased from poor (0.58) to acceptable (0.75) (Table 4-20).

Table 4-20: Intra-rater between days in real time percentage agreement, AC1, positive and negative agreement for the sitting hip flexion test in male controls (n=11). Shaded criteria indicate ones that remain unchanged in the updated HLLMS.

Movement criteria	Side	AC1	Negative agreement	Positive agreement	% Agree
*Does the pelvis rotate (axial plane) or hitch/hike (frontal plane)? **					
Is there axial rotation of the pelvis? ¥	Right	0.66	0.75 (0.41-1.00)	0.86 (0.66-1.00)	82
	Left	1.00	1.00 (1.00-1.00)	1.00 (1.00-1.00)	100
Does the pelvis hitch? #	Right	0.12	0.62 (0.30-0.93)	0.50 (0.15-0.85)	55
	Left	-0.08	0.40 (0.02-0.78)	0.50 (0.15-0.85)	45
Does the foot fail to align with the ankle, knee and hip?	Right	0.32	0.50 (0.08-0.92)	0.71 (0.45-0.98)	64
Does the foot fail to align with the ankle, knee and hip? (rate both legs)	Left	0.58	0.40 (0.00-0.94)	0.82 (0.63-1.00)	73
Does the pelvis tilt backwards (posteriorly)?	Right	0.66	0.75 (0.41-1.00)	0.86 (0.66-1.00)	82
Does the pelvis begin in, or move backwards (posteriorly)?	Left	0.64	0.00 (0.00-0.00)	0.84 (0.67-1.00)	73
Does the hip fail to bend (flex) just beyond 90 degrees (approximate 110 degrees)?	Right	1.00	1.00 (1.00-1.00)	N/A	100
	Left	0.90	0.95 (0.86-1.05)	0.00 (0.00-0.00)	91
Does the trunk lean backwards (extend)?	Right	0.45	0.73 (0.43-1.00)	0.73 (0.43-1.00)	73
	Left	0.66	0.75 (0.41-1.00)	0.86 (0.66-1.00)	82
Mean agreement (n=6)		0.58			77
Mean agreement of unchanged criteria (n=3)		0.75			86

*new criterion created by combining criteria ¥ and #

4.3.2.6 *Hip abduction with lateral rotation test*

Overall intra-rater between days agreement for the hip abduction with lateral rotation test without updated criteria was excellent (AC1 0.86) (Table 4-21).

Table 4-21: Intra-rater between days in real time percentage agreement, AC1, positive and negative agreement for the hip abduction with lateral rotation test in male controls (n=11). Shaded criteria indicate ones that remain unchanged in the updated HLLMS.

Movement criteria	**Side**	**AC1**	**Negative agreement**	**Positive agreement**	**% Agree**
Does the hip fail to abduct to 45 degrees?	Right				
	Left				
Does the leg lose lateral rotation?	Right	0.90	0.95 (0.86-1.00)	0.00 (0.00-0.00)	91
	Left	0.90	0.95 (0.86-1.00)	0.00 (0.00-0.00)	91
Does the hip/knee (leg) move into flexion?	Right	0.74	0.50 (0.00-1.00)	0.89 (0.74-1.00)	82
	Left	0.90	0.00 (0.00-0.00)	0.95 (0.86-1.05)	91
Does the pelvis move backward?	Right	0.48	0.00 (0.00-0.00)	0.78 (0.57-0.99)	64
Does the pelvis fail to stay vertical (rotate backwards or forwards)?	Left	0.74	0.50 (-0.10-1.10)	0.89 (0.74-1.00)	82
Does the pelvis hitch/drop?	Right	0.20	0.29 (-0.15-0.72)	0.67 (0.39-0.94)	55
Does the pelvis fail to stay vertical (rotate up or down)?	Left	0.30	0.00 (0.00-0.00)	0.71 (0.46-0.95)	55
Mean agreement (n=4)		0.65			76
Mean agreement of unchanged criteria (n=2)		0.86			89

4.3.2.7 *Hip abduction with medial rotation test*

In contrast to Hip abduction with lateral rotation test the medial rotation overall agreement without revised criteria was poor (AC1 0.49) (Table 4-22).

Table 4-22: Intra-rater between days in real time percentage agreement, AC1, positive and negative agreement for the hip abduction with medial rotation test in male controls (n=11). Shaded criteria indicate ones that remain unchanged in the updated HLLMS.

Movement criteria	**Side**	**AC1**	**Negative agreement**	**Positive agreement**	**% Agree**
Does the hip fail to abduct to 35 degrees?	Right				
	Left				
Does the leg lose medial rotation?	Right	0.30	0.00 (0.00-0.00)	0.71 (0.46-0.95)	55
	Left	0.86	0.80 (0.42-1.00)	0.94 (0.83-1.00)	91
Does the hip/knee (leg) move into flexion?	Right	0.32	0.71 (0.45-0.98)	0.50 (0.08-0.92)	64
	Left	0.47	0.77 (0.52-1.00)	0.67 (0.31-1.00)	73
Does the pelvis move backward?	Right	0.52	0.80 (0.58-1.00)	0.57 (0.13-1.00)	73
Does the pelvis fail to stay vertical (rotate backwards or forwards)?	Left	0.52	0.80 (0.58-1.00)	0.57 (0.13-1.00)	73
Does the pelvis hitch/drop?	Right	0.20	0.29 (-0.15-0.72)	0.67 (0.39-0.94)	55
Does the pelvis fail to stay vertical (rotate up or down)?	Left	0.32	0.50 (0.08-0.92)	0.71 (0.45-0.98)	64
Mean agreement (n=4)		0.44			68
Mean agreement of unchanged criteria (n=2)		0.49			70

Overall intra-rater agreement for the updated HLLMS was acceptable (AC1 = 0.69) although the deep squat (AC1 = 0.58) and hip abduction with medial rotation (AC1 = 0.49) both had poor overall agreement (Table 4-23).

Table 4-23. Summary of intra-rater real time between day agreement for observational rating for male controls from the HLLMS (n=11) for the updated HLLMS.

Test	**Mean AC1 (range)**	**Mean percent agreement (range)**
Small knee bend	0.74 (0.32-1.00)	84 (64-100)
Small knee bend with rotation	0.67 (0.20-1.00)	80 (55-100)
Standing hip flexion	0.74 (0.45-1.00)	83 (73-100)
Deep squat	0.58 (0.30-0.74)	73 (55-82)
Sitting hip flexion	0.75 (0.45-1.00)	86 (73-100)
Hip abduction with lateral rotation	0.86 (0.74-0.90)	89 (82-91)
Hip abduction with medial rotation	0.49 (0.30-0.86)	70 (55-92)
Overall mean	0.69 (0.20-1.00)	82 (55-100)

4.3.3 Inter-rater reliability in footballers

Overall inter-rater agreement was just above the acceptable AC1 cut off of 0.6. Three of the tests Deep squat, sitting hip flexion and Hip abduction with medial rotation tests had poor agreement with AC1 scores of 0.40, 0.41 and 0.35 respectively (Table 4-24).

Table 4-24. Summary of inter-rater agreement for observational rating of footballers during the HLLMS (n=20) (raters NB and DW)

Test	Mean AC1 (range)	Mean percent agreement (range)
Small knee bend	0.75 (0.48-1.00)	85 (70-100)
Small knee bend with rotation	0.65 (0.31-100)	78 (60-100)
Standing hip flexion	0.69 (0.41-0.95)	82 (65-95)
Deep squat	0.40 (0.10-0.66)	69 (55-80)
Sitting hip flexion	0.41 (-0.47 0.-89)	66 (25-90)
Hip abduction with lateral rotation	0.86 (0.68-1.00)	88 (75-100)
Hip abduction with medial rotation	0.35 (-0.39-0.83)	64 (45-85)
Overall mean	0.6 (-0.47-1.00)	76 (25-100)

4.3.3.1 *SKB test*

The overall inter-rater agreement without revised criteria for the SKB test was excellent (AC1 = 0.82). However, the criterion ‘Does the trunk lean forwards?’ for the left side was poor (AC1 = 0.55) (Table 4-25).

Table 4-25: Inter-rater percentage agreement, AC1, positive and negative agreement for the SKB test in adolescent footballers (n=20). Shaded criteria indicate ones that remain unchanged in the updated HLLMS.

Movement criteria	**Side**	**AC1**	**Negative agreement**	**Positive agreement**	**% Agree**
Does the knee move inward from the 2nd toe?	Right	0.50	0.74 (0.51-0.96)	0.76 (0.56-0.96)	75
Is there an increase in dynamic valgus from the start position?	Left	0.48	0.50 (0.15-0.85)	0.79 (0.62-0.95)	70
Does the pelvis hitch/drop?	Right	0.88	0.50 (-0.10-1.10)	0.94 (0.87-1.00)	90
Does the pelvis fail to stay level?	Left	0.77	0.67 (0.31-1.00)	0.90 (0.79-1.00)	85
Does the knee fail to move 2cm past the toes?	Right	0.89	0.95 (0.87-1.00)	0.00 (0.00-0.00)	90
	Left	1.00	1.00 (1.00-1.00)	N/A	100
Does the trunk lean forwards?	Right	0.83	0.83 (0.61-1.00)	0.93 (0.83-1.00)	90
	Left	0.55	0.62 (0.30-0.93)	0.81 (0.66-0.97)	75
Does the pelvis tilt forwards?	Right	0.83	0.83 (0.61-1.00)	0.93 (0.83-1.00)	90
Does the pelvis begin in, or tilt forwards (anterior)?	Left	0.77	0.67 (0.31-1.00)	0.90 (0.79-1.00)	85
Mean agreement (n=5)		0.75			85
Mean agreement of unchanged criteria (n=2)		0.82			89

4.3.3.2 *SKB Rotation test*

The overall inter-rater agreement for the SKB Rot test was acceptable for the agreement of unchanged criteria (AC1 = 0.71) (Table 4-26).

Table 4-26: Inter-rater percentage agreement, AC1, positive and negative agreement for the SKB with rotation test in adolescent footballers (n=20). Shaded criteria indicate ones that remain unchanged in the updated HLLMS.

Movement criteria	Side	AC1	Negative agreement	Positive agreement	% Agree
Does the pelvis follow the trunk?	Right	0.79	0.57 (0.13-1.00)	0.91 (0.81-1.00)	85
	Left	0.31	0.33 (-0.01-0.68)	0.71 (0.52-0.90)	60
Does the trunk side-bend? *	Right	0.68	0.86 (0.73-0.98)	0.00 (0.00-0.00)	75
	Left	0.60	0.82 (0.68-0.96)	0.00 (0.00-0.00)	70
Does the pelvis hitch/drop? *Does the pelvis stay level?*	Right	0.51	0.00 (0.00-0.00)	0.79 (0.63-0.94)	65
	Left	0.81	0.40 (-0.14-0.94)	0.91 (0.82-1.00)	85
Does the trunk rotate less than 30°?	Right	0.95	0.97 (0.92-1.00)	0.00 (0.00-0.00)	95
	Left	1.00	1.00 (1.00-1.00)	N/A	100
Do the toes claw or any loss of balance? *	Right	0.52	0.40 (0.02-0.78)	0.80 (0.64-0.96)	70
	Left	0.66	0.67 (0.36-0.97)	0.86 (0.72-1.00)	80
Does the trunk lean forwards?	Right	0.51	0.71 (0.46-0.95)	0.78 (0.60-0.97)	75
	Left	0.53	0.67 (0.39-0.94)	0.80 (0.63-0.97)	75
Mean agreement (n=6)		0.65			78
Mean agreement of unchanged criteria (n=3)		0.71			83

*criteria removed from the latest version of the HLLMS

4.3.3.3 *Standing hip flexion test*

The overall inter-rater agreement without revised criteria was acceptable for the Standing hip flexion test. However, 'Does the weight bearing knee bend (flex)?' criterion had poor agreement on both sides (AC1 = 0.50 right, 0.41 left) (Table 4-27).

Table 4-27 Inter-rater video percentage agreement, AC1, positive and negative agreement for the standing hip flexion test in adolescent footballers (n=20) with updated movement criteria from the latest HLLMS in italics. Shaded criteria indicate ones that remain unchanged in the updated HLLMS.

Movement criteria - Stand Hip Flex	Side	AC1	Negative agreement	Positive agreement	% Agree
Does the pelvis drop (hitch)?	Right	0.62	0.44 (0.04-0.85)	0.84 (0.70-0.98)	75
Does the pelvis fail to stay level?	Left	0.51	0.00 (0.00-0.00)	0.79 (0.63-0.94)	65
Does the pelvis tilt backwards (posteriorly)?	Right	0.94	0.67 (0.05-1.28)	0.97 (0.92-1.00)	95
Does the pelvis begin in, or move backwards (posteriorly)?	Left	0.95	0.00 (0.00-0.00)	0.97 (0.92-1.00)	95
Does the hip fail to bend (flex) just beyond 90 degrees (approximate 110 degrees)?	Right	0.87	0.94 (0.86-1.00)	0.67 (0.23-1.10)	90
	Left	0.94	0.97 (0.92-1.00)	0.67 (0.05-1.28)	95
Does the trunk lean backwards (extend)?	Right	0.68	0.87 (0.74-1.00)	0.60 (0.24-0.96)	80
	Left	0.45	0.77 (0.59-0.95)	0.57 (0.26-0.88)	70
Does the weight bearing knee bend (flex)?	Right	0.50	0.74 (0.51-0.96)	0.76 (0.56-0.96)	75
	Left	0.41	0.67 (0.42-0.92)	0.73 (0.52-0.94)	70
Mean agreement (n=5)		0.69			83
Mean agreement of unchanged criteria (n=3)		0.64			80

4.3.3.4 *Deep squat test*

The mean inter-rater agreement for the deep squat test was poor, with an AC1 for the overall agreement without revised criteria of 0.50. The lowest agreement for the criteria in the updated HLLMS was for the criterion 'Does the bodyweight shift to one side?' of an AC1 score of 0.21 (Table 4-28).

Table 4-28: Inter-rater percentage agreement, AC1, positive and negative agreement for deep squat in adolescent footballers (n=20) with updated movement criteria from the latest HLLMS in italics. Shaded criteria indicate ones that remain unchanged in the updated HLLMS.

Movement criteria	**AC1**	**Negative agreement**	**Positive agreement**	**% Agree**
Does the trunk fail to stay parallel with the shin (tibia)?	0.63	0.71 (0.45-0.98)	0.85 (0.70-1.00)	80
Does the thigh (femur) fail to be horizontal with the floor?	0.66	0.86 (0.72-1.00)	0.67 (0.36-0.97)	80
Does the pelvis tilt forwards (anteriorly)? *Does the pelvis begin in, or move forwards (anteriorly)?*	0.10	0.53 (0.25-0.80)	0.57 (0.32-0.82)	55
Does the bodyweight shift to one side?	0.21	0.64 (0.40-0.87)	0.56 (0.28-0.83)	60
Mean agreement (n=4)	0.40			69
Mean agreement of unchanged criteria (n=3)	0.50			73

4.3.3.5 *Sitting hip flexion test*

The overall inter-rater agreement for the sitting hip flexion test without the revised criteria was poor (AC1 = 0.52). The lowest inter-rater agreement was for the criterion 'Does the trunk lean backwards (extend)?' with AC1 scores of 0.32 on the right and 0.12 on the left (Table 4-29).

Table 4-29: Inter-rater percentage agreement, AC1, positive and negative agreement for the sitting hip flexion test in adolescent footballers (n=20) with updated movement criteria from the latest HLLMS in italics. Shaded criteria indicate ones that remain unchanged in the updated HLLMS.

Movement criteria	Side	AC1	Negative agreement	Positive agreement	% Agree
*Does the pelvis rotate (axial plane) or hitch/hike (frontal plane)? **					
Is there axial rotation of the pelvis? ¥	Right	0.76	0.00 (0.00-0.00)	0.89 (0.78-1.00)	80
	Left	0.89	0.00 (0.00-0.00)	0.95 (0.87-1.00)	90
Does the pelvis hitch? #	Right	-0.40	0.30 (0.04-0.56)	0.35 (0.10-0.60)	30
	Left	-0.47	0.12 (-0.09-0.33)	0.35 (0.10-0.60)	25
Does the foot fail to align with the ankle, knee and hip?	Right	0.38	0.46 (0.13-0.80)	0.74 (0.56-0.93)	65
Does the foot fail to align with the ankle, knee and hip? (rate both legs)	Left	0.48	0.50 (0.15-0.85)	0.79 (0.62-0.95)	70
Does the pelvis tilt backwards (posteriorly)?	Right	0.62	0.44 (0.04-0.85)	0.84 (0.70-0.98)	75
Does the pelvis begin in, or move backwards (posteriorly)?	Left	0.56	0.25 (-0.15-0.65)	0.81 (0.67-0.96)	70
Does the hip fail to bend (flex) just beyond 90 degrees (approximate 110 degrees)?	Right	0.83	0.92 (0.83-1.00)	0.00 (0.00-0.00)	85
	Left	0.81	0.91 (0.82-1.00)	0.40 (-0.14-0.94)	85
Does the trunk lean backwards (extend)?	Right	0.32	0.59 (0.31-0.87)	0.70 (0.48-0.91)	65
	Left	0.12	0.47 (0.18-0.76)	0.61 (0.37-0.84)	55
Mean agreement (n=6)		0.41			66
Mean agreement of unchanged criteria (n=3)		0.52			73

*new criterion created by combining criteria ¥ and #

4.3.3.6 *Hip Abduction with lateral rotation test*

The overall inter-rater agreement for the Hip abduction with lateral rotation test without revised criteria was excellent (AC1=0.89) with AC1 scores ranging from 0.76 to 1.00 (Table 4-30).

Table 4-30: Inter-rater percentage agreement, AC1, positive and negative agreement for the hip abduction with lateral rotation in adolescent footballers (n=20) with updated movement criteria from the latest HLLMS in italics. Shaded criteria indicate ones that remain unchanged in the updated HLLMS.

Movement criteria	**Side**	**AC1**	**Negative agreement**	**Positive agreement**	**% Agree**
Does the hip fail to abduct to 45 degrees?	Right				
	Left				
Does the leg lose lateral rotation?	Right	0.89	0.95 (0.87-1.00)	0.00 (0.00-0.00)	90
	Left	0.76	0.89 (0.78-1.00)	0.00 (0.00-0.00)	80
Does the hip/knee (leg) move into flexion?	Right	1.00	N/A	1.00 (1.00-1.00)	100
	Left	0.89	0.00 (0.00-0.00)	0.95 (0.87-1.00)	90
Does the pelvis move backward?	Right	0.68	0.00 (0.00-0.00)	0.86 (0.73-0.98)	75
Does the pelvis fail to stay vertical (rotate backwards or forwards)?	Left	0.76	0.00 (0.00-0.00)	0.89 (0.78-1.00)	80
Does the pelvis hitch/drop?	Right	0.89	0.00 (0.00-0.00)	0.95 (0.87-1.00)	90
Does the pelvis fail to stay vertical (rotate up or down)?	Left	1.00	1.00 (1.00-1.00)	1.00 (1.00-1.00)	100
Mean agreement (n=4)		0.86			88
Mean agreement of unchanged criteria (n=2)		0.89			90

4.3.3.7 *Hip abduction with medial rotation test*

In contrast to the hip abduction with lateral rotation, overall inter-rater agreement calculated without revised criteria was poor for the medial rotation test (AC1= 0.11). All but three of the criteria ('Does the pelvis hitch right and left?' and 'Does the pelvis move backwards?' on the left) had poor reliability (<0.60 AC1 score).

Table 4-31: Inter-rater percentage agreement, AC1, positive and negative agreement for the hip abduction with medial rotation in adolescent footballers (n=20). Shaded criteria indicate ones that remain unchanged in the updated HLLMS.

Movement criteria	Side	AC1	Negative agreement	Positive agreement	% Agree
Does the hip fail to abduct to 35 degrees?					
Does the leg lose medial rotation?	Right	-0.08	0.35 (0.06-0.64)	0.52 (0.27-0.77)	45
	Left	-0.39	0.36 (0.11-0.62)	0.22 (-0.03-0.48)	30
Does the hip/knee (leg) move into flexion?	Right	0.48	0.50 (0.15-0.85)	0.79 (0.62-0.95)	70
	Left	0.42	0.63 (0.35-0.90)	0.75 (0.56-0.94)	70
Does the pelvis move backward?	Right	0.30	0.67 (0.43-0.90)	0.63 (0.38-0.89)	65
Does the pelvis fail to stay vertical (rotate backwards or forwards)?	Left	0.60	0.82 (0.64-0.99)	0.78 (0.57-0.99)	80
Does the pelvis hitch/drop?	Right	0.83	0.00 (0.00-0.00)	0.92 (0.83-1.00)	85
Does the pelvis fail to stay vertical (rotate up or down)?	Left	0.60	0.00 (0.00-0.00)	0.82 (0.68-0.96)	70
Mean agreement (n=4)		0.35			64
Mean agreement of unchanged criteria (n=2)		0.11			54

The overall inter-rater reliability for the criteria remained unchanged in the updated HLLMS was acceptable (AC1 =0.60) although the range of AC1 scores of -0.39 to 1.00 highlight the variation in agreement for the criteria. Similarly, overall percentage agreement was 78% but with a large range 30-100% (Table 4-32).

Table 4-32. Summary of inter-rater agreement for observational rating from the HLLMS (n=20) for the updated HLLMS.

Test	Mean AC1 (range)	Mean percent agreement (range)
Small knee bend	0.82 (0.55-1.00)	89 (75-100)
Small knee bend with rotation	0.68 (0.31-1.00)	82 (60-100)
Standing hip flexion	0.64 (0.41-0.94)	80 (70-95)
Deep squat	0.50 (0.21-0.66)	73 (60-80)
Sitting hip flexion	0.52 (0.12-0.83)	73 (55-85)
Hip abduction with lateral rotation	0.88 (0.76-1.00)	90 (80-100)
Hip abduction with medial rotation	0.11 (-0.39-0.48)	54 (30-70)
Overall mean	0.60 (-0.39-1.00)	78 (30-100)

4.3.4 Inter-rater reliability in Golfers

An older version (Version 2, Appendix F) of the HLLMS was used to assess the movement patterns of the male professional golfers and only five of the seven tests from the HLLMS were assessed. The overall mean inter-rater AC1 for golfers was 0.68 for all of the criteria, which increased to 0.76 if only the results from the unchanged criteria in the updated HLLMS from the five tests were assessed.

Table 4-33. Summary of inter-rater agreement in male professional golfers for observational rating for five of the tests from the HLLMS (n=45).

	All criteria		**Criteria that remain in the updated HLLMS.**	
Tests	**AC1 mean (range)**	**Percent agreement mean (range)**	**Mean AC1 (range)**	**Mean percent agreement (range)**
Small knee bend	0.55 (0.15-0.98)	75 (42-98)	0.81 (0.58-0.98)	89 (78-98)
Small knee bend with rotation	0.66 (0.28-0.98)	79 (62-98)	0.62 (0.28-0.98)	80 (62-98)
Standing hip flexion	0.65 (0.29-0.95)	81 (64-96)	0.75 (0.51-0.93)	85 (76-93)
Deep squat	0.82 (0.38-0.98)	89 (64-98)	0.86 (0.78-0.93)	90 (87-93)
Hip abduction with lateral rotation	0.83 (0.76-0.90)	87 (82-91)	0.84 (0.77-0.89)	87 (82-91)
Overall mean	0.68 (-0.15-0.98)	81 (42-98)	0.76 (0.28-0.98)	86 (62-98)

4.3.4.1 *Small knee bend test*

The overall inter-rater agreement without revised criteria for the golfers was excellent (AC1 = 0.81). The low AC1 scores from the criterion 'Does the pelvis tilt forward?' (right = -0.07 and left = -0.15) were due to one of the rater's initially interpreting the criterion incorrectly (Table 4-34). The highest inter-rater agreement movement criterion was the knee moving 2cm past the toe with and AC1 score of 0.98 and lowest AC1 score of 0.33 for the knee move medially criterion of the left (Table 4-34).

Table 4-34: Inter-rater AC1, positive and negative agreement and percentage agreement for the SKB test in male professional golfers (n=45). Shaded criteria indicate ones that remain unchanged in the updated HLLMS.

Movement criteria	**Side**	**AC1**	**Negative agreement (95% CI)**	**Positive agreement (95% CI)**	**% Agree**
Does the knee move inward from the 2nd toe?	Right	0.52	0.60 (0.39-0.81)	0.80 (0.69-0.91)	73
Is there an increase in dynamic valgus from the start position?	Left	0.33	0.41 (0.19-0.64)	0.72 (0.59-0.85)	62
Does the pelvis hitch/drop? *Does the pelvis fail to stay level?*	Right	0.80	0.36 (0.00-0.73)	0.91 (0.85-0.98)	84
	Left	0.81	0.22 (-0.14-0.58)	0.91 (0.85-0.98)	84
Does the knee fail to move 2cm past the toes?	Right	0.98	0.99 (0.97-1.00)	0.80 (0.42-1.00)	98
	Left	0.98	0.99 (0.97-1.00)	0.00 (0.00-0.00)	98
Does the trunk lean forwards?	Right	0.58	0.71 (0.53-0.88)	0.82 (0.71-0.93)	78
	Left	0.70	0.81 (0.67-0.95)	0.87 (0.77-0.96)	84
Does the pelvis tilt forwards?	Right	-0.07	0.45 (0.27-0.64)	0.48 (0.30-0.66)	47
Does the pelvis begin in, or tilt forwards (anterior)?	Left	-0.15	0.43 (0.26-0.61)	0.41 (0.23-0.59)	42
Mean agreement (n=5)		0.55			75
Mean agreement of unchanged criteria (n=2)		0.81			89

Negative agreement = no fault
Positive agreement = fault

4.3.4.2 *Small knee bend with rotation*

Overall, inter-rater reliability was acceptable with an AC1 score of 0.62 for the SKB Rot without the revised criteria (Table 4-35). The lowest AC1 agreement score was 0.34 for the trunk lean forward, left side and the highest was 0.98 for trunk rotate less than 30°, left side (Table 4-35).

Table 4-35: Inter-rater AC1, positive and negative agreement and percentage agreement for the SKB with rotation test in male professional golfers (n=45). Shaded criteria indicate ones that remain unchanged in the updated HLLMS.

Movement criteria	Side	AC1	Negative agreement (95% CI)	Positive agreement (95% CI)	% Agree
Does the pelvis follow the trunk?	Right	0.65	0.85 (0.74-0.95)	0.79 (0.65-0.93)	82
	Left	0.34	0.69 (0.55-0.84)	0.63 (0.46-0.81)	67
Does the trunk side-bend? *	Right	0.83	0.93 (0.87-0.98)	0.25 (-0.15-0.65)	87
	Left	0.84	0.93 (0.87-0.99)	0.25 (-0.15-0.65)	87
Does the pelvis hitch/drop?	Right	0.63	0.42 (0.14-0.70)	0.85 (0.75-0.94)	76
Does the pelvis stay level?	Left	0.70	0.53 (0.25-0.80)	0.87 (0.79-0.96)	80
Does the trunk rotate less than 30°?	Right	0.95	0.98 (0.95-1.00)	0.00 (0.00-0.00)	96
	Left	0.98	0.99 (0.97-1.00)	0.00 (0.00-0.00)	98
Do the toes claw or any loss of balance? *	Right	0.49	0.42 (0.17-0.66)	0.79 (0.68-0.90)	69
	Left	0.65	0.35 (0.06-0.64)	0.85 (0.76-0.94)	76
Does the trunk lean forwards?	Right	0.53	0.57 (0.35-0.79)	0.81 (0.70-0.91)	73
	Left	0.28	0.51 (0.31-0.72)	0.69 (0.55-0.83)	62
Mean agreement (n=6)		0.66			79
Mean agreement of unchanged criteria (n=3)		0.62			80

*criteria removed from the latest version of the HLLMS

Negative agreement = no fault
Positive agreement = fault

4.3.4.3 *Standing hip flexion*

Overall, inter-rater reliability was acceptable with an AC1 score of 0.75 for the criteria that remained, unchanged in the latest version of the HLLMS. Of the criteria that remained in the HLLMS only the criterion 'Does the weight bearing knee bend (flex)?' on the right side, had poor reliability with an AC1 score of 0.51 (Table 4-36).

Table 4-36: Inter-rater AC1, positive and negative agreement and percentage agreement for the standing hip flexion test in male professional golfers (n=45), Shaded criteria indicate ones that remain unchanged in the updated HLLMS.

Movement criteria	**Side**	**AC1**	**Negative agreement (95% CI)**	**Positive agreement (95% CI)**	**% Agree**
Does the pelvis drop (hitch)?	Right	0.95	0.98 (0.94-1.00)	0.50 (-0.10-1.10)	96
Does the pelvis fail to stay level?	Left	0.90	0.95 (0.91-1.00)	0.00 (0.00-0.00)	91
Does the pelvis tilt backwards (posteriorly)?	Right	0.29	0.64 (0.47-0.80)	0.65 (0.49-0.81)	64
Does the pelvis begin in, or move backwards (posteriorly)?	Left	0.51	0.74 (0.60-0.89)	0.77 (0.63-0.90)	76
Does the spine flex? *	Right	0.43	0.76 (0.64-0.88)	0.56 (0.36-0.77)	69
	Left	0.44	0.75 (0.63-0.88)	0.65 (0.47-0.83)	71
Does the trunk lean backwards (extend)?	Right	0.85	0.93 (0.87-0.99)	0.00 (0.00-0.00)	87
	Left	0.93	0.97 (0.93-1.00)	0.00 (0.00-0.00)	93
Does the weight bearing knee bend (flex)?	Right	0.51	0.78 (0.65-0.90)	0.73 (0.58-0.88)	76
	Left	0.70	0.87 (0.78-0.97)	0.80 (0.65-0.95)	84
Mean agreement (n=5)		0.65			81
Mean agreement of unchanged criteria (n=2)		0.75			85

Negative agreement = no fault
Positive agreement = fault

*fault removed from updated HLLMS

4.3.4.4 *Deep Squat*

Overall inter-rater reliability for the criteria that were included in the updated HLLMS was excellent (AC1 = 0.84, 90% agreement) (Table 4-37). The lowest scoring criterion (AC1= 0.38), ‘Does the pelvis tilt forwards?’ has been updated with does the pelvis begin in, or, added to the criterion (Table 4-37).

Table 4-37: Inter-rater AC1, positive and negative agreement and percentage agreement for the deep squat test in male professional golfers (n=45). Shaded criteria indicate ones that remain unchanged in the updated HLLMS.

Movement criteria	**AC1**	**Negative agreement (95% CI)**	**Positive agreement (95% CI)**	**% Agree**
Does the trunk fail to stay parallel with the shin (tibia)?	0.78	0.75 (0.56-0.94)	0.91 (0.84-0.98)	87
Does the thigh (femur) fail to be horizontal with the floor?	0.86	0.94 (0.89-1.00)	0.80 (0.61-0.99)	91
Does the pelvis tilt forwards (anteriorly)? *Does the pelvis begin in, or move forwards (anteriorly)?*	0.38	0.43 (0.20-0.66)	0.74 (0.62-0.86)	64
Does the knee move inward from the 2nd toe? *	0.98	0.99 (0.97-1.00)	0.00 (0.00-0.00)	98
Does the knee move outward from the 2nd toe? *	0.98	0.99 (0.97-1.00)	0.00 (0.00-0.00)	98
Does the bodyweight shift to one side?	0.93	0.97 (0.93-1.00)	0.00 (0.00-0.00)	93
Mean agreement (n=6)	0.82			89
Mean agreement of unchanged criteria (n=3)	0.86			90

*deleted from updated HLLMS

4.3.4.5 *Hip abduction with lateral rotation*

Overall, inter-rater reliability for the criteria that remained in the updated HLLMS excellent (AC1= 0.84, 88% agreement) for the hip abduction with lateral rotation test. All criteria had an AC1 ≥ 0.76 (Table 4-38).

Table 4-38: Inter-rater AC1, positive and negative agreement and percentage agreement for the hip abduction with lateral rotation test in male professional golfers (n=45). Shaded criteria indicate ones that remain unchanged in the updated HLLMS.

Movement criteria	Side	AC1	Negative agreement (95% CI)	Positive agreement (95% CI)	% Agree
Does the leg lose lateral rotation?	Right	0.87	0.94 (0.89-0.99)	0.29 (-0.15-0.72)	89
	Left	0.83	0.93 (0.87-0.98)	0.40 (0.02-0.78)	87
Does the hip/knee (leg) move into flexion?	Right	0.77	0.33 (-0.01-0.68)	0.90 (0.83-0.97)	82
	Left	0.89	0.60 (0.24-0.96)	0.95 (0.90-1.00)	91
Does the pelvis move backward?	Right	0.77	0.63 (0.38-0.89)	0.90 (0.83-0.97)	84
Does the pelvis fail to stay vertical (rotate backwards or forwards)?	Left	0.76	0.67 (0.43-0.90)	0.90 (0.82-0.97)	84
Does the pelvis hitch/drop?	Right	0.86	0.55 (0.19-0.90)	0.94 (0.88-0.99)	89
Does the pelvis fail to stay vertical (rotate up or down)?	Left	0.90	0.33 (-0.15-0.82)	0.95 (0.91-1.00)	91
Mean agreement (n=4)		0.83			87
Mean agreement of unchanged criteria (n=2)		0.84			87

4.3.1 AC1 Summary for all reliability

The golf data was excluded from the analysis as only five tests were assessed and there were some differences in the criteria assessed due to an older version of the HLLMS being used compared to the footballer and control studies. There was inconsistent variation in agreement measured by AC1 between the different types of rater agreement assessed in this chapter. An example of the variation is shown for the criterion 'Does the knee move inwards?' from the SKB test which had in the different types of rater agreement on the left side with AC1 values ranging from 0.32 to 0.80 (Table 4-39). In contrast the criterion 'Does the pelvis hitch/drop?' had very consistent rater agreement AC1 values (0.85 to 0.88) (Table 4-39). Tables for the other tests from the HLLMS are in Appendix K.

Table 4-39. Intra-rater video, intra-rater between day and inter-rater footballers AC1 agreement scores for the SKB test.

		AC1		
Movement criteria	**Side**	**Intra-rater video (n=20)**	**Intra-rater between day (n=11)**	**Inter-rater footballers (n=20)**
Does the knee move inward from the 2nd toe?	Right	0.60	0.88	0.50
Is there an increase in dynamic valgus from the start position?	Left	0.80	0.32	0.48
Does the pelvis hitch/drop?	Right	0.85	0.86	0.88
Does the pelvis fail to stay level?	Left	0.93	0.74	0.77
Does the knee fail to move 2cm past the toes?	Right	0.95	0.90	0.89
	Left	0.89	1.00	1.00
Does the trunk lean forwards?	Right	1.00	0.32	0.83
	Left	0.91	0.74	0.55
Does the pelvis tilt forwards?	Right	0.55	0.70	0.83
Does the pelvis begin in, or tilt forwards (anterior)?	Left	0.66	0.52	0.77

4.4 Discussion

Analysing the reliability of the HLLMS is important to try and identify sources of error that could be addressed to develop a reliable tool. Due to the limitations of percentage agreement highlighted in the introduction (section 4.1.1.1) in that it does not consider the potential for chance agreement, AC1 values will be the main agreement statistic reported in the discussion. The high overall mean AC1 values for the reliability of the observational rating for the HLLMS considered in this chapter suggest that the screen is reliable. Despite this some of the criteria showed poor reliability highlighting those that needed to be improved. Some of the criteria have been revised to improve clarity, aiming to improve reliability in future.

4.4.1 Intra-rater reliability on video analysis

The intra-rater video had the highest overall agreement of 0.80 for the AC1 of the rater agreements assessed in this thesis for the HLLMS. Despite 39/64 of the criteria rating as excellent agreement (AC1 > 0.8) seven of the criteria were rated as less than acceptable agreement as defined by an AC1 less than 0.6. These results suggest that there are some criteria that are not reliable and need to be improved to develop a reliable HLLMS.

Comparing the overall intra-rater video agreement results for the HLLMS to other studies is limited due to a lack of research on rating multi segment and multiple criteria from more than one test movement (Whatman et al., 2015). Most of the research on reliability has been carried out using the SKB test (Whatman et al., 2015) and often only one criterion Ageberg et al. (2010). Also, Whatman et al. (2015) suggested that rater agreement is specific to the movement criteria being rated and also may be affected by how many criteria are being rated at the same time. Therefore, any comparison of the reliability findings of this thesis need to be compared to research on similar movements and criteria.

One study by Mischiati et al. (2015) used multi segments and multiple criterion rating, and reported slightly higher overall intra-rater agreement using video footage for the two raters of 97.5% (range 87.5-100%) and 93.9% (range 75-100%) compared to 88% (range 60-100%) for the HLLMS in the present study. A potential reason for the higher intra-rater agreement reported by Mischiati et al. (2015) could be due to the greater rater experience which Whatman et al. (2013b) suggested could improve agreement. The rater in the present study had only five years musculoskeletal experience and three months movement control experience which was substantially lower than the least experienced rater from Mischiati et al. (2015) who had 14 years musculoskeletal and 7 years movement control rating experience. In support of the role of experience on intra-rater agreement Mischiati et al. (2015) reported the most experienced rater (with 14 years MSK and 7 years movement control) had the highest agreement (97.5%).

Although the use of video footage allows a constant movement to be rated, Mischiati et al. (2015) reported a low percentage agreement of 74.5% between real time and video footage rating. The difference between rating from live compared to video footage was suggested by Mischiati et al. (2015) to be due to not being able to see the exact movement on video, whereas when scoring live the rater is able to adjust their position to get the view they need. The above limitation of rating from video footage may explain the low AC1 0.63 (right) and 0.68 (left) for the movement criterion of 'Does the hip move into flexion?' for the hip abduction test with medial rotation (Table 4-13).

4.4.2 Intra-rater reliability real-time between days

Potential variation in rating for the HLLMS between sessions is important to assess, as it considers the performance of the participant and not just the ability of the rater, as examined using video analysis. However, at present there are no studies to compare the results from the present study on the variation in between day rating of individual criterion.

One potential cause of the lower intra-rater reliability for between day compared to intra-rater video may be due to the variation in how the participants performed the movement on different days. It could be hypothesised that a learning effect by the participant could have occurred, reducing the reliability due to improved performance on the second testing session. The total number of criteria for all participants for session 1 was 349 compared to 341 for session 2 suggesting that overall there was not a learning effect present. The difference in the reliability for video analysis and real-time rating on different days could have been due to natural variation in the participants' performance. One method of comparing the performance between the two sessions is to analyse the kinematics related to the criteria which will be analysed in the next chapter. Another way to identify if a change in performance occurred would be to compare video footage from session 1 and 2 side by side to see if there was a change. It was not possible to do this in the present study as video footage was not collected for the controls but warrants investigation in future studies.

Comparing the rater agreement in footballers, the overall intra-rater between day agreement (AC1 of 0.63) and inter-rater agreement (AC1 = 0.6) were lower than the intra-rater video agreement (AC1 was 0.80). However, it is not possible to determine if the lower agreement for intra-rater between day and inter-rater reliability was due to rater inconsistencies or variation in the participant's movement. The overall high intra-rater video agreement suggests that assessor consistency can be good when there is no movement variability between observation sessions. The lower between day agreement suggests there may be some variation in the movement patterns or there is a difference between rating live and video footage. Despite the lower rater agreement for between day compared to video, this is not consistent for the individual tests. For example, there were similar mean AC1 scores for the standing hip flexion test of 0.80 and 0.82 for intra-rater between day and using video respectively. In contrast, the mean AC1 intra-rater agreement for the hip abduction with medial rotation test for between day (live) was substantially lower than using video, 0.44 and 0.71 respectively. Further work is needed, with possibly the use of video footage to ascertain if lower intra-rater between day and inter-rater agreement is due to movement variability or assessor inconsistency.

Another factor that could have led to the lower overall reliability for the between day reliability could have been that the rater only had 3 trials to rate up to 6 criteria per movement compared to the video, where the repetitions could be viewed as many times as needed. This could have resulted in the rater for the between day study effectively having to rate more criteria per trial, which Park et al. (2013) suggested would result in lower agreement.

The lower reliability for between days may have been caused by the rater having to rate the participants while also coordinating the kinematic data collection. This multitasking by the rater may have reduced the ability to fully focus on rating. In future, ensuring that the rater only has to focus on scoring the HLLMS may lead to greater intra-rater between day agreement and better reflect day to day use of screening tools.

In conclusion, the overall low mean intra-rater between day agreement suggests that there may be a natural variation in performance of the HLLMS that needs to be taken into account when comparing results pre and post intervention. However, methodological issues may have reduced the agreement between days and further research is needed to better establish the true level of variability between days being due to variation in rating and that due to participant performance.

4.4.3 Inter-rater reliability in academy footballers real-time

The overall mean AC1 for the inter-rater reliability in footballers was 0.6 (range -0.47-1.00) which was lower than intra-rater video overall AC1 0.80 (range 0.36 – 1.00). The lower inter-rater than intra-rater video agreement scores is similar to results reported by Whatman et al. (2012) and Mischiati et al. (2015). The lower inter-rater agreement may be due to two factors compared to the intra-rater video, variation in performance between the three trials and differences in interpretation of the fault criteria by the raters.

There is difficulty in comparing the inter-rater result from the present study to other studies as differences in methodology such as Whatman et al. (2012) using video footage and comparing over 60 raters. Whatman et al. (2015) reported that most research only assessed one movement criterion mostly during a single leg squat type movement. It has been suggested that the greater number of scoring criteria the greater probability of disagreement between raters (Park et al., 2013). The mean inter-rater agreement for knee moving medially reported by Ageberg et al. (2010) of 96% for two raters was higher than 75% on the right and 70% on the left for the present study. Having to carry out a more comprehensive evaluation of movement control may increase the probability of disagreement between the raters, as suggested by Park et al. (2013). In the present study the raters had to assess five criteria during the SKB including trunk, pelvis and knee alignment, compared to only medial knee movement in the study by Ageberg et al. (2010).

In comparing the overall inter-rater scores from the HLLMS in footballers to a similar movement screen, Mischiati et al. (2015) reported a higher inter-rater agreement from videos of 86.5% (67.5-100%) than the present study 76% (25-100%). One possible reason for the higher agreement in the study by Mischaiti et al. (2015) was that the raters reviewed criteria prior to making their ratings to ensure consistency. In a similar study, rating multiple segment movement including the pelvis and trunk, Park et al. (2013) reported a higher overall inter-rater agreement (84%) than the present study. Although Park et al. (2013) only assessed one test, a forward step down, the raters undertook five hours training, discussing definitions and practice scoring which may have led to more consistent interpretation of movement fault criteria between raters. In support of the importance of rater training Whatman et al. (2015) concluded that rater training would increase inter-rater agreement. The raters in present study did not undertake any formal training (as the movement screen is so new) or discussion of the fault criteria which might have increased the level of inter-rater agreement.

There is conflicting research on the effect of rater experience of the inter-rater reliability (Whatman et al. 2015). The raters in the present study has less experience than those in the study by Mischiati et al. (2015) which may have affected agreement. However, for a movement screen to be used widely by many raters the reliability should not be dependent on experience. In support of the lack of effect of rater experience on inter-rater agreement, Ageberg et al. (2010) reported that previous experience was not necessary to achieve high inter-rater agreement, although this may be affected by the complexity of the assessment tool.

4.4.4 Inter-rater reliability in golfers real-time

The overall mean AC1 was 0.68 (range 0.15-0.98) for the five HLLMS tests on male professional golfer's inter-rater agreement (Table 4-33) suggesting an acceptable agreement. Comparison between the inter-rater agreement for the golfers and footballers is hindered by the use of a slightly different criterion in the different versions of the HLLMS used and the golfers were only rated on five tests. Comparting the mean inter-rater agreement from the five tests and only the criteria that remained unchanged in the updated HLLMS, golfers had a similar AC1 of 0.76 (range 0.28-0.98) compared to the footballers AC1 of 0.70 (range 0.21 -1.00) (Table 4-32, Table 4-33). These results suggest the HLLMS has similar overall inter-rater agreement in different cohorts.

The overall mean percentage agreement for all the criteria assessed for the golfers was 81% (range 42-98%) (Table 4-33) which was slightly lower than Mischiati et al. (2015) reported of 87% (range 62-98%). The main aim for involvement of the present investigator in the golfer study was to provide a training opportunity in using the HLLMS and examine reliability early on, which may explain the lower inter-rater agreement in golfers compared to Mischiati et al. (2015). Slight differences in some of the criterion definitions (detailed in the results section) mean an exact comparison between the golfer and footballer inter-rater agreement is not always possible. However, the similar results of the inter-rater agreement for golfers and footballers indicate that the HLLMS could be used with other athletes, not just footballers.

Although the overall mean for inter-rater agreement for the golfers was considered acceptable, some criteria had very low agreement, e.g. the criterion of 'Does the pelvis tilt forwards?' (AC1 values of -0.07 right, -0.15 left) which was due to an error in the author's understanding of the criteria. The misunderstanding of the fault criteria highlights the need for rater training to ensure there is standardisation, possibly using videos and images for clarification purposes. Additionally, highlights the importance of examining results for individual criteria not just a composite score from all the criteria.

Overall the acceptable inter-rater reliability of the HLLMS in male professional golfers and similar results to those in academy footballers suggest that the screen can be used in different athlete populations, although this would need to be explored in various sports. However, some of the criteria had poor reliability which highlights those needing consideration to develop a reliable HLLMS which will be discussed further below (Section 4.4.5).

4.4.5 Revised HLLMS criteria for defining criteria

Having considered the overall rater agreement for the HLLMS in the sections above, this section will consider the reliability of the individual criteria to define criteria and how they have been revised to refine the tool and produce an updated version of the HLLMS Appendix J). Due to limitations of the golfers' study, including differences in the criterion definitions and only assessing five of the seven tests, their results were not included when revising the HLLMS criteria. Similarly, due limitations of the results from the intra-rater between day results, as discussed above, their results were not considered.

4.4.5.1 *Revised Criteria*

Based on the intra-rater video and footballers' inter-rater reliability results from the present study, and in consultation with other researchers using the HLLMS, an updated version has been produced to improve the overall reliability. The latest version of the HLLMS is shown in Appendix J. A flow diagram (Figure 4-3) summarises the number of criteria that had an AC1 score above or below 0.6 from the intra-rater video and inter-rater footballer studies and if they were combined, reworded, deleted or unchanged in the latest HLLMS. Of the 34 criteria (right and left combined) from the HLLMS, 17 of them remained unchanged. The sections below will consider the remaining criteria that were either combined, deleted or reworded.

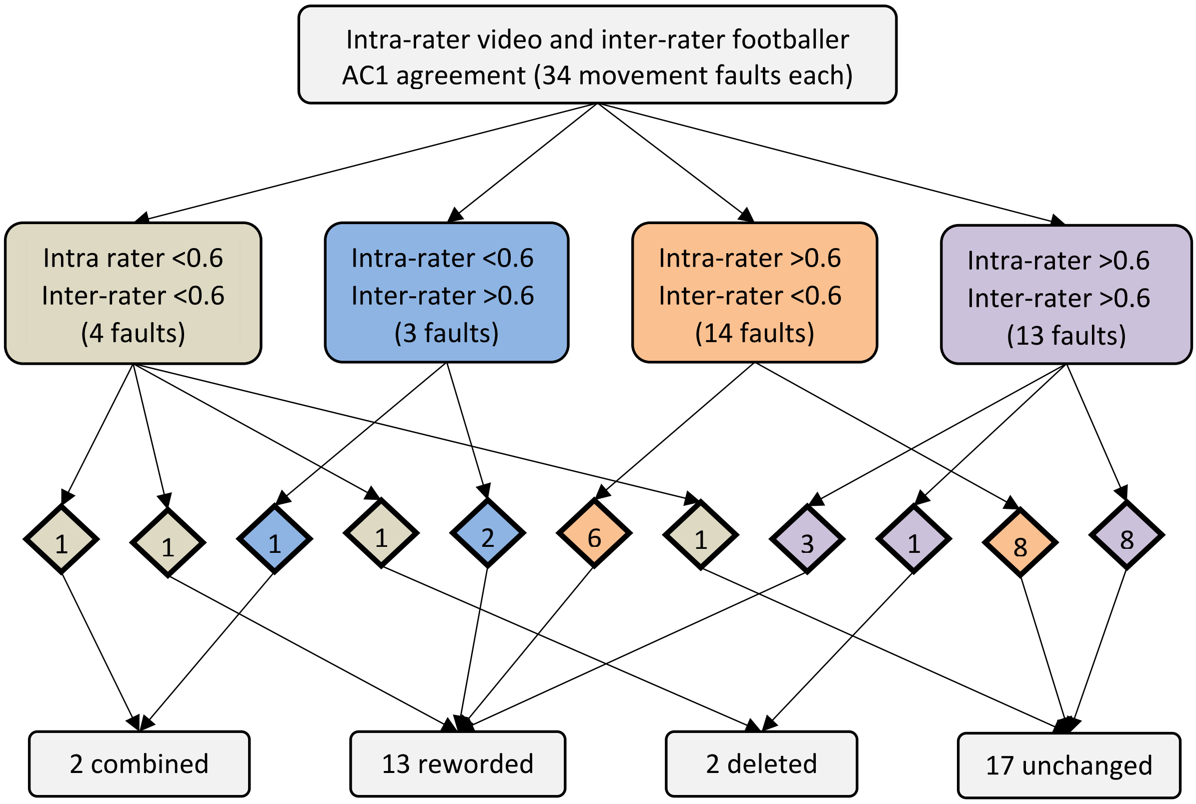


Figure 4-3: Flow chart showing how many criteria were combined, reworded, deleted or unchanged in the updated HLLMS related to if the criteria' AC1 scores were above or below the AC1 cut off of 0.6 from the intra-rater video and inter-rater footballers agreement results.

In the latest version of the HLLMS, axial rotation of the pelvis and pelvic hitch from the sitting hip flexion test were combined, due to the poor reliability (both criteria having intra-rater video AC1 scores below 0.6, Table 4-11). In these criteria, the criterion now reads as: 'Does the pelvis rotate (axial plane) or hitch/hike (frontal plane)?'. Also, poor reliability was reported for these criteria by other researches using the HLLMS. Trying to differentiate between pelvic hitch or axial rotation may be difficult and therefore combining the criteria could lead to greater agreement. Also observing for movement of the pelvis may be difficult compared to the trunk, for example, a small change in movement may be easier to observe in the trunk than pelvis. The rating of movement of the pelvis appears difficult and has led to changes in other pelvic ratings of criteria from the HLLMS, which are considered below.

Two criteria 'Does the trunk side bend'? and 'Do the toes claw or any loss of balance?' from the SKB Rot test have been deleted from the latest version of the HLLMS. The loss of balance criterion had poor reliability (AC1 <0.6) for both intra-rater video and inter-rater results (Table 4-8). The lack of specific criteria for the loss of balance may have reduced the agreement which Mischiati et al. (2015) suggested would make a test less robust. Additionally, loss of balance is not commonly assessed in movement screening (Whatman et al., 2012, Whatman et al., 2013b, Whatman et al., 2015, Mischiati et al., 2015). Therefore, the criterion was removed from the HLLMS.

The criterion of trunk side bend was also removed from the latest version of the HLLMS. The inter-rater agreement AC1 score of 0.68 for the right and 0.60 on the left (Table 4-8) from the present study were low but suggest the criterion has acceptable reliability. Low inter-rater agreement for trunk side bend was also reported by Mischiati et al. (2015) of 75% and 77.5% which was at the lower end of the range for all the criteria (67.5-100%). Despite the acceptable reliability for the criterion from the present study, the trunk side bend was removed from the HLLMS due findings from other researchers using the HLLMS and the results from Mischiati et al. (2015).

Thirteen criteria were re-worded in the updated HLLMS with the majority related to pelvic movement. For criteria that assessed anterior or posterior pelvic tilt, the words 'Does the pelvis begin ….' have been added to the criteria due to discussions with other researchers. It was felt that a participant who started in anterior tilt but did not move anymore, who would be rated as no criterion with the old HLLMS, should be rated as a criterion similar to someone who anteriorly tilted during the test. In particular, the low AC1 scores of 0.36 and 0.10 for the video intra-rater and footballer inter-rater respectively for anterior tilt from the deep squat, support the need to change the movement fault criteria to improve clarity and reliability.

The pelvic movement criteria that rated other directions of movement to anterior or posterior tilt, such as 'Does the pelvis drop?' from the standing hip flexion test, were changed to 'Does the pelvis stay level?'. The change was due to discussions with other researchers using the HLLMS where the inability to keep the pelvis still was considered important to assess and easier to rate consistently, rather than rating for movement in a specific direction such as a hitch. The rater agreement from the present study showed a range for the criteria involving pelvic movement. Low inter-rater AC1 scores for 'Does the pelvis drop?' for the standing hip flexion test of 0.62 and 0.51 on the right and left respectively, may show an increase with the rewording of the criterion.

Criteria related to movements other than the pelvis that were re-worded in the updated HLLMS included the knee moving medially during a SKB, which is commonly rated in movement screening (Mischiati et al., 2015, Whatman et al., 2015, Ageberg et al., 2010, Herrington and Munro, 2014).

The low inter-rater AC1 scores of 0.50 and 0.48 for the right and left respectively from the present study suggest that assessing that criterion may not be reliable. Also, the less than excellent intra-rater agreement for the criterion on the right (0.60) in the present study and those reported by Whatman et al. (2013b) (mean 0.71, range 0.41-0.95) suggest the criterion is not reliable. In discussion with other raters using the HLLMS, the criterion was changed to 'Is there an increase in dynamic valgus from the start position?', as this was thought to be a more accurate description of what the raters were looking for.

The criterion of 'Does the foot fail to align with the ankle, knee and hip?' was changed from rating the moving leg to rating both legs, as the author agreed with researchers using the HLLMS believed that control of both lower limbs was important. Also, some participants could focus and control the rated leg but lose control of the other leg, which sometimes had a more obvious movement criterion. It is anticipated that the low inter-rater AC1 scores of 0.38 and 0.48 on the right and left respectively may be improved with the updated fault criteria.

4.4.5.2 *Justification for poor criteria not revised*

Having considered the criteria that were combined, reworded or deleted for the updated HLLMS, the next section will consider the criteria that had poor rater reliability (AC1 <0.6) but remained unchanged in the screen.

From the SKB test the criterion of trunk leaning forward, only inter-rater agreement on the left had an AC1 score below 0.6 (0.55). A similar pattern for trunk movement criteria was seen for the SKB Rot, Standing and Sitting Hip Flexion tests, where intra-rater agreement was acceptable to excellent and inter-rater agreement was poor to acceptable. Similar reliability was reported for the criterion 'Does the trunk follow the pelvis?' from the SKB Rot test with only inter-rater AC1 agreement on the left being poor (0.31). The overall rater agreement results for trunk movement criteria from the present study suggest that they are reliable. However, some poor inter-rater agreement, such as trunk lean backwards for the sitting hip flexion test AC1 scores of 0.32 and 0.12 on right and left respectively suggest the reliability needs to be improved.

The low inter-rater AC1 of 0.21 for the criterion 'Does the bodyweight shift to one side?' suggests that the criterion reliability needs to be improved. The low inter-rater reliability compared to the high intra-rater video AC1 of 0.9, indicates different interpretation of the criteria between the raters in the present study. For example, are raters considering movement of different body parts, such as pelvis or lower limb to indicate a shift in body weight? Discussion amongst raters using video footage could be carried out to identify and clarify what criteria are to be used for rating fault/not fault.

The last criteria to be considered in relation to poor agreement from the present study but remaining unchanged in the updated HLLMS are the leg loosing medial rotation and hip/knee move into flexion from the Hip Abduction with medial rotation tests. The very low inter-rater AC1 scores for those criteria (range -0.39 – 0.48) suggest the criteria are not reliable. However, the range of inter-rater AC1 scores from the corresponding criteria from the hip abduction with lateral rotation tests (0.76 to 1.00) suggest the criteria can be reliable. As mentioned before, a possible cause of the high inter-rater agreement for the criteria from the hip abduction with lateral rotation is the large number of footballers all rated the same as indicated by no score or 0.00 for positive or negative agreement. The 0.00 score for positive agreement for both left and right for the criterion of the leg losing lateral rotation for the hip abduction with lateral rotation test is due to no participant being rated as having the fault by both raters. This is in contrast to the criteria for the hip abduction with medial rotation test which had positive and negative agreement scores indicating there were some participants that both raters scored as fault and some as no fault. The score of 0.00 for positive or negative agreement highlights criterion that have agreement values such as AC1 based on mainly either fault or no fault ratings and therefore not represent the agreement on both ratings.

The criterion ‘Does the leg lose medial rotation?’ from the hip abduction with medial rotation test had an AC1 score of 0.66 on the right and 0.45 on the left (Table 4-13) but was included in the latest version of the HLLMS because this observation was reliable for the lateral rotation criterion which had an intra-rater video AC1 > 0.95 from the hip abduction with lateral rotation test (Table 4-12). One potential cause of the difference in agreement between the medial and lateral rotation criteria could be due to the lower range of movement for hip medial rotation due to loss of hip medial rotation reported in footballers (Manning and Hudson, 2009). Lower values of hip medial rotation could make it more difficult to judge if the leg loses medial rotation compared to lateral rotation. Other researchers using the HLLMS have not reported low agreement for the hip medial rotation criterion suggesting that clarification of what is a fault would improve the reliability of the author and also improve the low AC1 inter-rater agreement in footballers (-0.08 right, -0.39 left Table 4-31).

4.4.6 Limitations of the present study

One of the limitations of the study is the homogeneity of the fault rating for some of the criteria. For example, the criterion for the 'Does the knee move 2cm past the toes?' had a high AC1 of 0.95 on the right side, however 19/20 footballers rated as no fault (Table 4-7). Therefore, the reliability for rating of the participant having a fault is not known. Having a more even number of footballers who rated fault and no fault may alter the rater agreement. The lack of balance between participants rating as fault and no fault is highlighted with nine of the 39 criteria that had an AC1 above 0.8 having no score for positive or negative agreement. No score for positive or negative agreement was due to all the participants being rated as fault or no fault. The high levels of agreement reported for specific criteria may not truly reflect the ability to rate the movement and should be interpreted with caution. For example, a different athletic population that had more of a balance between fault and no fault rating may lead to different rater agreement. The number of fault and no fault was not reported by Mischiati et al. (2015) so it is not possible to see if their rater agreement results were affected by homogeneity of the fault rating. Reporting the numbers of participants rated fault and no fault may be worthwhile in future studies.

Another limitation that applied to all the rater agreement results, apart from the intra-rater using video, was it was not possible to determine if movement variability or assessor inconsistency led to lower levels of agreement. For example, a difference in rater scoring with inter-rater agreement could have been due to the participant demonstrating the fault for one trial and no fault for another, and the raters assessing different trials, or the raters observing the same trial but rated differently. The rater agreement is therefore determined by how consistent the movement patterns are over three trials, if the raters observed the same trial and how consistent the raters scored the same movement.

4.4.7 Recommendations

Due to the complexity of rating the HLLMS, such as having to rate the movement of multiple body segments and criteria during a repetition, it is recommended that the rater focuses on rating alone and not having to do other tasks at the same time such as managing motion analysis data collection.

There is a need for training of the raters to try and standardise the criteria for what is a fault/no fault. The importance of training of raters has been highlighted by several authors (Park et al., 2013, Ageberg et al., 2010) with the use of photos to show examples of fault/no fault (Herrington and Munro, 2014). Also, raters could be given practice video footage to compare their ratings to an agreed rating. In addition to assessing reliability following training for the raters, there is a need to establish the reliability of the updated HLLMS. More recent studies in the author's research group are now using the updated version (no. 4), so the reliability will be established for these studies.

The use of video footage is essential for assessing intra-rater agreement and the only practical way for large numbers of inter-rater reliability to be assessed, as it is not feasible to enable more than a few raters to score live footage. As highlighted by Mischiati et al. (2015) there can be low agreement between rating from live compared to video footage, possibly due to not having a clear view of the fault with video footage. Therefore, a compromise is needed and where possible video footage is captured by a person who is familiar with the HLLMS and not required to rate the HLLMS at the same time. Furthermore, before the video footage is rated it should be checked with several raters to ensure that all the criteria can be clearly rated.

As highlighted in the limitations sections, some criteria had good reliability, but this was based on all or a majority of the participants all being rated as either fault or no fault. Where possible, an even balance of participants rating as fault or not fault should be used to assess the reliability, which has been done by several authors (Whatman et al., 2012, Ageberg et al., 2010).

The use of video footage to eliminate participant movement variability from rater agreement would allow comparison of pure rater agreements for inter-rater and between day intra-rater. Additionally, blind rating the three trials would allow examination of the movement variability between the trials. With assessing live inter-rater agreement, ensuring the raters observed same trial when rating each fault would allow more accurate assessment of rater consistency.

4.4.8 Future research

To develop a reliable HLLMS that can be used to measure changes is movement patterns it is important to assess the two areas of variability, reliability of the rater and reliability of the performance of the participant with the updated HLLMS.

Further work is required to assess a wider range of raters to ensure that the HLLMS is a generalisable tool to reliably measure movement patterns. To improve the reliability of the rater, development and use of a training manual to try and standardise what is classified a fault or no fault, similar to that used by Herrington and Munro (2014) needs to be undertaken. Such a manual is being developed by the author's research group in the Faculty of Health Sciences at the University of Southampton.

Considering the reliability of movement patterns, it is important that further work is carried out to understand what factors could affect performance of the HLLMS. Human movement is possibly not consistent with factors such as practice, fatigue, time of day affecting performance which need to be assessed. For example, it is not known if a participant performs three repetitions in a row whether they would be rated consistently fault/no fault. To assess consistency of performance a random order of video recordings of three repetitions from a range of participants, including duplicates, could be rated to try and ensure the rater scores each repetition without memory of previous rating. Rating the three repetitions independently should identify if movement criteria are consistent within a session.

4.4.1 Conclusions

The overall mean AC1 for the observational reliability for the HLLMS ranged from 0.8 for intra-rater video to 0.6 for inter-rater in footballers suggesting acceptable to excellent rater agreement. The overall mean inter-rater agreement was similar between golfers and footballers in the five tests that were assessed in the HLLMS and indicates the screen could be used in different athletic populations. The importance of not just looking at the overall reliability of the screen but individual criterion was underlined by the large range in AC1 values of -0.47 to 1.00. The majority of individual criterion had acceptable reliability but low AC1 values for some criterion such as 'Does the pelvis tilt forwards (anteriorly)?' (AC1 = 0.36, intra-rater video from the deep squat). This criterion has been reworded in the updated HLLMS to 'Does the pelvis begin in, or move forwards (anteriorly)?' and the rater agreement needs to be reassessed. High reliability for some of the criteria may have been due to a lack of balance of between fault and no fault rating. For example, of the 39 criteria with an AC1 above 0.8, nine had participants being rated as all fault or all no fault. Some of the criteria had poor reliability which needs to be improved to develop a reliable HLLMS. Due to some low between day reliability, possibly related to methodological issues, more testing is needed to identify if there is true variation in participant movement patterns between sessions.

Chapter 5: Reliability of the HLLMS: Kinematics

5.1 Introduction

The reliability of the observational rating from the HLLMS was determined in the previous chapter (Chapter 4:). This chapter examines the kinematic reliability of the observational rating from the HLLMS.

Assessing kinematic reliability is important to try and ascertain if there is consistency in movement patterns. For any measurement tool such as the HLLMS it is important to know how much variation there is in the movement patterns. For example, low kinematic reliability between trials could suggest a high level of variation in movement patterns and potentially variation in observational rating between the trials. Establishing the natural variability in movements during the various movements will help determine if the observed difference, following an intervention for example, are true responses (i.e. beyond the natural variation in movement).

The literature on reliability of the kinematics related to movement screening was detailed in Chapter 2, section 2.3 with a lack research. The kinematic reliability during the SKB has most commonly been studied with high ICC values for within day peak trunk, pelvis, hip and knee (range 0.82 – 0.99) values reported (Whatman et al., 2011). In agreement Alenezi et al. (2014) reported high within day ICC of 0.92 for knee valgus during a SKB task.

In regard to between day kinematic reliability, Whatman et al. (2011) reported slightly lower range of ICC values of 0.79 to 1.0 for trunk, pelvis, hip, knee and ankle peak kinematics. Similarly Alenezi et al. (2014) reported lower between day ICC value of 0.48 for knee valgus.

In addition to using ICC to assess kinematic reliability, there is a need to measure agreement. According to Bland and Altman (1986) high correlation does not necessarily mean high agreement. For the kinematics related to the criteria from the HLLMS a measure of within trial and between day correlation and agreement would be useful to assess the reliability of the kinematics.

Assessing the reliability of the kinematics from the HLLMS based on peak kinematic values only gives a limited analysis as it only uses one value to represent the movement pattern. Analysing the whole waveform from start to end of the movement would allow a more thorough analysis of the kinematics. One method used to analyse the similarity of waveforms is the Coefficient of Multiple Correlation (CMC) originally used in gait (Kadaba et al., 1989). Although CMC assesses similarity in the kinematic waveforms it does not quantify the absolute difference. To calculate the absolute difference between the trials for the entire kinematic waveform the waveform measurement error has been used gait (Schwartz et al., 2004). Waveform similarity analysis using CMC has been used with some movement screening tasks such as the drop jump (Ford et al., 2007), but this movement is substantially different to those assessed by the HLLMS. There is a need to examine kinematic waveforms using CMC and waveform measurement error with movements from the HLLMS.

Regarding the kinematics, stability of the movement patterns both within day and between day need to be established (Alenezi et al., 2014). With the lack of research on movements that are performed in the HLLMS and use of a functional approach to collect 3D motion analysis data there is a need to assess the kinematic reliability of the HLLMS.

5.1.1 Aims

To investigate the reliability of the kinematics measured using a skin based marker system (3D motion analysis) related to the movement criterion from the SKB, SKB Rot, standing hip flexion and deep squat from the HLLMS.

Objectives

The objectives were to quantify the reliability of lower limb kinematics from the HLLMS in relation to:

- intra trial (within session) variability measured in a single testing session.
- between day (between session) variability

5.2 Methodology

An outline of what kinematic reliability was evaluated and which studies the data were collected from is shown in Figure 4-1 in Chapter 4.

5.2.1 Ethics

Two separate studies were carried out to gather the data for kinematic reliability. Ethical approval was granted for male academy footballers and male students (controls) (23370 and 27322) by the Faculty of Health Sciences, University of Southampton Ethics Committee.

5.2.2 Participant recruitment

For the within session, data were collected on 21 footballers and 14 controls. Between day kinematic reliability was calculated on 11 controls as due to time commitments of the participants three of the 14 were not able to be retested within a week. Details of participant recruitment and consent are outlined in section 3.2.2 of Chapter 3.

5.2.3 Data collection

The standardised protocol for carrying out the HLLMS is outlined in section 3.3 of Chapter 3. Between day participants (controls) were studied on two occasions separated by at least two days as used by Leigh et al. (2014) and within one week. The gap of at least two days was used to ensure any marks remaining from the removal of the reflective markers would have disappeared. On the second testing session the rater placed the markers with no reference to the previous trial, which McGinley et al. (2009) suggested was needed to get a more accurate measure of reliability. All setup and data collection were carried out by the current author.

5.2.4 Data Analysis

The Intraclass Correlation Coefficient (ICC) (3,3) was used to calculate within day reliability and ICC (3,1) for between day values outlined from the HLLMS. The ICC of two-way mixed effects model with average measures (3,3) was chosen to assess within day agreement. This model was chosen as the rater who performed the measurements (i.e. DW) is the only one of interest and has not been selected randomly and the three trials cannot be considered independent. An average measure approach was chosen as the average of three trials is used in the following chapters when assessing kinematic differences in the HLLMS between controls and footballers. For the between day reliability a two-way mixed effects model with single measures ICC (3,1) as, again, the rater who performed the measurements (i.e. DW) is the only one of interest and has not been selected randomly and the two sessions cannot be considered independent. A single measures approach was adopted as the results from a single session are used to determine kinematic differences in the HLLMS between controls and footballers. According to Fleiss (1986) ICC values below 0.4 are classified as poor, 0.4-0.75 fair, and > 0.75 excellent agreement.

No one test alone provides sufficient information on reliability, therefore, several analyses should be used (Bland and Altman, 1986). Bland and Altman plots (Bland and Altman 1986) were used to compare agreement in HLLMS kinematics related to the criteria with a mean reported of the difference between trial 1 and 2, 2 and 3, 1 and 3 for the within day correlation. The mean of the kinematics for the three trials was used for the between day comparison. Mean, lower and upper limits of agreement were reported for each criterion.

Reporting the reliability in the units measured was suggested by McGinley et al. (2009) to obtain a more clinically relevant analysis of reliability. Reliability in units used for measurement were calculated using the Standard Error of Measurement (SEM) (Wilken et al., 2012) defined as;

$$\mathrm{SEM} = \mathrm{SD}\sqrt{1 - ICC} \qquad \text{Equation 1}$$

The minimal detectable change (MDC) is the amount of change in a score that needs to occur to state the change in score exceeds errors in measurement (Davidson and Keating, 2014). The MDC was calculated as outlined in (Haley and Fragala-Pinkham, 2006), as defined;

$$\mathrm{MDC} = 1.96 * \mathrm{SEM} * (\sqrt{2}\ ) \qquad \text{Equation 2}$$

The Coefficient of Multiple Correlation (CMC) (Kadaba et al., 1989) and waveform measurement error (Schwartz et al., 2004) were used to assess the within session trial and between day reliability of the kinematic waveform. The CMC and waveform measurement error were calculated on the joint kinematics related to the criteria from the HLLMS over the normalised 1001 data points from the start to end of the movements as detailed in section 3.5.2.

The assessment of within session reliability using CMC is defined as the absolute square root of the coefficient of multiple determination (R_a^2) (Equation 3).

$$R_a^2 = 1 - \frac{\sum_{i=1}^{M}\sum_{j=1}^{N}\sum_{t=1}^{T}(Y_{ijt} - \overline{Y_{ij}})^2 \,/\, MT(N-1)}{\sum_{i=1}^{M}\sum_{j=1}^{N}\sum_{t=1}^{T}(Y_{ijt} - \overline{Y_i}\,)^2 \,/\, M(NT-1)} \qquad \text{Equation 3}$$

For within session Y_{ijt} is a single sample at the *t*th time point, of the *j*th repetition in the *i*th session, $\bar{Y}it$ represents the mean at each *t*th time point the *ith* session. $\overline{Y_i}$ represents the total mean of every data point for the *i*th session. For both within and between session, M, N and T denotes number of sessions, number of repeated trials and number of data points respectively.

To calculate the CMC for evaluating the similarity or repeatability of waveforms between test days the absolute square root of the coefficient of multiple determination (R_a^2) (Equation 4).

$$R_a^2 = 1 - \frac{\sum_{i=1}^{M}\sum_{j=1}^{N}\sum_{t=1}^{T}(Y_{ijt} - \bar{Y}_\iota)^2 \,/\, T(MN-1)}{\sum_{i=1}^{M}\sum_{j=1}^{N}\sum_{t=1}^{T}(Y_{ijt} - \bar{Y})^2 \,/\, (MNT-1)} \qquad \text{Equation 4}$$

where *Yi*, is the average at time point *t* over *NM* cycles (Equation 5)

$$\bar{Y}_\iota = \frac{1}{MN}\sum_{i-1}^{M}\sum_{j=1}^{N} Y_{ijt} \qquad \text{Equation 5}$$

and $\bar{Y}$ is the grand mean over time and is outlined by Equation 6. Similar to ICC, values below 0.4 were poor agreement, 0.4-0.75 fair, and > 0.75 excellent (Fleiss, 1986) as limits for agreement for CMC were not defined by Kadaba et al. (1989).

$$\bar{Y} = \frac{1}{MNT}\sum_{i-1}^{M}\sum_{j=1}^{N}\sum_{t=1}^{T} Y_{ijt} \qquad \text{Equation 6}$$

Additional to CMC, Waveform measurement error (σ) was calculated, which provides an equivalent to the SEM over the entire kinematic waveform. To calculate σ values, firstly the mean of the data over each *t*th data point was calculated for each variable (v) for the three repetitions (Equation 7).

$$\bar{v}_i = \frac{1}{N}\sum_{j=1}^{N} Yij \qquad \text{Equation 7}$$

The sum of the difference between the mean at each data point and the overall mean for the session was calculated (Equation 8).

$$\Delta Vijt = Vijt - \bar{v}_i \qquad \text{Equation 8}$$

The mean over each *t*th data point was also calculated over both sessions (Equation 9).

$$\bar{v} = \frac{1}{NM}\sum_{i=1}^{M}\sum_{j=1}^{N} Yij \qquad \text{Equation 9}$$

The difference between the mean and each data point was then calculated for each participant (Equation 10).

$$\Delta Vijt = Vijt - \bar{v} \qquad \text{Equation 10}$$

The final estimated error of the waveform measurement error (σ) is mean standard deviation for each *t*th time point.

5.3 Results

Kinematic reliability for the tests from the HLLMS for right and left side and also session one and two in controls (Appendix L) were similar therefore data in the results section were only shown for the right side and session one of the controls.

The within day ICC related to the kinematics from the SKB, SKB Rot, standing hip flexion and deep squat tests in controls and footballers ranged from poor (0.27) to excellent (0.97). Between day ICC values were slightly lower ranging from poor (0.07) to excellent (0.91). Similarity in kinematic waveforms measured with CMC for the SKB, SKB Rot, standing hip flexion and deep squat values ranged from fair (0.48) to excellent (0.96). Between day CMC values ranged from fair (0.62) to excellent (0.97).

5.3.1 Within session reliability

5.3.1.1 *SKB test*

The within day ICC related to the kinematics from the SKB ranged from poor (0.27, pelvic hitch, controls, Table 5-1) to excellent (0.97, anterior tilt of the pelvis, controls, Table 5-1). The low within session for the kinematic reliability for pelvic hitch in controls in session 1 (ICC 0.27) session 2 for controls had a higher ICC of 0.63 (Appendix L). Additionally, ICC values for the left side ranged from 0.81 to 0.90 in controls and footballers (APPENDIX). The ICC of 0.27 for the pelvic hitch identified above and the medial knee excursion at peak knee flexion in footballers (0.63) were the only criteria below the excellent (>0.75). The criteria of pelvic hitch and medial knee excursion highlighted above with low ICC values also had proportionally large SEM values related to the mean -2.0° (SEM 1.72), and 12.3mm (SEM 9.83) respectively (Table 5-1). However, the ICC of 0.27 for the pelvic hitch identified above and the medial knee excursion in footballers (0.63) were the only criteria below the excellent (>0.75). The range of ICC was similar between controls session 1 (0.27-0.97), and footballers (0.63-0.97) (Table 5-1). The mean difference between trials was <2.50°.

The range of mean difference between the trials of -2.5mm (peak medial knee displacement, controls) to 0.87° (peak knee valgus, footballers) suggest good agreement. However, there were large limits of agreement for the medial knee movement both peak excursion and at peak knee flexion ranging from -23.82-21.76mm (peak medial knee displacement, footballers) to 36.27-32.35mm (medial knee excursion at peak knee flexion, footballers).

In considering the overall waveform CMC ranged from poor (0.52, medial knee movement in footballers) to excellent (0.93, knee flexion, controls). The highest waveform measurement error was for medial knee displacement in footballers (9.49mm) and lowest was for pelvic hitch (1.45°) (Table 5-1). Mean medial knee displacement for footballers and controls from session one showed similar waveforms patterns (Figure 5-1).

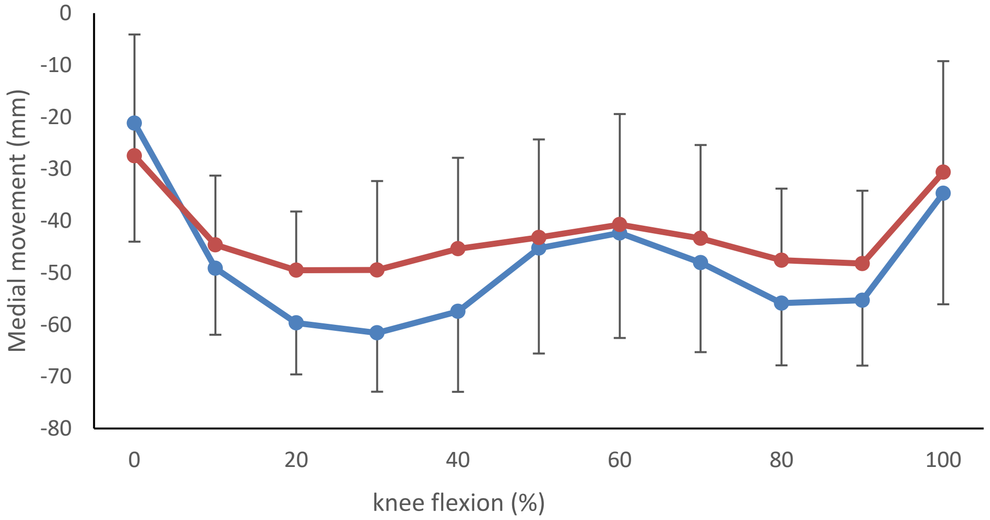


Figure 5-1: Mean medial knee displacement kinematics on right side during the SKB for footballers (red) and controls session 1 (blue). Error bars (single sided) represent 1 SD.

Table 5-1: Within session ICC, mean, (SEM), mean difference ($\bar{d}$), limits of agreement (LOA), CMC (SD) and waveform measurement error (WE) for the kinematics related to the criteria from the SKB test on the right side in footballers (Foot) (n=21) and controls session 1 (n=14). Criteria highlighted in grey remain unchanged in the updated HLLMS.

	Does the knee move inward from the 2nd toe? ***Is there an increase in dynamic valgus from the start position?***						**Does the pelvis hitch/drop?** ***Does the pelvis fail to stay level?***		**Does the knee fail to move 2cm past the toes?**		**Does the trunk lean forwards?**		**Does the pelvis tilt forwards?** ***Does the pelvis begin in, or tilt forwards (anterior)?***	
	Peak medial knee displacement (mm)		**Medial knee excursion at peak knee flexion (mm)**		**Peak knee valgus excursion (°)**		**Peak pelvic lateral rotation excursion anti clockwise (right) clockwise (left) (°)**		**Knee flexion peak excursion (°)**		**Trunk flexion peak excursion (°)**		**Pelvic anterior rotation peak excursion (°)**	
	Control	Foot	Control	Foot	Control	Foot	Control	Foot	Control	Foot	Control	Foot	Control	Foot
ICC	0.81	0.75	0.77	0.63	0.96	0.96	0.27	0.91	0.97	0.95	0.93	0.87	0.89	0.97
Mean (SEM)	25.6 (6.19)	20.3 (5.79)	18.5 (8.51)	12.3 (9.83)	-6.8 (1.10)	-12.2 (2.60)	-2.0 (1.72)	-3.5 (0.84)	57.2 (2.04)	56.3 (2.70)	9.5 (1.69)	8.6 (1.97)	12.0 (2.08)	13.2 (1.35)
$\bar{d}$ **(LOA)**	-2.50 (-28.30-23.30)	-1.03 (-23.82-21.76)	-1.96 (-36.27-32.35)	0.66 (-34.99-36.32)	0.38 (-4.71-5.48)	0.87 (-11.34-13.08)	-0.09 (-5.45-5.28)	0.29 (-3.50-4.08)	-1.08 (-10.63-8.48)	-0.39 (-12.59-11.81)	-1.06 (-8.56-6.45)	-1.03 (-23.82-21.76)	-1.46 (-10.35-7.43)	0.66 (-34.99-36.32)
CMC (SD)	0.62 (0.16)	0.52 (0.24)	N/A	N/A	0.64 (0.17)	0.63 (0.24)	0.61 (0.14)	0.61 (0.20)	0.93 (0.07)	0.81 (0.18)	0.66 (0.17)	0.66 (0.22)	0.75 (0.23)	0.72 (0.20)
WME (SD)	8.88 (2.82)	9.49 (7.36)	N/A	N/A	1.66 (0.88)	2.78 (3.49)	1.45 (0.72)	1.49 (0.71)	5.78 (2.95)	8.62 (4.97)	2.22 (1.64)	2.76 (1.45)	2.02 (1.12)	3.11 (3.01)

5.3.1.2 *SKB Rot test*

The reliability of the kinematics for 'Does the trunk rotate less than 30 degrees?' was not analysed as it is was considered more of a benchmark than a criterion. Additionally, the trunk rotation was not to a set amount, so a participant could rotate 30 degrees on trial one and 45 degrees on trial two which would show low reliability but would not be rated as a fault. In discussion with supervisors and other researchers using the HLLMS it was agreed that examining the reliability of the kinematics of the trunk rotating less than 30 degrees was not warranted.

The ICC for the kinematics from the SKB Rot test were excellent (>0.75) apart from trunk side flexion in control (0.63) and footballers (0.56) (Table 5-2). The trunk side bend criterion was removed from the updated HLLMS due to poor observational reliability and its results were not considered in the results section. Regarding the waveform analysis CMC values ranged from fair (0.48, trunk flexion, controls) to excellent (0.75, pelvic rotation, controls) (Table 5-2). Highest of waveform measurement errors were 5.79° and 6.46° for pelvic hitch in controls and footballers respectively.

Table 5-2: Within session ICC, mean, (SEM), mean difference ($\bar{d}$), limits of agreement (LOA), CMC (SD) and waveform measurement error (WME) for the kinematics related to the criteria from the SKB Rot test on the right side in footballers (Foot) (n=21) and controls session 1 (n=14). Criteria highlighted in grey remain unchanged in the updated HLLMS.

	Does the pelvis follow the trunk?		**Does the trunk side-bend? ***		**Does the pelvis hitch/drop?** ***Does the pelvis fail to stay level?***		**Does the trunk lean forwards?**	
	Percentage trunk and pelvis in phase (%)		**Peak side flexion excursion right plus left (°)**		**Peak pelvic lateral rotation excursion anti clockwise (right) clockwise (left) (°)**		**Trunk flexion peak excursion (°)**	
	Control	Foot	Control	Foot	Control	Foot	Control	Foot
ICC	0.93	0.92	0.63	0.56	0.92	0.92	0.90	0.95
Mean (SEM)	66.8 (5.22)	53.3 (4.72)	9.9 (2.82)	10.4 (4.58)	-5.2 (1.43)	-7.4 (1.40)	11.3 (1.66)	9.6 (1.65)
$\bar{d}$ (LOA)	-2.50 (-28.30-23.30)	-1.03 (-23.82-21.76)	-1.96 (-36.27-32.35)	0.66 (-34.99-36.32)	0.38 (-4.71-5.48)	0.87 (-11.34-13.08)	-0.09 (-5.45-5.28)	0.29 (-3.50-4.08)
CMC (SD)	N/A	N/A	0.78 (0.16)	0.65 (0.19)	0.75 (0.19)	0.70 (0.35)	0.48 (0.20)	0.72 (0.35)
Trunk Rot	0.63 (0.20)	0.72 (0.13)	N/A	N/A	N/A	N/A	N/A	N/A
Pelvic Rot	0.72 (0.19)	0.73 (0.34)	N/A	N/A	N/A	N/A	N/A	N/A
WME (SD)	N/A	N/A	3.84 (1.14)	3.78 (1.83)	5.79 (2.48)	6.46 (3.10)	1.88 (0.67)	2.14 (0.92)
Trunk Rot	1.81 (0.59)	1.81 (0.71)	N/A	N/A	N/A	N/A	N/A	N/A
Pelvic Rot	1.99 (0.84)	1.93 (1.11)	N/A	N/A	N/A	N/A	N/A	N/A

*****criterion removed from the updated HLLMS

5.3.1.3 *Standing hip flexion test*

The ICC for within session kinematic reliability for the standing hip flexion test ranged from fair (0.46, peak hip flexion, controls) to excellent (0.95, peak pelvic posterior tilt, controls) (Table 5-3). Of the criteria that remain unchanged in the updated HLLMS only peak hip flexion in controls had an ICC < 0.77. Waveform reliability measured using CMC ranged from fair (0.51, trunk extension, footballers) to excellent (0.95, trunk extension, controls) (Table 5-3). Ranges of waveform measurement error were <2.39°, apart from femur flexion 8.68° (controls) 9.81° (footballers) although this was for a large movement (mean hip flexion >106°) (Table 5-3).

Table 5-3: Within session ICC, mean, (SEM), mean difference ($\bar{d}$), limits of agreement (LOA), CMC (SD) and waveform measurement error (WME) (SD) for the kinematics related to the criteria from the standing hip flexion test on the right side in footballers (Foot) (n=21) and controls session 1 (n=14). Criteria highlighted in grey remain unchanged in the updated HLLMS.

	Does the pelvis drop (hitch)? ***Does the pelvis fail to stay level?*** **Peak pelvic lateral rotation excursion anti clockwise (left) clockwise (right) (°)**		**Does the pelvis tilt backwards (posteriorly)?** ***Does the pelvis begin in, or move backwards (posteriorly)?*** **Peak pelvic posterior tilt excursion (°)**		**Does the hip fail to bend (flex) just beyond 90 degrees (approximate 110 degrees)?** **Peak hip flexion excursion (°)**		**Does the trunk lean backwards (extend)?** **Trunk extension peak excursion (°)**		**Does the weight bearing knee bend (flex)?** **Peak knee flexion excursion (°)**	
	Control	Foot	Control	Foot	Control	Foot	Control	Foot	Control	Foot
ICC	0.91	0.89	0.95	0.92	0.46	0.77	0.89	0.81	0.93	0.84
Mean (SEM)	9.7 (0.94)	10.2 (0.92)	-13.1 (0.91)	-15.6 (1.45)	110.1 (4.76)	106.1 (4.05)	-3.7 (0.89)	-4.4 (1.29)	6.9 (1.56)	7.9 (2.44)
$\bar{d}$ (LOA)	0.03 (-4.21-4.27)	0.61 (-3.49-4.72)	-0.53 (-5.99-4.93)	-0.54 (-7.13-6.05)	2.24 (-13.14-17.61)	0.99 (-15.40-17.38)	-0.53 (-4.33-3.26)	-0.39 (-5.76-4.98)	0.99 (-5.47-7.45)	-0.12 (-10.56-10.32)
CMC (SD)	0.83 (0.18)	0.85 (0.16)	0.90 (0.06)	0.84 (0.18)	0.95 (0.05)	0.93 (0.09)	0.64 (0.18)	0.51 (0.23)	0.65 (0.17)	0.56 (0.26)
WME (SD)	1.33 (0.57)	1.26 (0.47)	1.85 (0.73)	2.22 (1.00)	8.68 (3.82)	9.81 (3.73)	1.60 (0.88)	1.78 (1.00)	2.01 (0.92)	2.39 (1.24)

5.3.1.4 *Deep squat test*

The ICC for the kinematics related to the criteria from the deep squat test were excellent apart from anterior pelvic tilt in footballers (0.61) with all the remaining criteria ICC >0.83 (Table 5-4). Similarly, the CMC for the kinematic waveforms were excellent, ranging from 0.87 (anterior pelvic tilt in controls) to 0.96 (femur flexion in footballers) (Table 5-4). Highest waveform measurement error occurred with femur flexion excursion 5.89° (controls) 4.97° (footballers) however this was small compared to the mean peak excursion for femur flexion of 76.0°.

Table 5-4: Within session ICC, mean, (SEM), mean difference ($\bar{d}$), limits of agreement (LOA), CMC (SD) and waveform measurement error (WME) (SD) for the kinematics related to the criteria from the deep squat test in footballers (Foot) (n=21) and controls session 1 (n=14). Criteria highlighted in grey remain unchanged in the updated HLLMS.

	Does the thigh (femur) fail to be horizontal with the floor? **Peak excursion of femur flexion (°)**		**Does the trunk fail to stay parallel with the shin (tibia)?** **Difference between tibia and trunk at peak femur flexion (°)**		**Does the pelvis tilt forwards (anteriorly)?** ***Does the pelvis begin in, or move forwards (anteriorly)?*** **Peak pelvis flexion excursion (°)**	
	Control	Foot	Control	Foot	Control	Foot
ICC	0.83	0.9	0.91	0.90	0.92	0.61
Mean (SEM)	76.0 (5.57)	76.0 (3.04)	9.2 (1.76)	9.5 (1.83)	23.3 (2.93)	22.9 (6.56)
$\bar{d}$ **(LOA)**	-2.56 (-24.40-19.28)	-1.50 (-11.22-8.23)	-0.77 (-8.66-7.13)	-0.29 (-10.64-10.07)	-0.33 (-12.97-12.31)	0.12 (-9.79-10.04)
CMC (SD)	0.92 (0.21)	0.96 (0.04)	N/A	N/A	0.87 (0.16)	0.91 (0.09)
Trunk	N/A	N/A	0.90 (0.15)	0.89 (0.19)	N/A	N/A
Tibia	N/A	N/A	0.91 (0.21)	0.93 (0.06)	N/A	N/A
WME (SD)	5.89 (5.39)	4.97 (2.63)			2.57 (1.22)	2.74 (0.99)
Trunk	N/A	N/A	3.54 (1.75)	3.76 (2.45)	N/A	N/A
Tibia	N/A	N/A	2.35 (2.37)	2.11 (0.63)	N/A	N/A

5.3.2 Between day reliability

Bland and Altman plots for between day kinematics related to the movement criteria from the SKB, SKB Rot, standing hip flexion and deep squat tests are contained in Appendix M.

5.3.2.1 *SKB*

The between day ICC scores for the kinematics for the criteria from the SKB test ranged from poor (0.07, pelvic hitch) to excellent (0.91, knee 2cm past toes) (Table 5-5). The very low ICC of 0.07 for pelvic hitching corresponded with a low mean and high SEM (-1.8°, 1.24) (Table 5-5). CMC vales ranged from fair (0.52, medial knee displacement) to excellent (0.81, knee flexion) (Table 5-5). Mean medial knee displacement kinematics during knee flexion on the right for session one and two had similar waveforms (Figure 5-2).

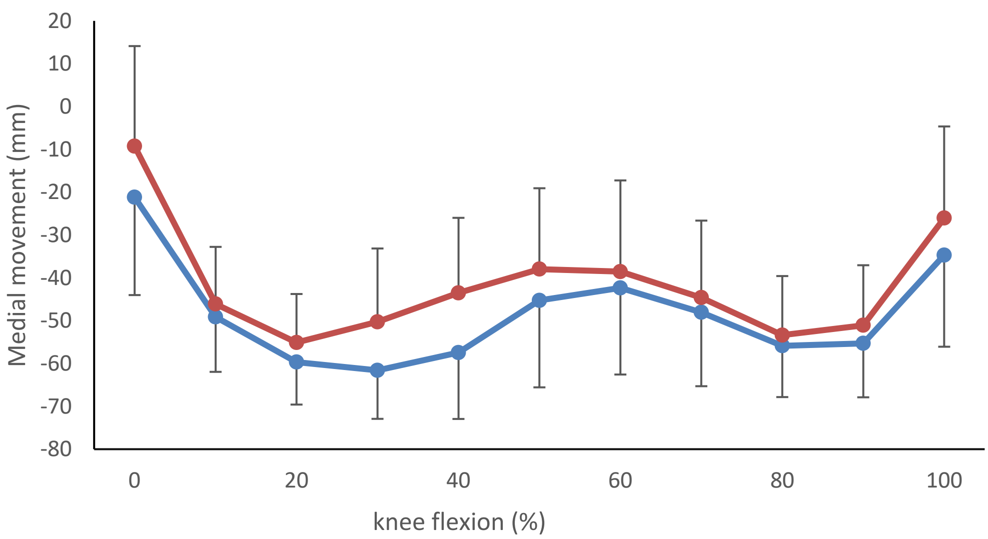


Figure 5-2: Mean for medial knee displacement kinematics on right side during the SKB for controls session 2 (red) and controls session 1 (blue). Error bars (single sided) represent 1 SD.

Table 5-5: Between day ICC, mean, (SEM), minimal detectable change (MDC), mean difference ($\bar{d}$), limits of agreement (LOA), CMC (SD) and waveform measurement error (WME) (SD) for the kinematics related to the criteria from the SKB test in controls (n=11). Criteria highlighted in grey remain unchanged in the updated HLLMS

Movement criteria	**Kinematic variable**				**Bland and Altman**			
		ICC	**Mean (SEM)**	**MDC**	$\bar{d}$	**LOA**	**CMC (SD)**	**WME (SD)**
Does the knee move inward from the 2nd toe? *Is there an increase in dynamic valgus from the start?*	Peak medial knee displacement (mm)	0.64	26.1 (15.09)	10.8	-0.93	(-20.78-18.92)	0.52 (0.24)	9.49 (7.36)
	Medial knee excursion at peak knee flexion (mm)	0.67	18.9 (8.29)	7.98	-0.76	(-24.92-23.41)	N/A	N/A
	Peak knee valgus excursion (°)	0.60	-6.8 (2.67)	4.53	-0.01	(-7.78-7.76)	0.63 (0.24)	2.78 (3.49)
Does the pelvis hitch/drop? *Does the pelvis fail to stay level?*	Peak pelvic lateral rotation excursion anti clockwise (right) clockwise (left) (°)	0.07	-1.8 (1.24)	3.08	-0.38	(-3.88-3.13)	0.61 (0.20)	1.49 (0.71)
Does the knee fail to move 2cm past the toes?	Knee flexion peak excursion (°)	0.91	58.3 (3.10)	4.88	-1.91	(-10.08-6.26)	0.81 (0.18)	8.62 (4.97)
Does the trunk lean forwards?	Trunk flexion peak excursion (°)	0.83	10.0 (2.73)	4.58	-0.94	(-8.74-6.86)	0.66 (0.22)	2.76 (1.45)
Does the pelvis tilt forwards? *Does the pelvis begin in, or tilt forwards (anterior)?*	Pelvic anterior rotation peak excursion (°)	0.67	12.8 (3.50)	5.19	-1.37	(-11.29-8.54)	0.72 (0.20)	3.11 (3.01)

The pelvic lateral rotation had low values of movement and similar waveform patterns for mean kinematics for controls in session one and two (Figure 5-3).

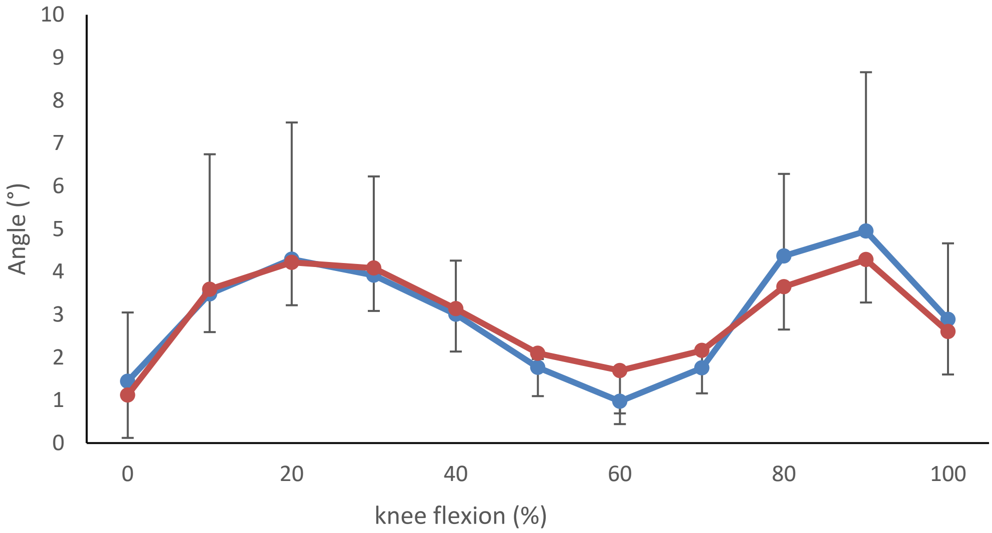


Figure 5-3: Mean for pelvic lateral rotation on right side during the SKB for controls session 1 (blue) and controls session 2 (red). Error bars (single sided) represent 1 SD.

The low mean ICC value of 0.64 and CMC of 0.52 (Table 5-5) for between session reliability for the medial knee displacement kinematics suggest the movement was not consistent. A plot of the six trial's (three session 1 and three session 2) medial knee displacement kinematics for a single participant highlight the variation with in trial and between session (Figure 5-4).

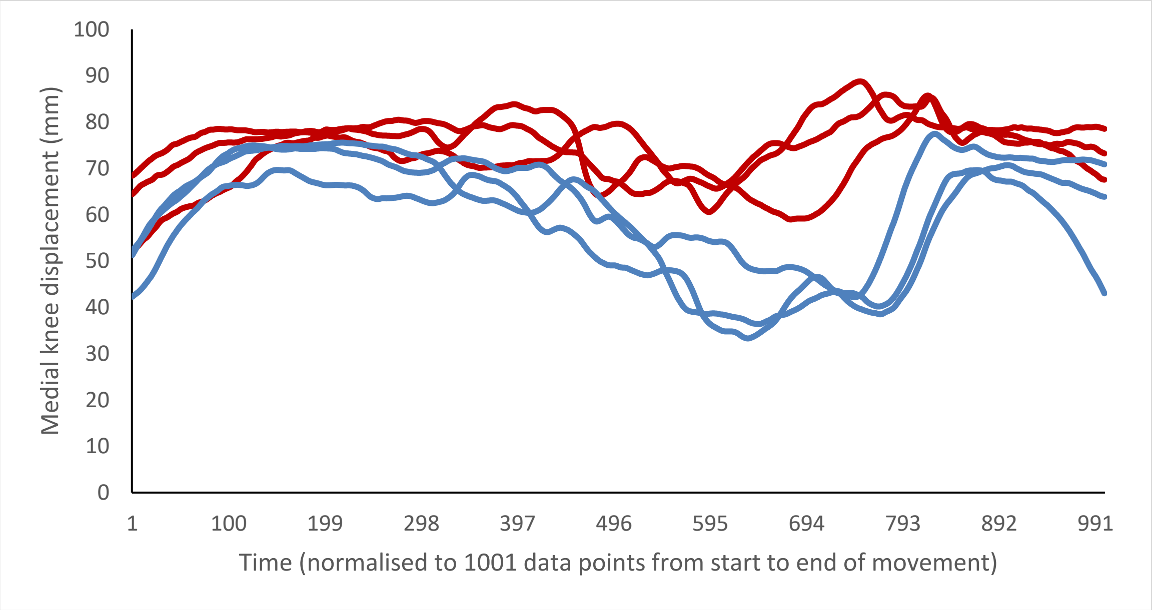


Figure 5-4: Plot of medial knee displacement kinematics on right side during the SKB for participant 11 from controls (CMC = 0.51). Three trials from session 1 (red) and session 2 (blue).

In contrast to the low mean reliability between session for medial knee displacement, trunk flexion kinematic reliability was higher with an ICC for peak values of 0.83 and CMC of 0.66 (Table 5-5). Figure 5-5 shows similar waveforms for the six trials of a participant’s trunk flexion kinematics from the SKB test.

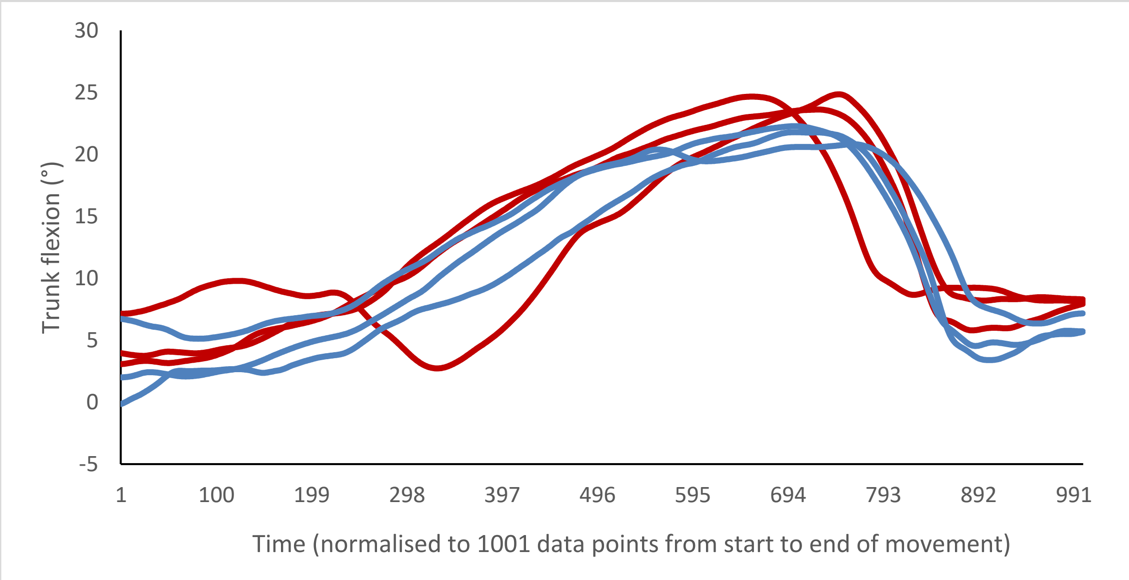


Figure 5-5: Plot of trunk flexion kinematics on right side during the SKB for participant 11 from controls (CMC = 0.94). Three trials from session 1 (red) and session 2 (blue).

The waveform kinematics for mean trunk flexion during the SKB showed similar waveforms for controls in session one and two, with a bell-shaped curve and peak flexion occurring around the midpoint of knee flexion (Figure 5-6).

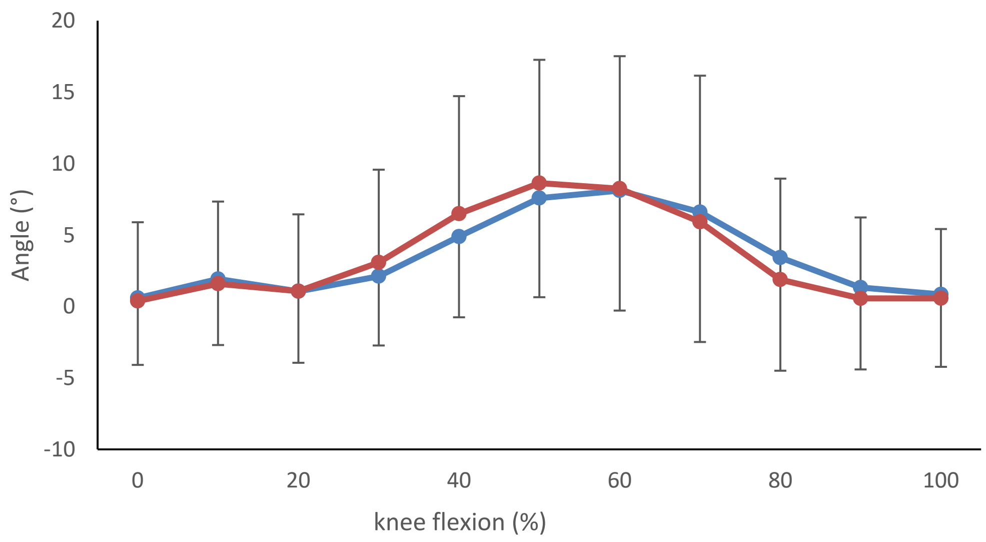


Figure 5-6: Mean for trunk flexion on right side during the SKB for controls session 1 (blue) and controls session 2 (red). Error bars (single sided) represent 1 SD.

5.3.2.2 *SKB Rot*

The trunk side bend criterion was removed from the updated HLLMS and therefore its results were not considered in the results section. The ICC for the criteria from the SKB Rot test range from just below excellent (0.73, pelvis follow trunk) to excellent (0.81, trunk flexion). Similar values for waveform reliability with CMC ranging from fair (0.67, pelvic hitch) to excellent (0.85, trunk rotation) (Table 5-6). Waveform measurement error was low at <2.65° and 4.34 to 6.46% for trunk and pelvic rotation in phase (Table 5-6).

Table 5-6: Between day ICC, mean, (SEM), minimal detectable change (MDC), mean difference ($\bar{d}$), limits of agreement (LOA), CMC (SD) and waveform measurement error (WME) (SD) for the kinematics related to the criteria from the SKB Rot test in controls (n=11). Criteria highlighted in grey remain unchanged in the updated HLLMS

					Bland and Altman			
Movement criteria	**Kinematic variable**	**ICC**	**Mean (SEM)**	**MDC**	$\bar{d}$	**LOA**	**CMC (SD)**	**WME (SD)**
Does the pelvis follow the trunk?	Percentage trunk and pelvis in phase (%)	0.73	63.9 (9.43)	8.5	6.98	(-19.22-33.18)	0.85 (0.10)a 0.79 (0.15)b	6.46 (1.62)a 4.34 (1.44)b
Does the trunk side-bend? *	Peak side flexion excursion right plus left (°)	0.85	10.4 (1.56)	3.36	-1.08	(-5.49-3.33)	0.55 (0.14)	2.09 (0.62)
Does the pelvis hitch/drop? *Does the pelvis stay level?*	Peak pelvic lateral rotation excursion anti clockwise (right) clockwise (left) (°)	0.46	-4.9 (2.88)	4.71	-0.87	(-4.67-2.93)	0.67 (0.15)	2.10 (0.78)
Does the trunk lean forwards?	Trunk flexion peak excursion	0.81	11.1 (2.24)	4.15	0.10	(-6.52-6.73)	0.69 (0.15)	2.65 (1.25)

*criterion removed from updated HLLMS
a – trunk axial rotation
b – pelvic axial rotation

5.3.2.3 *Standing Hip Flexion*

A high level of between day agreement was seen for all criteria from the standing hip flexion test with ICC values >0.74. Similarly, between day mean difference for all the criteria was <2.38°. The kinematic waveforms showed good between day agreement with CMC values ranging from 0.61 to 0.96. Waveform measurement errors were low apart from peak hip flexion (9.01°) however this was small compared to the mean peak hip flexion excursion of 112.5° (Table 5-7).

Table 5-7: Between day ICC, mean, (SEM), minimal detectable change (MDC), mean difference ($\bar{d}$), limits of agreement (LOA), CMC (SD) and waveform measurement error (WME) (SD) for the kinematics related to the criteria from the standing hip flexion test in controls (n=11). Criteria highlighted in grey remain unchanged in the updated HLLMS

Movement criteria	Kinematic variable	ICC	Mean (SEM)	MDC	Bland and Altman $\bar{d}$	Bland and Altman LOA	CMC (SD)	WME (SD)
Does the pelvis drop (hitch)? *Does the pelvis fail to stay level?*	Peak pelvic lateral rotation excursion anti clockwise (left) clockwise (right) (°)	0.87	9.7 (1.14)	3.0	-0.13	(-3.48-3.22)	0.85 (0.09)	1.57 (0.54)
Does the pelvis tilt backwards (posteriorly)? *Does the pelvis begin in, or move backwards (posteriorly)?*	Peak pelvic posterior tilt excursion (°)	0.89	-12.9 (1.65)	3.56	-0.54	(-5.27-4.19)	0.82 (0.11)	2.95 (1.55)
Does the hip fail to bend (flex) just beyond 90 degrees (approximate 110 degrees)?	Peak hip flexion excursion (°)	0.74	112.5 (2.65)	4.51	-2.38	(-8.89-4.12)	0.96 (0.03)	9.01 (3.38)
Does the trunk lean backwards (extend)?	Trunk extension peak excursion (°)	0.75	-3.0 (1.39)	3.27	-0.72	(-4.58-3.14)	0.61 (0.15)	2.05 (1.14)
Does the weight bearing knee bend (flex)?	Peak knee flexion excursion (°)	0.79	8.5 (2.53)	4.41	-1.61	(-8.41-5.20)	0.64 (0.24)	2.42 (1.00)

The excellent levels of between day reliability for peak weight bearing knee flexion excursion (ICC = 0.79) in Table 5-7 from standing hip flexion test are contrasted by the Bland and Altman plot (Figure 5-7) which show increasing between day variation as the magnitude of the movement increases.

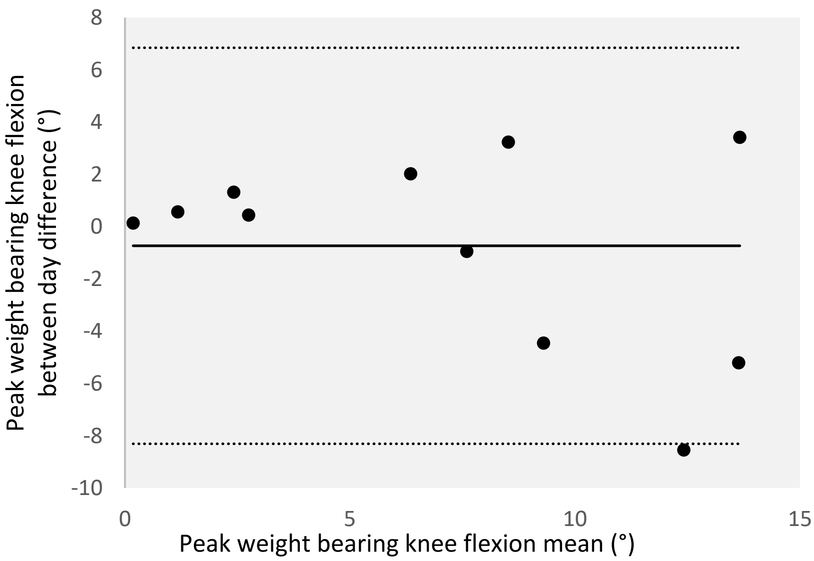


Figure 5-7: Right standing hip flexion test, peak weight bearing knee flexion: Bland and Altman distribution plots showing the mean measurement (day one mean + day two mean / 2) against the differences between measurements (day one minus day two). The middle horizontal line represents the mean value of the difference between the score on day one minus day two. The other two horizontal lines represent the lower and upper levels of agreement (mean day difference ± 2 standard deviation).

5.3.2.4 *Deep squat*

Between day reliability ICC values for the criteria from the deep squat test ranged from poor (0.39) to excellent (0.86). The criterion of peak excursion of femur flexion had a large mean difference between day of -6.34°. There were high levels of kinematic waveform agreement for all criteria with CMC values >0.87.

Table 5-8: Between day ICC, mean, (SEM), minimal detectable change (MDC), mean difference ($\bar{d}$), limits of agreement (LOA), CMC (SD) and waveform measurement error (WME) (SD) for the kinematics related to the criteria from the deep squat test in controls (n=11). Criteria highlighted in grey remain unchanged in the updated HLLMS

					Bland and Altman			
Movement criteria	**Kinematic variable**	**ICC**	**Mean (SEM)**	**MDC**	$\bar{d}$	**LOA**	**CMC (SD)**	**WME (SD)**
Does the thigh (femur) fail to be horizontal with the floor?	Peak excursion of femur flexion (°)	0.39	79.2 (7.48)	7.6	-6.34	(-26.32-13.65)	0.97 (0.02)	5.71 (1.33)
Does the trunk fail to stay parallel with the shin (tibia)?	Difference between tibia and trunk at peak femur flexion (°)	0.55	9.5 (5.50)	6.50	-0.18	(-16.12-15.76)	0.93 (0.05) a 0.88 (0.06) b	3.94 (1.22)a 3.53 (0.99)b
Does the pelvis tilt forwards (anteriorly)? *Does the pelvis begin in, or move forwards (anteriorly)?*	Peak pelvic anterior tilt excursion (°)	0.86	23.7 (3.28)	5.02	-0.98	(-10.47-8.51)	0.87 (0.14)	3.46 (1.21)

a – trunk flexion

b – tibia flexion

The mean difference for between day for peak excursion of femur flexion from the deep squat was -6.43° (Table 5-8) suggests a systematic error with greater femur flexion occurring on the second testing session as shown in Figure 5-8. However, difference was lower than the MDC of 7.6° (Table 5-8).

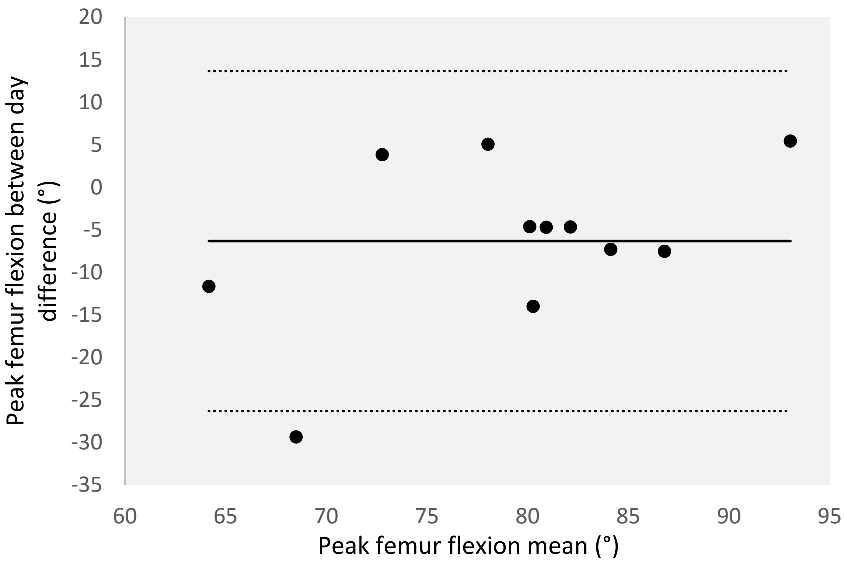


Figure 5-8: Deep squat test, peak femur flexion: Bland and Altman distribution plots showing the mean measurement (day one mean + day two mean / 2) against the differences between measurements (day one minus day two). The middle horizontal line represents the mean value of the difference between the score on day one minus day two. The other two horizontal lines represent the lower and upper levels of agreement (mean day difference ± 2 standard deviation).

5.4 Discussion

The observational reliability of criteria for the HLLMS was examined in Chapter 4 and shown to be good to excellent for most of them. It is important to consider the reliability of an objective assessment of the observational rating from the HLLMS. Analysing the relevant kinematics related to the criteria gives an indication of how stable the movement patterns are. Measuring the natural variability of the kinematics would help determine the amount of movement required to be confident that a true change in movement patterns had occurred.

5.4.1 Within session reliability

The observational reliability for the HLLMS was examined in Chapter 4 and shown to be good to excellent for most criteria. It is important to consider the reliability of an objective assessment of the observational rating from the HLLMS to provide a more in-depth assessment of the reliability of movement patterns. Analysing the relevant kinematics related to the criteria gives an indication of movement pattern stability. Measuring the natural variability of the kinematics would help determine the amount of movement required to be confident that a true change in movement patterns had occurred.

5.4.1.1 *SKB test*

The majority of the criteria from the SKB test had excellent peak kinematics reliability with ICC values >0.8. The criterion 'Does the pelvis hitch/drop?' had a lower ICC of 0.27 in controls compared to footballers (ICC = 0.91) which may have been caused by the low mean and relatively high SEM which can indicate the magnitude of the error (-2.0°, SEM1.72) (Table 5-1). The large SEM related to the small amount of pelvic lateral tilt suggest it may not be a reliable criterion. Additionally, the accuracy of 3D motion analysis has been questioned. Potential sources of error include soft tissue artefact and marker misplacement (Cappozzo et al., 2005, Chiari et al., 2005, Della Croce et al., 2005, Leardini et al., 2005). To reduce soft tissue artefact the OCST method was utilised (Taylor et al., 2005). Also to reduce the potential error from variation in individual marker placement a functional approach using the SCoRE and SARA to determine the hip joint centre and knee joint axes (Ehrig et al., 2006). There were small values of pelvic lateral rotation reported in this chapter which given the potential errors in using 3D motion analysis, it is debatable if it is possible to accurately measure such small values. Therefore, the measurement error may be greater than the movement and possibly meaning the pelvic lateral rotation criterion may not be reliable.

The criterion of 'Does the pelvis hitch/drop?' has been updated in latest HLLMS to 'Does the pelvis fail to stay level?' which would affect how the kinematics are calculated. To assess the updated criterion calculating the difference between peak clockwise and anticlockwise rotation could be used and would likely lead to increased kinematic values. Changing the kinematic criterion may affect the reliability and need to be investigated.

There is a lack of research on the kinematic reliability of pelvic lateral rotation during movement screening type tasks to compare to the results from the present study. A higher range of within session reliability ICC's for pelvic lateral tilt ICC's (range 0.94 to 0.98) were reported by Whatman et al. (2011). Comparison of the results from the present study to the findings of Whatman et al. (2011) is difficult due to substantial differences in methodology including use of peak rather than peak excursion. Also Whatman et al. (2011) did not report the ICC for the SKB specifically, only for a range of tasks including the drop jump, lunge and SKB. Despite the mostly high ICC values outlined above it is questionable as to whether pelvic lateral rotation kinematics calculated using the methodology in this study are reliable based on small ranges of movement and with substantial measurement errors.

The kinematics that had the lower ICC values from the SKB test were for medial knee movement both at peak knee flexion and peak excursion (Table 5-1). In addition to the lower ICC values, the medial knee kinematics had high SEM relative to the mean (up to 80% for medial knee movement at peak excursion in footballers) and high waveform error measurement 9.49° relative to the mean of 20.3° for peak medial knee displacement in footballers. Analysing the kinematic waveforms for medial knee movement in Figure 5-1 and Figure 5-2 shows a variation in the values throughout the knee flexion cycle. This is in contrast to the trunk flexion kinematic waveform in Figure 5-6 which increases to a peak around the middle of knee flexion and subsequently decreases. The variation in mean medial knee displacement kinematics during the knee flexion cycle suggests a less consistent pattern of movement and possibly a cause of the lower within session kinematic reliability outlined above. The variation in mean medial knee displacement kinematics in the present study is similar to the results from Horan et al. (2014). Similarly Horan et al. (2014) found more consistent pattern for mean kinematics in other joints such as pelvis tilt and hip adduction similar to the bell shaped curve for trunk flexion in Figure 5-6.

Comparing the medial knee displacement kinematics from the present study to the literature suggests similar amounts of movement. Horan et al. (2014) reported peak medial knee displacement during a single leg squat of 38.4mm (SD 14.3) and 53.7mm (SD 16.8) or participants rated good vs poor respectively. Although the present study reported peak excursion values the peak values from Figure 5-1 and Figure 5-2 suggest similar peak values to Horan et al. (2014). The results of the present study and Horan et al. (2014) suggest that medial knee displacement may not be reliable kinematic and questions the use of the criterion rating medial knee movement. low reliability.

5.4.1.2 *SKB Rot test*

All the criteria apart from 'Does the trunk side bend?' had excellent ICC values with all above 0.9 (Table 5-2). The trunk side flexion criterion has been deleted from the updated HLLMS, so its results will not be considered further.

Further analysis of the kinematics from the criterion that remain unchanged in the updated HLLMS 'Does the pelvis follow the trunk?' and 'Does the trunk lean forwards?' show fair similarity in their waveforms with CMC values ranging from 0.48 to 0.73. Additionally, waveform errors were < 1.99% for trunk and pelvic rotation and <2.1° for trunk flexion. The CMC values and waveform error suggest the kinematics for the criteria are reliable.

5.4.1.3 *Standing hip flexion test*

The kinematic reliability for the criteria from the standing hip flexion test was high with all but one result having ICC values > 0.77 (Table 5-3). The only ICC below 0.77 was for the peak hip flexion excursion (0.46) for controls. However, this is in contrast to the ICC for control for session 2 of 0.96 and footballers of 0.77. Additionally, the CMC for hip flexion kinematics was >0.93 with a low waveform error (range 8.7° to 9.8°) relative to the mean (range 106° to 110°). Overall the results for hip flexion kinematics suggest they are reliable.

5.4.1.4 *Deep squat test*

The only ICC value below excellent for the deep squat test kinematics was for peak pelvis flexion excursion in footballers (0.61) which was in contrast to the ICC for the controls of 0.92 (Table 5-4). However, the criterion has been updated in the latest HLLMS from 'Does the pelvis tilt forwards (anteriorly)?' to 'Does the pelvis begin in, or move forwards (anteriorly)?' and therefore the kinematic values used to calculate the ICC may change. Therefore, the kinematic reliability will need to be re assessed.

5.4.2 Between day reliability

The range of between day reliability for the kinematics was slightly lower with the range of ICC values from 0.07 to 0.91 compared to within session values (0.27 to 0.97).

5.4.2.1 *SKB test*

Between day kinematic ICC values for the SKB test was fair with all above 0.60 apart from pelvic lateral rotation for the pelvic hitch criterion (ICC 0.07). Similar to the within session reliability, pelvic lateral rotation between day range of motion had a relatively high SEM of 1.24° relative to the mean -1.8° suggesting a large measurement error. Additionally, the MDC for pelvic lateral tilt was 3.08°, almost double the mean, suggesting that a change of almost twice the mean would be needed to be confident that a change had occurred. The ICC and MDC values suggest that the between day kinematics are not reliable for pelvic hitch. The between day ICC for pelvic lateral rotation in the present study (ICC =0.07) was lower than the between day reliability ICC values reported by Whatman et al. (2013a) (ICC = 0.80 right, 0.67 left) during a single leg SKB. Comparison of the results from the present study to Whatman et al. (2013a) are limited as they did not report kinematic values, used peak rather than peak excursion values and participants had a mean age of 11 years. The low ICC, small kinematic means and relatively large SEM values in the present study and the below excellent ICC values reported by Whatman et al. (2013a) suggest the between day kinematic reliability for the pelvic lateral rotation my not be reliable. However, the criterion has been updated from 'Does the pelvis hitch/drop?' to 'Does the pelvis stay level?'. The change in criterion may lead to greater ranges of movement due to changes in how the kinematics are calculated and reduce the size of the measurement error relative to the mean values, increasing the reliability of the kinematics which need to be investigated.

The potential low reliability for within session medial knee displacement kinematics during the SKB test was discussed above (section 5.4.2.1). The between day ICC for knee valgus and medial knee displacement ICC values ranged from 0.6 to 0.67 indicating fair reliability which are slightly above the values reported by Whatman et al. (2013a) for medial knee displacement of 0.27 for the right and 0.51 on the left and for right knee valgus ICC of 0.48 reported by Alenezi et al. (2014). A potential source of error for between day kinematics is the variation in marker placement. To reduce this error Whatman et al. (2011) used marker pen to ensure optimal reproduction of reflective marker placement when the participants were tested two days apart. Although it is not possible to specifically assess the between day medial knee displacement kinematic reliability as the combined the results from five tests which included a SKB, the large range of ICC (0.59 to 0.93) from the study by Whatman et al. (2011) suggest even with optimal marker repositioning the there is substantial between day kinematic variation.

Comparison with the ICC results from the present study to the literature is limited due to different populations studied including children by Whatman et al. (2013a) and Alenezi et al. (2014) studying males and females and both authors using peak kinematics. It is not certain what effect these differences may have had on the between day reliability results compared to the present study. However, along with the high SEM relative to the mean for the between day knee kinematics from the present study (Table 5-5) the results outlined above suggest medial knee movement or knee valgus kinematics may not be reliable.

For the criteria that remain unchanged for the SKB test in the latest version of the HLLMS (knee move past the toes and trunk flexion) both have excellent ICC values (>0.83) and fair to good CMC values (0.60 and 0.81) for between day suggest that they are reliable. In considering when there two measures of agreement are different for a test, which one is most relevant to why the kinematics are being assessed. For example trunk flexion kinematic reliability ICC for peak values was 0.83, suggesting it has excellent reliability, but the waveform agreement measured using CMC was only 0.66, fair (Table 5-5). As the observational criterion is 'Does the trunk lean forwards?', which would relate to a peak value more than how consistent their movement pattern was during the test, the ICC value would appear the more appropriate value to consider than the CMC. Therefore, for the criterion 'Does the trunk lean forwards?' the excellent ICC value suggests that the kinematics related to the criterion are reliable.

5.4.2.2 *SKB Rot*

The SKB Rot test had high between day ICC values (>0.73) apart from kinematics for the criterion for 'Does the trunk side bend?' with ICC values of 0.46 (Table 5-6). Due to the poor reliability outlined in Chapter 4 the criterion has been removed from the latest HLLMS. There is limited research on lateral trunk flexion during movements used for movement screening to compare to the findings from the present study. In support of the low reliability of trunk lateral flexion reported in the present study (ICC 0.46) Whatman et al. (2011) report low between day ICC for lateral trunk flexion of 0.46. However, Whatman et al. (2011) did not report how they calculated lateral flexion so it is not possible to compare the kinematic values between the studies. The low reliability for trunk lateral flexion kinematics may be due to variation in movement caused by the participants possibly loosing balance for certain trials which would result in large differences in lateral flexion values. The low ICC for trunk lateral flexion in the present study and results from Whatman et al. (2011) support the removal of the criterion from the updated HLLMS.

There was a large mean difference between day for the percentage that the trunk and pelvic was in phase (6.98%) suggesting they criterion may not be reliable, despite a high ICC of 0.73. Similarly, the mean WME was high for trunk axial rotation (6.46%) and pelvic axial rotation (4.34) but both had excellent CMC values (0.85 and 0.79). However, the large errors for the mean difference and WME are measurements of percentage, therefore are relatively low compared to the mean of 69.3%. Despite the large errors for the percentage the trunk and pelvis are in phase, overall the kinematics for the criterion appear to be reliable.

5.4.2.3 *Standing hip flexion test*

The between day kinematic reliability for the standing hip flexion test was high with ICC values ranging from 0.74 to 0.89 and CMC values from 0.61 to 0.96 suggesting criteria are reliable. Despite the high ICC and CMC values the peak trunk extension excursion MDC was large (3.27°)

relative to mean 3.0° suggesting a large change in kinematics was required to detect a true change in movement.

The criterion 'Does the weight bearing knee bend (flex)?' mean, between day agreement ($\bar{d}$ -1.61, LOA -8.41-5.20) suggests the associated kinematics are consistent. However, the Bland and Altman plot (Figure 5-7) indicates that between day variation is related to the magnitude, with greater between day variation as the amount of knee flexion increases. Also the large LOA (-8.41-5.20°) relative to the mean of 8.5° suggests large range in between day agreement. The greater between day differences as peak knee flexion increases may be due to variation in participant's movement or amplification of the error due to how the kinematic data were calculated, such as marker placement. Another criterion 'Does the trunk lean backwards' appeared to have good between day reliability (ICC of 0.75) although the MDC (3.27°) was higher than the mean (-3.0°) which questions how accurately such small movements can be measured. These results outlined above suggest it may be difficult to state if the kinematics related criteria are reliable due to potential inconsistencies in movement and/or measurement error.

5.4.2.4 *Deep squat test*

The deep squat test had a large range of ICC values from 0.39 to 0.86 suggesting variable between day kinematic reliability. The low ICC was for peak excursion of the femur which was in contrast to the high ICC for within session in controls (ICC, 0.83, Table 5-4). One of the possible causes for the low between day ICC values could be due to the high mean difference between the values of femur flexion ($\bar{d}$, -6.34°). This high mean difference suggests there may have been a learning effect with participant's increasing the amount of femur flexion from session one to two. This large difference in mean femur flexion and low ICC suggests the between day kinematics may not be reliable with further examination required.

The between day reliability of the kinematics related to the difference between the tibia and trunk at peak femur flexion has fair level of agreement according to its ICC value of 0.53. Conversely the criterion has a high SEM (5.50°) and high MDC (MDC, 6.50°) relative to the mean of 9.5°. These values suggest that the criterion may not be reliable due to large errors in measurement and a large change in values to detect a true change in movement.

5.4.3 Limitations

The between day kinematic reliability results have only been calculated on 11 controls. As highlighted by Whatman et al. (2011) a small sample size leads to a greater uncertainty in the true magnitude of the reliability of the population.

The lower between day kinematic reliability compared to the within session may have been due to movement variability or variation in marker placement and it is not possible to state which had the greater effect. The importance of the effect of consistent marker placement was highlighted by Whatman et al. (2011) who used a pen to ensure identical placing of the markers between the testing sessions. However, this approach would not be practical if there was more than a few days between sessions, for example testing pre and post intervention, which may be months apart. The use of the OCST, SCoRE and SARA (Taylor et al., 2005) methods used to collect the kinematic data in this thesis were used to reduce the effect of placing markers in different locations on joint kinematics. Further work to try and estimate the variation in kinematics due to data collection methods such as using marker pen as outlined above, measuring distances between joint centres or comparing joint kinematics with stable task such as gait would be useful to estimate the movement variability for between day.

Some of the low ICC values may have been related to low ranges of movement as larger ranges of measurement produce higher ICC values. It may be possible that the ICC values may have been affected by how good the movement control is. For example, if a group of participants had poor control and subsequently large movements the ICC values may be higher compared to a group of participants that had similar consistency but small movements due to good movement control.

5.4.4 Recommendations and future research

Assessment was not carried out on the kinematics from sitting hip flexion and hip abduction test due to marker occlusion. Therefore, development of marker sets that reduce occlusion are needed to allow examination of the kinematic reliability of other three tests from the HLLMS not assessed in this chapter. Furthermore, most marker sets are designed to be used on participants in standing which may have limited accuracy when the participant is lying on their side such as for the hip abduction tests. There is a need to design a marker set that accurately measures pelvic movement in side lying to allow analysis of the kinematics from the hip abduction tests.

Due to changes in some of the criterion adjustment of the kinematic criteria may be needed and subsequent data analysis carried out to assess their reliability. For example, the criterion ‘Does the knee move inward from the 2nd toe?' has changed to 'Is there an increase in dynamic valgus from the start position?' from the SKB test. During discussions with other raters when changes were made to the updated HLLMS it became apparent that different raters were analysing different movements. Some raters where rating the pelvis related to femur movement while others were observing femur and tibia angles. There is a need to gain a consensus on exactly what movement is being observed for and subsequently what kinematics need to be measured as asses this.

As mentioned in the limitations section, there is a need to assess the between day kinematic reliability of footballers compared to controls. Measuring the between day reliability will increase the confidence in determining if a true change has occurred following an intervention. In assessing between day reliability in athletes there is a need to investigate other factors that may alter reliability, such as fatigue. For example, there may be a difference in footballer's kinematics from the HLLMS if they are fatigued meaning that with assessing pre to post intervention performance on the HLLMS, testing needs to be carried out with consistent levels of fatigue.

5.4.5 Conclusions

Examining the reliability of the kinematics related to the criteria from the HLLMS is an important in the development of the movement screen. The majority of the ICC values for within day reliability for the kinematics from the SKB, SKB Rot, standing hip flexion and deep squat tests in controls and footballers were above 0.75 suggesting they were reliable. Between day kinematic reliability was slightly lower than within day, ranging from poor to excellent with 10 of the 19 ICC values < 0.75. Analysis of the kinematic waveform reliability for the SKB, SKB Rot, standing hip flexion and deep squat test showed fair to excellent reliability for within session with CMC values ranging from 0.48 to 0.96 with slightly higher between day CMC values of 0.62 to 0.97.

The criterion 'Does the pelvis hitch/drop?' from the SKB test had low ICC for both the within and between day highlight that the peak lateral pelvic rotation excursion kinematics are not reliable. The criterion has been updated in the latest HLLMS and the reliability of the kinematics will need to be re assessed. Similar to the pelvic hitch criterion above the fair ICC, CMC and high SEM relative to the mean of the kinematics related to the criterion 'Does the knee move inward from the 2nd toe?' from the SKB test suggest it is not reliable. Although the criterion has been updated in the latest version of the HLLMS, the kinematic results from the present study suggest further investigation is required to establish if the kinematics related to the criterion are reliable.

Chapter 6: **Kinematic validity of the HLLMS: observational ratings versus 3D motion analysis**

6.1 Introduction

The previous two chapters have examined the observational and kinematic reliability of the HLLMS. The results suggest the HLLMS has fair to excellent reliability with some criteria that could be improved with changes in definitions, possible training of raters and other criteria that have since been removed from the screen due to poor reliability.

In developing the HLLMS it is essential that if it is to be used as an outcome measure there is a need to establish the reliability and validity. Having examined the reliability in Chapters 4 and 5 the next step is to establish the validity, i.e. accuracy. There has been considerable research looking at various forms of reliability for movement screening but there has been little research on the validity of observational rating, which was suggested by Frohm et al. (2012) to be one of the key considerations in the development of a movement screen. According to Portney and Watkins (2009) validity is the extent to which an instrument or tool measures what it is intended to. A review of validity and the current research on movement screening was discussed in section 2.2 of Chapter 2. Comparing the observational rating of the criteria to the kinematics calculated using 3D motion analysis assesses the concurrent validity of the HLLMS, which was examined in this chapter.

There has been limited research comparing the visual rating to 3D motion analysis for specific movements from screening tools. A significant (mean 11.6 (SE 1.5) vs 5.0 (SE 0.8) degrees, $p < 0.001$) difference in peak knee valgus angle in 2D was found between those rated as showing medio-lateral knee movement during a single leg mini squat compared to those who did not (Ageberg et al., 2010). The small knee bend (SKB) task used in the HLLMS has some key differences to the single limb mini squat that was used by Ageberg et al. (2010), who used fingertip support, with the participant looking down during the task and their rater only having to observe for a single fault criterion. As highlighted by Whatman et al. (2015) validity is only related to the exact protocol used, therefore the differences between the methodology used by Ageberg et al. (2010) and the HLLMS warrant the need to investigate the validity of the SKB test from the HLLMS. The lack of research on the validity of the movements and protocols similar to those from the HLLMS highlights the need for further study.

6.1.1 Aim

To assess the kinematic validity of the observational rating for the criteria from the HLLMS in young males.

6.1.1.1 *Objectives*

To compare observational ratings of fault or no fault during the HLLMS with relevant 3D motion analysis of specific movement criteria

6.2 Methodology

6.2.1 Ethics

Ethical approval was granted by the Faculty of Health Sciences, University of Southampton Ethics Committee (Ethics approval numbers 23370 and 27322) to study male academy footballers and male University students prior to data collection.

6.2.2 Participant and rater characteristics

All rating was carried out by the present author whose experience is detailed in sections 4.2.2 and 4.2.3 of Chapter 4. Details of participant characteristics and recruitment processes are outlined in section 3.2. Data was collected on 21 academy footballers (mean 17.5 years, SD 0.6, range 16-18) and 14 young male controls (mean 26.2 years, SD 1.3, range 24-28).

6.2.3 Data collection

The standardised protocol for carrying out the HLLMS is described in section 3.3. All kinematic data collection and processing were carried out by the present author, as described in section 3.5.2.

6.2.4 Data Analysis

As detailed in section 3.5 due to issues with marker occlusion with the sitting hip flexion and hip abduction tests, only the kinematics for the SKB, SKB Rot, standing hip flexion and deep squat test were processed. Data from the footballers and controls were combined.

For some of the criterion it was not possible to obtain kinematics for three complete trials and therefore participants were removed from the analysis, where appropriate. Problems with kinematic data collection included data recording starting after the test had begun and the participant not completing the task correctly.

6.2.4.1 *Statistics analysis.*

Kinematics for the fault and no-fault rating from the footballers and controls were visually checked on a frequency distribution histogram for normal distribution prior to analysis. Right and left sides were analysed separately. To test the data for normal distribution with small samples (<50) the Shapiro-Wilk test has become the standard and recommended (Sen and Srivastava, 2013). If the kinematic data were found to be not normally distributed the Mann-Whitney U-test for non-parametric data was used to see if there was a significant difference in the kinematics for those rated as fault and no fault, by comparing the mean ranks. This is similar to the method using by Ageberg et al. (2010) and was suggested by Sean Ewings, a statistician, to be the most appropriate method at this early exploratory stage of trying to validate the observational rating. Another method to assess validity could be the use of a threshold to assess if the observational rating is valid. However, a cut off normally needs a gold standard and at present it is not known if observational rating is a gold standard.

Although there are limitations to trying to use a cut off, analysis was carried out using a Receiver Operating Characteristic (ROC) curve on some of the movement criteria to compare to the Mann-Whitney U results. From the specificity and sensitivity data, Youden’s Index (J = sensitivity + specificity -1) was calculated to get a cut of with the highest combined sensitivity and specificity values (Youden, 1950).

Box plots were used to display the median, inter quartile range, maximum and minimum for the kinematics for fault and no-fault rating. Data were analysed using SPSS version 22 for Windows (SPSS Inc, Chicago, Ill, USA).

6.3 Results

There were 35 criteria from the SKB, SKB Rot, standing hip flexion and deep squat tests from the HLLMS that had their validity assessed. Of those 35 criteria 17 had a significant difference between the kinematics for fault and no-fault rating suggesting that approximately 50% of the observational rating criteria required revisiting to see if they could be improved to make more of the criteria valid. Some of the criteria used for data collection in the present thesis have been modified in the latest version of the HLLMS due to poor reliability. Modified criteria are in italics in the results tables and their reliability and validity needs to be established in future studies.

6.3.1 SKB test

Statistics were calculated on all kinematic criteria from the SKB test apart from knee flexion peak excursion on the left as all participants were rated as no fault. For the SKB test six of the kinematic criteria for the movement criteria had significant differences between fault and no fault. Only knee valgus on the right side had a significant difference ($p = 0.001$) between the kinematics for fault and no-fault rating from the criterion ‘Does the knee move inward from the 2nd toe?’ (Table 6-1). In contrast there was no significant difference between knee valgus on the left ($p = 0.845$).

Table 6-1. Validity of kinematics, significance (Mann-Whitney) median, inter quartile range (IQR) related to movement criterion from SKB test in adolescent footballers and controls. Updated movement criteria in italics. Shaded criteria indicate those that remained in the updated HLLMS.

Movement criteria	Kinematics	Side	Mann-Whitney	No Fault		Fault	
				Number rated	Median (IQR)	Number rated	Median (IQR)
Does the knee move inward from the 2nd toe? *Is there an increase in dynamic valgus from the start position?*	Peak excursion medial knee displacement	Right	0.708	17	18.5mm (15.0)	17	24.1mm (13.9)
		Left	0.958	16	-28.1mm (21.6)	17	-27.1mm (29.1)
	Medial knee excursion at peak knee flexion	Right	0.76	17	10.9mm (17.3)	17	17.9mm (17.3)
		Left	0.873	16	-19.5mm (24.6)	17	-14.4mm (24.6)
	Peak knee valgus excursion	Right	0.001	17	-5.0° (3.4)	17	-11.0° (14.0)
		Left	0.845	16	1.7° (2.4)	17	2.5° (3.1)
Does the pelvis hitch/drop? *Does the pelvis fail to stay level?*	Pelvic anti clockwise (right) clockwise (left) rotation peak excursion	Right	0.022	5	-1.3° (1.3)	29	-3.3° (3.1)
		Left	0.189	6	0.9° (1.7)	27	2.8° (4.1)
Does the knee fail to move 2cm past the toes?	Knee flexion peak excursion	Right	0.128	32	56.8° (19.0)	2	42.7° (0.0)*
		Left	N/A	33	58.0° (12.5)	0	N/A
Does the trunk lean forwards?	Trunk flexion peak excursion	Right	<0.001	8	3.8° (4.9)	26	8.9° (7.4)
		Left	0.001	5	2.9° (1.6)	28	8.3° (9.8)
Does the pelvis tilt forwards? *Does the pelvis begin in, or tilt forwards (anterior)?*	Pelvic anterior rotation peak excursion	Right	0.001	7	4.9° (5.9)	27	14.1° (6.3)
		Left	0.008	6	5.9° (7.8)	27	14.1° (8.8)

* not possible to calculate IQR as only data on two participants

N/A – all participants rated as no fault so not possible to calculate statistics or mean for no fault kinematics

For medial knee displacement excursion at peak and at peak knee flexion had a non significant difference between the kinematics between fault and no fault from the criterion ‘Does the knee move inward from the 2nd toe?’ was observed (Figure 6-1, Figure 6-2).

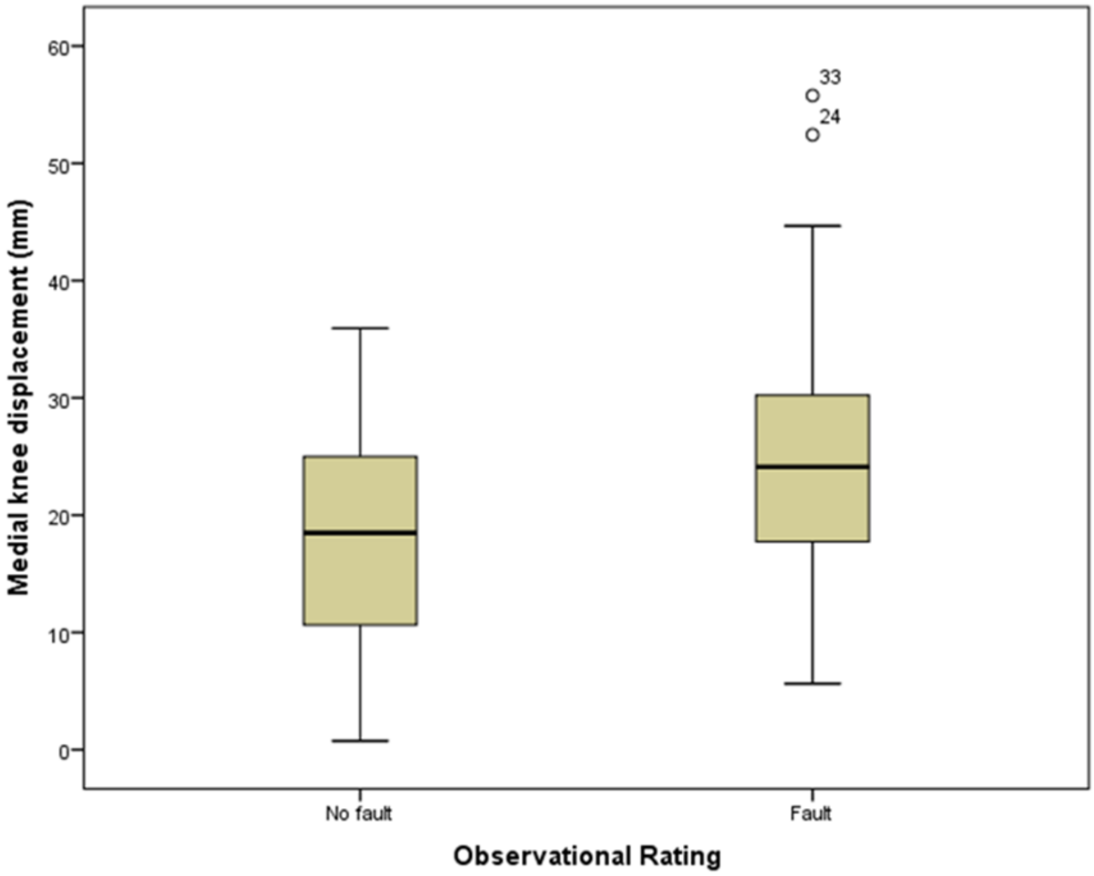


Figure 6-1: Box plots showing median, interquartile range, maximum, minimum and outliers for the peak medial knee excursion for fault and no fault from the SKB test on the right side.

In contrast to the medial knee displacement there was a significant difference between peak excursion for knee valgus kinematics for fault and no fault on the right but no significant difference on the left (Figure 6-2, Figure 6-3).

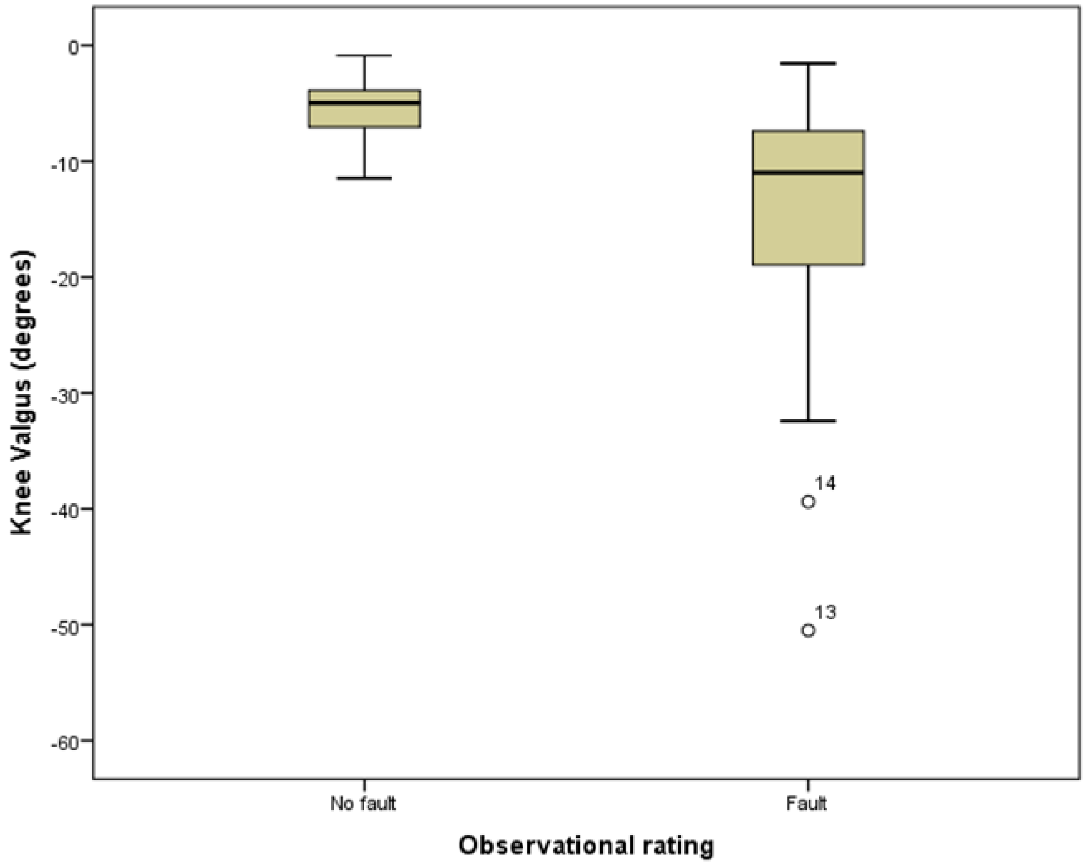


Figure 6-2: Box plots showing median, interquartile range, maximum, minimum and outliers for the peak excursion of knee valgus for fault and no fault from the SKB test on the right side.

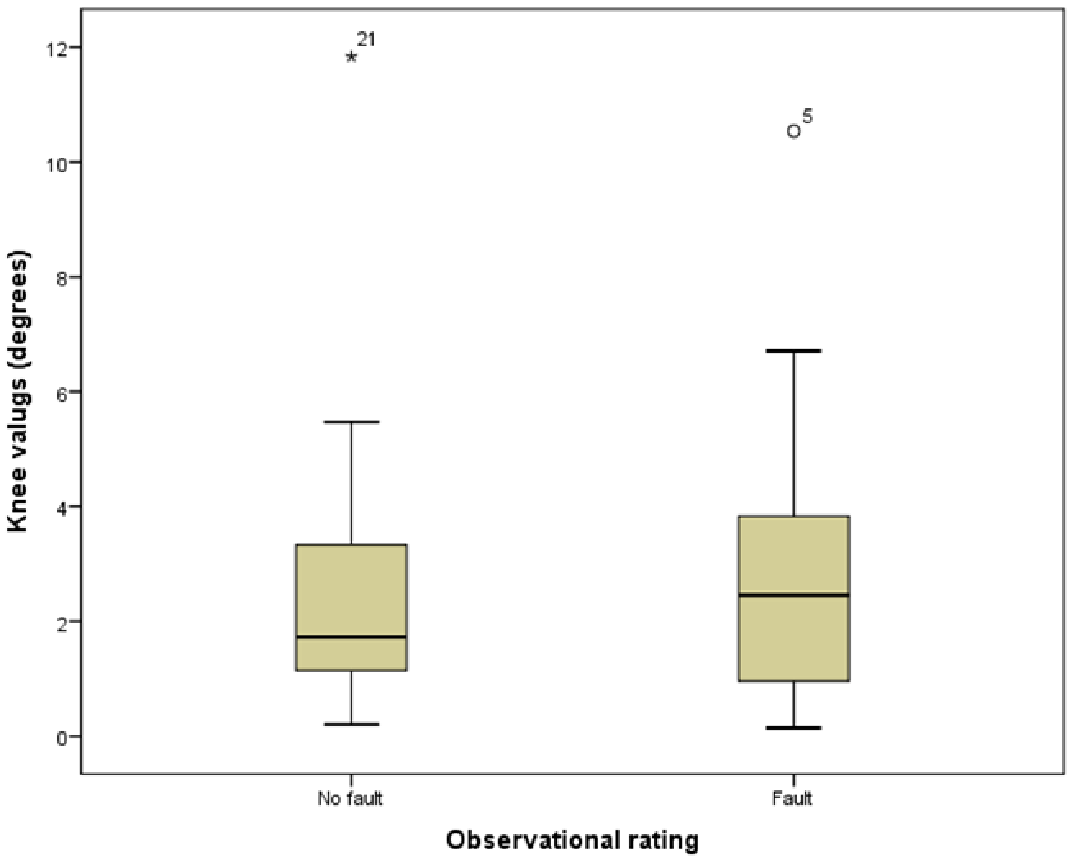


Figure 6-3: Box plots showing median, interquartile range, maximum, minimum and outliers for the peak excursion of knee valgus for fault and no fault from the SKB test on the left side

The criterion 'Does the trunk lean forwards?' (Figure 6-4) on the right side had significant differences between the kinematics for fault and no fault.

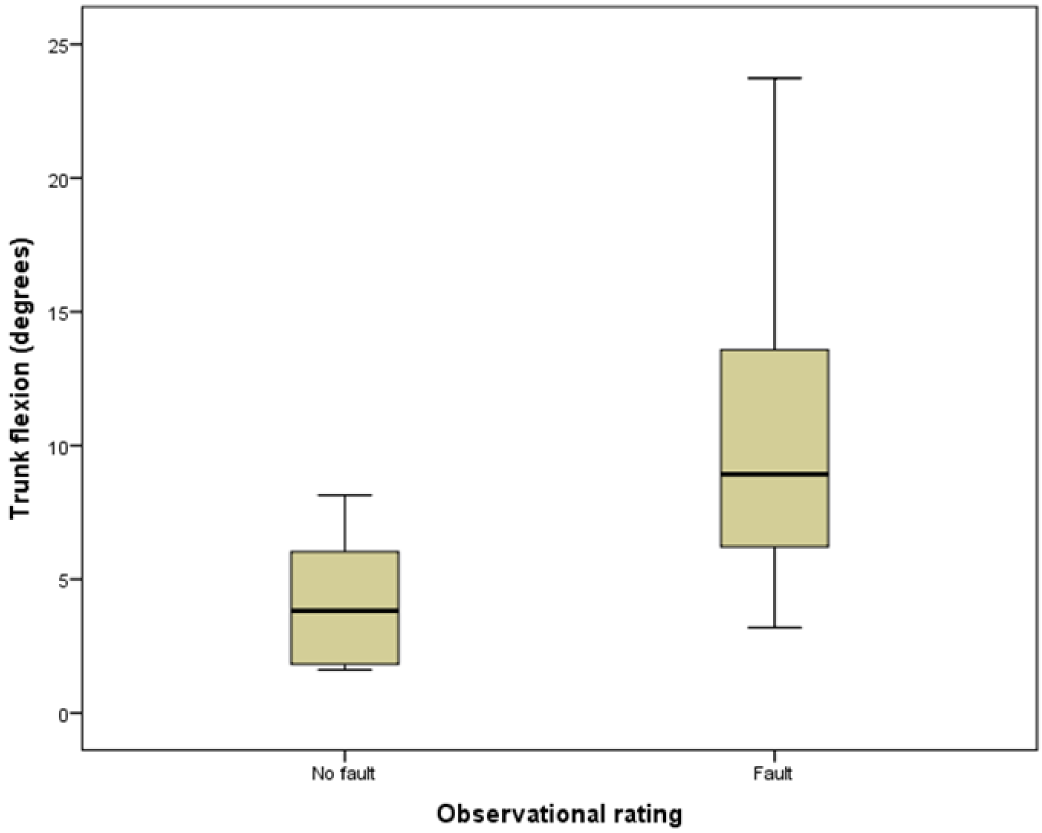


Figure 6-4: Box plots showing median, interquartile range, maximum, minimum and outliers for the peak excursion of trunk flexion for fault and no fault from the SKB test on the right side.

Peak trunk flexion angle from the SKB test on the right side was used in the ROC analysis, giving an area under the curve of 0.887 (SE 0.061, p=0.001) (Figure 6-5). Using the Youden index to maximise sensitivity and specificity a cut off of 5.0°, with a sensitivity of 0.89 and specificity of 0.75.

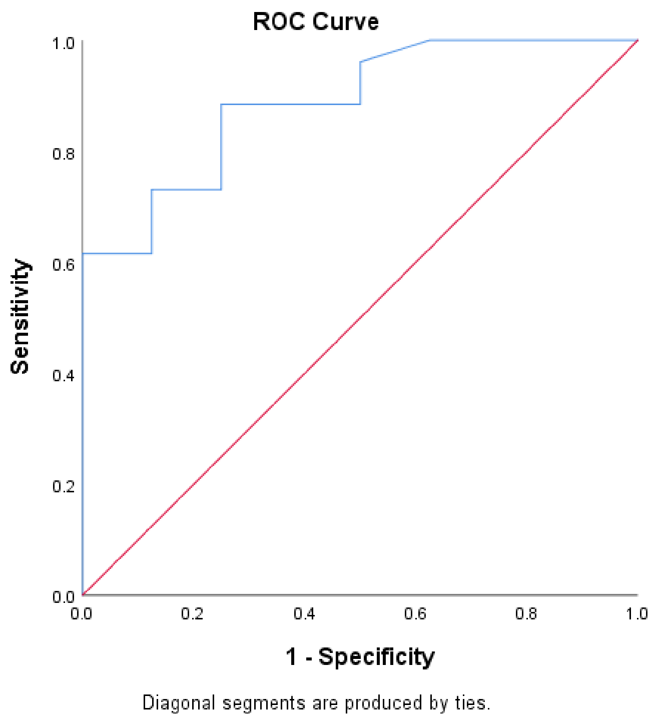


Figure 6-5: Receiver Operating Characteristic (ROC) curve linking observatory rating with the peak excursion trunk flexion from the SKB test on the right side. The ROC curve (blue) is not close to the red diagonal line indicating that the observational rating is good at discriminating those with and without the fault of trunk flexion in youth footballers and controls.

Peak anterior pelvic tilt angle from the SKB test on the right side was used in the ROC analysis, giving an area under the curve of 0.878 (SE 0.061, p=0.002) (Figure 6-6). Using the Youden index to maximise sensitivity and specificity a cut off of 7.5°, with a sensitivity of 0.89 and specificity of 0.71.

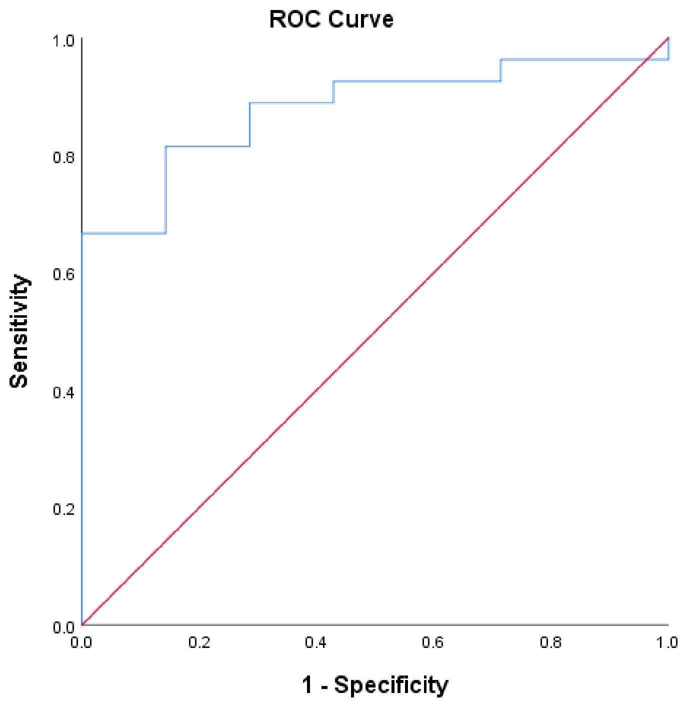


Figure 6-6: Receiver Operating Characteristic (ROC) curve linking observatory rating with the peak excursion anterior pelvic tilt from the SKB test on the right side. The ROC curve (blue) is not close to the red diagonal line indicating that the observational rating is good at discriminating those with and without the fault of anterior pelvic tilt in youth footballers and controls.

6.3.2 SKB Rot test

The SKB Rot test had significant differences in kinematics for criteria rated as fault and no fault for four of the eight criteria assessed. The movement criteria that remain unchanged in the updated HLLMS 'Does the pelvis follow the trunk?' and 'Does the trunk lean forwards?' had significant differences in fault and no-fault kinematics on both the right and left side (Table 6-2). The criterion 'Does the trunk side-bend?' had non-significant differences between fault and no fault and has been removed from the latest version of the HLLMS. The criterion 'Does the trunk rotate less than 30°?' was not assessed as all participants were rated as no fault and therefore it was not possible to assess differences in kinematics between fault and no fault.

Table 6-2: Validity of kinematics, significance (Mann-Whitney) median, inter quartile range (IQR) related to movement criteria SKB Rot test in adolescent footballers and controls. Updated movement criteria in italics. Shaded criteria indicate ones that remain in the updated HLLMS.

Movement criteria	Kinematics	Side	Mann-Whitney	No Fault		Fault	
				Number rated	Median (IQR)	Number rated	Median (IQR)
Does the pelvis follow the trunk?	Percentage trunk and pelvis in phase	Right	0.005	5	36.2% (20.3)	29	58.6% (26.2)
		Left	0.003	7	39.7% (22.7)	23	64.2% (23.6)
Does the trunk side-bend? *	Peak side flexion excursion right plus left	Right	0.218	17	11.4° (7.7)	17	8.6° (6.3)
		Left	0.746	20	7.9° (4.9)	10	8.4° (3.5)
Does the pelvis hitch/drop? *Does the pelvis stay level?*	Pelvic anti clockwise/clockwise rotation peak excursion	Right	0.848	9	5.6° (4.3)	25	5.4° (3.9)
		Left	0.527	6	-6.4° (8.9)	24	-4.9° (3.6)
Does the trunk lean forwards?	Trunk flexion peak excursion	Right	0.01	8	4.3° (5.9)	26	11.4° (9.0)
		Left	0.001	10	4.5° (4.3)	22	11.4° (8.3)

*criterion removed from updated HLLMS

Peak anterior pelvic tilt angle from the SKB Rot on the right side was used in the ROC analysis, giving an area under the curve of 0.524 (SE 0.115, p=0.830) (Figure 6-7). Due to the low area under the curve a cut off was not calculated.

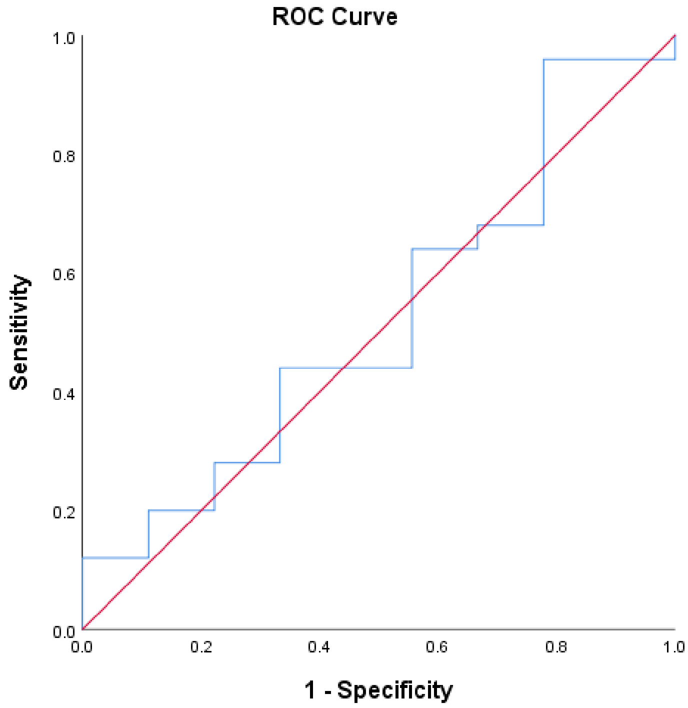


Figure 6-7: Receiver Operating Characteristic (ROC) curve linking observatory rating with the peak excursion anterior pelvic tilt from the SKB Rot test on the right side. The ROC curve (blue) is close to the red diagonal line indicating that the observational rating is not good at discriminating those with and without the fault of anterior pelvic tilt in youth footballers and controls.

6.3.3 Standing hip flexion test

The standing hip flexion test appears to have high validity due to six of the 10 criteria having significant differences in the kinematics for fault vs no fault (Table 6-3). However, for every criterion apart from 'Does the weight bearing knee bend (flex)?' the right and left are different in regard of significant or non-significant difference between the fault and no fault kinematics. For the criterion that remained in the updated HLLMS there were small differences between the left and right side Mann-Whitney U values (Table 6-3).

Table 6-3: Validity of kinematics, significance (Mann-Whitney) median, inter quartile range (IQR) related to movement criteria Standing Hip Flexion test in adolescent footballers and controls. Updated movement criteria in italics. Shaded criteria indicate ones that remain in the updated HLLMS.

Movement criteria - Stand Hip Flex	**Kinematics**	**Side**	**Mann-Whitney**	**No Fault**		**Fault**	
				Number rated	Median (°) (IQR)	Number rated	Median (°) (IQR)
Does the pelvis drop (hitch)? *Does the pelvis fail to stay level?*	Pelvic anti clockwise/ clockwise rotation peak excursion	Right	0.039	15	8.9 (3.5)	20	11.1 (3.5)
		Left	0.705	15	-10.1 (6.5)	20	-10.8 (2.6)
Does the pelvis tilt backwards (posteriorly)? *Does the pelvis begin in, or move backwards (posteriorly)?*	Peak pelvic posterior tilt excursion	Right	0.007	6	-9.3 (5.7)	29	-15.7 (4.4)
		Left	0.407	4	-14.3 (8.6)	31	-15.0 (5.7)
Does the hip fail to bend (flex) just beyond 90 degrees (approximate 110 degrees)?	Peak hip flexion excursion	Right	0.013	33	109.1 (6.5)	2	94.4 (0.0)*
		Left	0.072	32	109.4 (8.3)	3	102.4 (0.0)*
Does the trunk lean backwards (extend)?	Trunk extension peak excursion	Right	0.149	22	-3.2 (2.8)	13	-4.3 (4.7)
		Left	0.002	22	-2.8 (2.4)	13	-6.3 (3.9)
Does the weight bearing knee bend (flex)?	Knee flexion peak excursion	Right	<0.001	14	3.2 (3.3)	21	10.1 (8.4)
		Left	0.009	18	6.0 (6.5)	17	10.2 (7.0)

* not possible to calculate IQR as not enough data

6.3.4 Deep Squat test

For the deep squat test only one of the three criteria 'Does the thigh (femur) fail to be horizontal with the floor?', had a significant difference in the kinematics for fault and no fault ($p<0.001$) (Table 6-4).

Table 6-4: Validity of kinematics , significance (Mann-Whitney) median, inter quartile range (IQR) related to movement criteria deep squat test in adolescent footballers (n=21) and controls (n=14) calculated from kinematics on the left side. Updated movement criteria in italics. Shaded criteria indicate ones that remain in the updated HLLMS.

Movement criterion	Kinematics	Mann-Whitney	No Fault		Fault	
			Number rated	Median (°) (IQR)	Number rated	Median (°) (IQR)
Does the trunk fail to stay parallel with the shin (tibia)?	Difference between tibia and trunk at peak femur flexion	0.796	9	12.9 (14.4)	26	13.2 (13.3)
Does the thigh (femur) fail to be horizontal with the floor?	Peak excursion of femur flexion	<0.001	21	80.5 (9.3)	13	67.8 (16.9)
Does the pelvis tilt forwards (anteriorly)? *Does the pelvis begin in, or move forwards (anteriorly)?*	Peak pelvic anterior tilt excursion	0.363	16	25.0 (14.5)	17	27.5 (8.7)

6.4 Discussion

Analysing the validity of the observational rating of fault and no fault is important in the development of the HLLMS. There is a need to objectively assess if there is a difference between the participants rated as fault and no fault. For the criterion evaluated from the four tests from the HLLMS, approximately half of them had significant differences between the kinematics for fault and no fault, suggesting they are valid but the remaining criteria required attention to make them clearer and improve validity of the screen as a whole.

6.4.1 SKB test

The SKB test is one of the most commonly used and studied movement control tasks with medial knee movement being frequently assessed (Whatman et al., 2011). The results of the present study suggest that rating of medial knee movement is not valid, with non-significant differences between fault and no-fault kinematics for both peak excursion and excursion at peak knee flexion of medial knee displacement. There was substantial range of excursion of medial knee displacement at peak knee flexion and peak excursion for both fault and no-fault ratings, with substantial overlap between the ratings, highlighting the lack of difference between the kinematics from the ratings. This challenges the widespread use of this assessment criterion during the SKB test. The large ranges of medial knee movement may have been due to participants' natural unsteadiness while stood on one leg during the SKB. It could be possible that to try to reduce the amount of knee movement due to maintaining balance was the reason why Ageberg et al. (2010) allowed their participants to use fingertip support during the SKB. Additionally, to try to reduce the variation in start of knee position it may be worth considering defining the start as initiation of single leg stance rather than start of weightbearing knee flexion used in the present study. The present study used the start of weight bearing knee flexion as it was supposed that the observer would rate from the start of knee flexion. Using the initiation of single leg stance is likely to be more stable value than the start of weight bearing knee flexion in single leg stance, possibly reducing the variation in peak excursion due to participant's knee moving medially and laterally to try to maintain balance.

Relating the findings of the present study to the research literature, Horan et al. (2014) reported significantly greater ($p=0.02$) medio-lateral knee displacement of the knee joint centre of those rated as poor compared to good (53.7mm SD 16.8 vs 38.4mm SD 14.3). The values of medial knee displacement reported by Horan et al. (2014) are higher than those reported in the present study. The difference in values may be due to Horan et al. (2014) reporting peak values compared to peak excursion in the present study. The rating for good or poor performance by Horan et al. (2014) was calculated using a 1 to 10 scale of overall performance not specifically rating knee movement. Therefore, it is not possible state if the observational rating of medial knee movement is valid from the study by Horan et al. (2014).

In addition to medial knee movement, knee valgus was also assessed in the present study to examine the validity of the criterion 'Does the knee move inward from the 2nd toe?'.

In contrast to the non-significant differences between medial knee displacement kinematics for fault and no fault, knee valgus on the right side had significant ($p=0,001$) difference which was also reported by Ageberg et al. (2010). In contrast to the right there was a non-significant ($p=0.845$) difference in knee valgus the left side with lower peak excursion kinematics on the left side. Ageberg et al. (2010) only studied the right side so it is not possible to see if there were differences between the two sides. Similar differences between peak knee valgus kinematics, with lower values on the left than right side where shown on the figures from Herrington (2010), although no values were reported. Although there were differences between the present study and Herrington (2010) who studied females during jump tasks, the results indicate left knee peak valgus may be lower than on the right side. The greater knee valgus on the right side could be theorised to be due to footballers having better control on their left side as this would likely be their standing leg whilst kicking for the majority of the players, although leg dominance was not recorded. However, the right and left sides were almost identical in regard to the proportion of fault and no fault ratings, suggesting there was not a difference between sides in movement control. The potential difference between knee valgus kinematics between the right and left side and the low values suggest the use of valgus kinematics may not be valid

In considering the two criteria that remain unchanged in the updated HLLMS for the SKB test, there was a significant difference between fault and no-fault kinematics related to ‘Does the trunk lean forwards?’ suggesting this criterion is valid. The validity of the other criterion ‘Does the knee fail to move 2cm past the toes?’ is more difficult to assess as it was not possible to measure if the knee went past the toes with the current marker configuration, therefore knee flexion kinematics were used. There was a non-significant difference on the right side but due to all participants being rated as no fault on the left is was not possible to calculate the difference between fault and no fault on the left. Additionally, there may be low confidence in the results from the right side as these were based on only two of the 34 participants being rating as having a fault. Despite the methodology in the present study and Ageberg et al. (2010) trying to standardise the depth of the SKB, depth of the SKB may not be directly related to knee medial movement. Interestingly Horan et al (2014) reported knee flexion was significantly lower ($p < 0.01$) in the poor control group compared to the good control group (73.1° SD 8.7 vs 90.1° SD 12.1). However, medial knee displacement was significantly lower ($p=0.02$) in the good control group compared to the poor control (38.4mm SD 14.3 vs 53.7mm SD 16.8). The findings of Horan et al (2014) suggest that squat depth may not need to be standardised to identify movement criteria. Although a minimum depth of knee flexion may be required, for example if participants only flexed their knee 10° all participants may be rated as no fault.

There were contrasting significant values between the kinematics for fault and no fault for the criterion ‘Does the pelvis hitch/drop?’ on the right and left sides. However, there were very small amounts of peak excursion of pelvic movement (median range 0.9° to 3.3°) and large IQR (range 1.3° to 4.1°) relative to the medians. In addition, it could be proposed that it may not be possible to accurately detect such small quantity of pelvic movement by visual observation. Similar to the findings from the present study on pelvic lateral rotation, Horan et al (2014) reported small amounts of movement with high standard deviations between participants rated as good (5.7° SD 5.1) and poor (8.5° SD 4.5), with no significant difference between the ratings. However, lateral pelvic tilt was not specifically rated (Horan et al., 2014). The vales and results for pelvic movement reported in the present study and by Horan et al (2014) indicate that the criterion may not be valid. The criterion 'Does the pelvis hitch/drop?' has been re worded to 'Does the pelvis stay level?' in the updated HLLMS which needs further study to determine the validity of the observational rating of fault or no fault.

In comparing the Mann-Whitney U value ($p<0.001$) with the sensitivity (true positive) and specificity (true negative) results, both indicate good validity for trunk flexion criterion from the SKB test on the right. The cut off was calculated to be 5.0°, with high sensitivity (0.89) and specificity (0.75) values. The high area under the curve of 0.89 ($p=0.001$) also suggests the observational rating had criterion validity in detecting differences in kinematics between the participants rated as fault and no fault. Similarly, the results for the anterior pelvic tilt criterion from the SKB test on the right side showed significant difference between kinematics for participants rated as fault and no fault (Mann-Whitney U, $p=0.001$) and high sensitivity (0.89) and specificity (0.71) values with a cut of 7.5°.

6.4.2 SKB Rot test

The SKB Rot test had good validity for the criteria that are included in the updated HLLMS 'Does the pelvis follow the trunk?' and 'Does the trunk lean forwards?'. For the criterion 'Do the toes claw or any loss of balance?' it was not thought feasible to measure accurately toes clawing following discussion with supervisors, so it was difficult to validate the observational rating. Additionally, the criterion has been removed from the latest HLLMS due to poor observational reliability (section 4.3.1.2, Chapter 4) Similarly, 'Does the trunk side flex?' has been removed from the updated HLLMS due to poor observational reliability other researchers using the screen (section 4.3.2.2, Chapter 4) (personal communication with fellow PhD student, Nadine Booysen, University of Southampton). In support of the removal of the criterion the present study found non-significant differences in trunk side flexion on both the right and left sides.

The non-significant difference between the fault and no-fault kinematics of peak pelvic lateral rotation for the criterion 'Does the pelvis hitch/drop?' suggests the criterion is not valid. Comparable to the results for the SKB test, there was little difference between the median pelvic lateral rotation for fault and no fault on the right (0.2°) and the left (1.5°) with a large IQR relative to the median especially for fault on the left side (-6.4° IQR 8.9) (Table 6-2). As discussed above for the SKB test, the findings for the present study and Horan et al (2014) suggest that the criterion is not valid.

There were similar results for the different tests to detect if there was a difference between the fault and no fault groups from the ‘Does the pelvis hitch/drop?’ criterion from the SKB Rot test. The non-significant Mann-Whitney U (p=0.848) and ROC area under the curve (0.524). A ROC area under the curve that equals 0.5 represents no difference between the groups and 1 equals no overlapping between the groups. The lack of difference between the fault and no fault is clearly indicated by the almost identical median values for no fault (5.6°, IQR 4.3) and fault (5.4°, IQR 3.9) and therefore the observational rating is not valid for pelvic hitching. These results also suggest that it may be possible to calculate cuts offs for the kinematics related to the movement criteria from the HLLMS.

6.4.3 Standing Hip Flexion test

There were low numbers (2 and 3 participants) who rated as fault for the criterion of ‘Does the hip fail to bend (flex) just beyond 90 degrees (approximate 110 degrees)?’ but with the peak hip excursion median of around 110° for the no fault participants it appears valid.

Although there was a significant difference between fault and no fault for the trunk extension peak excursion on the left side but not on the right, the low median movement (range -2.8° to -6.3°) may be difficult to observe accurately for such small movements.

6.4.4 Deep Squat test

The median for the no fault for the peak excursion of the femur was less than 90° (80.5°) suggesting the observation for the criterion ‘Does the thigh (femur) fail to be horizontal with the floor?’ may not be valid. However, there was a significant difference (p<0.001) between the fault and no-fault kinematics indicating the criterion is valid.

The other criterion remaining unchanged in the updated HLLMS ‘Does the trunk fail to stay parallel with the shin (tibia)?’ had no significant difference (p=0.796) in the kinematics for fault (median 12.9° IQR 14.4°) and not fault (median 13.2° IQR 13.3°) for the difference between the tibia and trunk at peak femur flexion. The lack of validity of the kinematics related to the observational rating may be due to difficultly in trying to judge the relationship between two segments moving at the same time.

The criterion ‘Does the pelvis tilt forwards (anteriorly)?’ had non-significant difference (p=0.363) of peak excursion for anterior pelvic tilt between fault and no fault. The median pelvic anterior tilt for no fault (25.0°) was similar to fault (27.5°) highlighting the lack of difference. Additionally, no participant was able to perform the deep squat without anterior pelvic tilt (Table 6-4). Even though the criterion has been re worded to ‘Does the pelvis begin in or move forwards (anteriorly)?’ which will change how the kinematics are calculated to validate the criterion, it is still likely that the kinematics will suggest all participants anteriorly tilt their pelvis. Possibly, there is a need to re-define the kinematic criterion of anterior pelvic tilt such as anterior pelvic tilt relative to the trunk. The results of the present study indicate the need to discuss with raters what exactly they are rating and then re-define the kinematic criterion to assess the validity.

6.5 Limitations

Some of the validity calculations were based on low numbers of participants with a fault or no fault, such as ‘Does the hip fail to bend (flex) just beyond 90 degrees (approximate 110 degrees)?’ from the standing hip flexion test. Basing results on low numbers reduces the confidence in the result, therefore trying to get more balanced numbers of fault and no fault groupings would increase the certainty of the results.

The validity of the fault and no-fault observations is based on the current author’s ratings and therefore using different rates may alter the results. In addition to rating the HLLMS the author was coordinating the laboratory data collection which may have reduced the accuracy of rating due to not being able to focus solely on rating.

There was not a direct comparison between the observational rating and the kinematics as the kinematics were calculated as a mean of the three trials and the rating was most likely based on only one trial. The lack of direction comparison between kinematics and rating could have reduced the accuracy of assessing the criterion validity of the observational rating.

6.6 Recommendations and future research

With the change in some of the criteria for the updated HLLMS (see section 6.3) it would be useful to discuss with other raters involved with the validation study to define exactly what they are rating to ensure the relevant kinematics are measured to validate the observational rating.

The kinematics were based on the mean of three trials, whereas the observational rating was most likely based on one trial as it was not possible to rate all criteria for each trial. Assessing the validity comparing the kinematics and observational rating for one trial would potentially give a more accurate assessment of validity by reducing the effect that variation between trails may have. i.e. comparing the same movements more directly at the same time point.

Due to the altering of some of the criteria from the HLLMS, the kinematic criteria may need to be changed and investigated. For example, ‘Does the pelvis hitch/drop?’ has been updated to ‘Does the pelvis stay level?’. Therefore, the original kinematic criterion peak excursion pelvic lateral tilt in either clockwise or anti clockwise could be changed to different between peak clockwise and anticlockwise rotation to assess the reworded criterion. To aid the development of the HLLMS, collecting good quality video footage and corresponding 3D motion analysis data would be useful to allow multiple rating of the participants. Having video footage and 3D motion analysis data would allow direct comparison between observational rating and kinematics allowing rating of individual trials and re analysis if criteria change without the need to re-test participants in the laboratory. Calculating kinematics takes an extensive amount of time collecting and processing of the data, which would be substantially reduced if re-analysing 3D motion analysis data.

Finally, there is a need to examine the validity of the remaining tests, sitting hip flexion and hip abduction which would require the development of a specific marker configuration to enable the relevant kinematics to be calculated.

6.7 Conclusions

During development of a tool to assess movement control, such as the HLLMS, that uses observation to measure movement it is imperative that the rating of fault or no fault is compared against an objective measure. Of the 35 criteria assessed on both the right and left sides, 17 had a significant difference between the kinematics related to the criteria showing a fault and no fault rating. The results from the present study for the commonly used knee valgus movement fault suggest the observational criterion is valid on the right side with a significant difference between the fault and no fault (p=0.001, no fault = -5.0° IQR 3.4, fault = -11.0° IQR 14.0). In contrast, on the left side there was no significant difference between fault and no fault rating (p= 0.845, no fault = 1.7° IQR 2.4, fault = 2.5° IQR 3.1). Some of the criteria that were found to be invalid have been revised in the latest version of the HLLMS to improve their accuracy. The majority of the criteria that remained the same in the updated HLLMS as used in the present study, had significant differences between the fault and no fault rating suggesting they are valid. Further investigation of the criteria that have been changed in the updated HLLMS and analysis of the validity of the sitting hip flexion and hip abduction test are required.

Chapter 7: **Hip and Groin case study**

7.1 Introduction

There is a link between taking part in football and an increased risk of OA (Shepard et al., 2003). FAI is shown to increase the risk for developing hip OA and there appears to be a greater rate of FAI in footballers compared the general population which was outlined in section 1.1.2, (Gerhardt et al., 2012, Agricola et al., 2014). The relationship between altered movement patterns and FAI have been highlighted in Chapter 1 with a HLLMS developed to identify footballer with abnormal movement patterns by Botha (2013).

Research has reported a reduction in symptoms by altering movement patterns in people with FAI discussed in section 1.1.4, although there is little evidence on the longer term outcomes of interventions designed to alter movement patterns (Austin et al., 2008). However, there is some evidence that upper limb movement patterns such as posterior tilt of the scapular were significantly increased ($p<0.05$) by specific exercise programme in shoulder impingement patients (Worsley et al., 2013).

When considering the impact of an intervention, patient reported outcome measures are an important component of the assessment. The Copenhagen Hip and Groin Outcome Score (HAGOS) has been developed to be used with hip and or groin pain (Thorborg et al., 2011). The HAGOS has six subscales which are rated from 0–100 with zero representing extreme hip and/or groin problems and 100 representing no hip and/or groin problems. Harris-Hayes et al. (2013) suggests that the HAGOS was one of the best patient reported outcome measures for use in the treatment of FAI, although it has not been established in the literature. Several authors have used the HAGOS with FAI research (Diamond et al., 2014, Sansone et al., 2016) and (Bennell et al. (2014) will use it in their study on a physiotherapy rehabilitation with FAI. A significant change ($p<0.05$. mean change in sub scales ranged from 20-28) in all the HAGOS subscales following hip surgery was reported by Sansone et al. (2016). The research above suggests the HAGOS is an important measure to include with FAI.

Developing at valid HLLMS there was a need to compare the observed movement rating with 3D motion analysis. Part of the validation of the movement screen was to measure the changes in movement patterns following an exercise programme designed to improve movement in a participant with FAI. Additionally, measuring the change in muscle activation would increase the understanding of the mechanisms of any change following an exercise intervention.

7.1.1 Aim

The aim of the present study was to examine how a specific exercise intervention may change movement patterns of the hip and lower limb in a participant with FAI symptoms.

7.1.1.1 *Objectives*

1. To examine the differences in observational rating of the HLLMS following an exercise programme to validate its sensitivity to change.
2. To compare observed movement ratings with the kinematics from the HLLMS.
3. To examine changes in self-reported hip pain as a result of an exercise intervention.

7.2 Methodology

7.2.1 Study design

Single participant case study. Ethical approval (12680) for the study was gained from the University of Southampton, Faculty of Health Sciences ethics committee. Consent was gained prior to testing.

7.2.2 Participant characteristics and past medical history

The participant was a 25-year-old male (Weight 74.3kg, Height 182cm) with a nine year history of bilateral groin pain “pubalgia” aggravated by hip rotation and abduction. The participant was educated to a graduate level. The participant played football from the age of 6-19 years old at an amateur level with ambitions to be a professional footballer but had to stop due to their groin symptoms. The participant underwent several scans including MRI of the pelvis, one MRI of the right hip with contrast agent, two MRI scans of left hip (one required after a labral tear) with contrast agent. Based on a diagnosis of FAI the participant underwent arthroscopic surgery on their left hip in July 2013. No physiotherapy or any other treatment was carried out before their surgery. Following surgery, a period of rehabilitation was carried out for one month. The participant has been unable to return to football due to ongoing bilateral hip and groin pain.

7.2.3 Clinical assessment

The participant was clinically examined by a fellow PhD student and Senior Physiotherapist Nadine Booysen (NB). The clinical examination included palpation of the anterior structures of the hips for a pain response and measuring range of motion of the hips. The participant completed the HAGOS before testing was begun and pre and post intervention. Questionnaires were checked to ensure they were completed fully.

7.2.4 HLLMS

The participant completed the HLLMS (Appendix E) in the motion analysis laboratory at the University of Southampton. The HLLMS used in this study is an earlier version than the version in Table 3.1 with slightly different wording of the criteria and a couple of extra movement criteria for the standing hip flexion and deep squat tests. The methodology and data analysis were carried out as described in Methodology section (Chapter 3). The rating of the movement screen was carried out by NB. The participant was re assessed in the laboratory seven weeks after the initial assessment.

7.2.4.1 *Kinematic values*

Collection of kinematic data were carried out using a Vicon Motion Capture System. The set up for kinematic data collection is outlined in Section 3.3. The HLLMS was performed within the capture volume of the Vicon system. All procedures for laboratory setup and data collection are the same as outlined in Section 3.3.

7.2.5 Intervention

Using findings from the HLLMS the participant was prescribed an individual exercise programme by NB to correct the movements patterns identified. The participant was asked to complete a recording sheet of when they carried out their exercise programme. Reviews were carried out every two weeks to check progress and alter the programme as applicable. The participant undertook an intervention designed by NB. The intervention focused on improving movement control with exercises such as the lunge, clam, bridging, prone hip extension, hip abduction and squat. The correct technique was emphasised to ensure a good movement pattern was learnt and maintained. The difficulty of the intervention was progressed as clinically judged appropriate by NB. Details of the intervention are in Appendix O.

7.3 Results

Following an exercise intervention there was decreased symptoms according to the HAGOS score, improvement in the observational rating from the HLLMS and subsequent changes in the kinematics related to the movement criteria. Earlier onset and later termination of gluteus medius also occurred post intervention during the SKB test.

7.3.1 Clinical assessment

Hip active and passive ROM showed minimal change (range 5-10 degrees) from pre and post intervention and minimal differences between the participant's right and left sides (Table 7-1).

Table 7-1: Hip range of movements pre and post intervention

	Pre intervention				**Post intervention**			
	Right		**Left**		**Right**		**Left**	
	AROM (°)	PROM (°)	AROM (°)	PROM (°)	AROM (°)	PROM (°)	AROM (°)	PROM (°)
Hip Internal rotation prone	23	25	21	25	22	22	21	22
Hip Abduction - lateral rotation	40	45	40	45	30	35	30	40
Hip Abduction - medial rotation	25	35	30	35	30	30	30	30
Hip flexion	110	115	110	120	115	120	110	115
Hip internal rotation sitting 90° hip flexion	20	25	20	25	30	30	25	25

Palpation of anterior hip structures was pain free both pre-and post-intervention. Similarly, the hip impingement test was positive pre-and post-intervention with both hips painful at 90 degrees of hip flexion.

7.3.2 HAGOS

The only HAGOS score to show any improvement following the intervention was symptoms, which increased from 36% to 61% (Table 7-2).

Table 7-2: The Copenhagen Hip and Groin Pain Outcome Score (HAGOS) pre-and post-intervention

	Pre intervention (%)	Post intervention (%)	Smallest detectable change (SDC)	Change above SDC
Pain	70	73	18.8 (13.8–25.4)	No
Symptoms	36	61	17.7 (14.1–23.2	Yes
Activities of daily living	70	75	20.0 (14.9–25.7	No
Sport/Recreation	53	56	22.2 (16.6–29.6	No
Physical Activity	13	13	33.8 (25.4–44.8	No
Quality of life	20	30	17.7 (13.3–24.9)	No

SDC from Thorborg et al. (2011)

7.3.3 Hip and Lower Limb movement screen scores

There was a substantial decrease from 38 to 20 criteria from pre-to post intervention from the HLLMS with similar decreases on the left (18 to 8 criteria) and right (19 to 11 criteria) sides (Table 7-3).

Table 7-3: HLLMS pre-and post-intervention

	Total score (66)	Right side total (30)	Left side total (30)	Squat (6)
Pre-intervention	38	19	18	1
Post intervention	20	11	8	1

Squat was bilateral so separated from right and left side scores
Values in brackets are maximum scores possible

The SKB and SKB Rot tests had the largest change in number of faults from pre to post intervention, four to zero and five to one respectively (Table 7-4). Minimal change in the number of criteria was shown in standing hip flexion and hip abduction with lateral rotation and medial rotation pre to post intervention on both the right and left (Table 7-4). A Substantial decrease in number of faults in sitting hip flexion test on the left, three to zero but not on the right four to three was observed (Table 7-4).

Table 7-4: Number of fault ratings from the tests in the HLLMS which were rated on right and left sides

Screening Test	Right		Left	
	Pre-Intervention	**Post intervention**	**Pre-Intervention**	**Post intervention**
Small knee bend	4	0	4	0
Standing trunk rotation	5	1	5	1
Standing hip flexion	2	2	2	2
Sitting hip flexion	4	3	3	0
Hip abduction with lateral rotation	3	3	3	3
Hip abduction with medial rotation	1	2	1	2
Total	19	11	18	8

Observational fault rating for each fault from the HLLMS for pre to post intervention on right and left side are shown in Table 7-5 and Table 7-6 below.

Table 7-5: Right side, specific movement criteria from the HLLMS, pre and post intervention plus squat

Screening test	Movement Criterion	Fault pre intervention	Fault post intervention
Small knee bend	Knee move inwards	✓	
	Pelvic hitch	✓	
	Trunk flex		
	Knee past toe	✓	
	Anterior pelvic tilt	✓	
Standing trunk rotation	Pelvis follow trunk	✓	
	Trunk side flex	✓	
	Pelvic hitch	✓	
	Trunk rotate less than 30°		
	Toes claw/loss of balance	✓	✓
	Trunk flex	✓	
Standing hip flexion	Pelvis drop		
	Posterior pelvic tilt	✓	✓
	Spine flex	✓	✓
	Trunk lean backwards		
	Weight bearing knee flex		

Sitting hip flexion	Axial rotation of pelvis	✓	✓
	Pelvis drop		
	Foot fail to align with ankle/knee/hip	✓	
	Posterior pelvic tilt	✓	✓
	Spine flexion		✓
	Trunk extension	✓	
Deep squat	Trunk fail to stay vertical or parallel with tibia	✓	✓
	Femur fail to get horizontal		
	Anterior pelvic tilt		
	Knee move inwards from 2nd toe		
	Knee move outwards from 2nd toe		
	Bodyweight shift to one side		
Hip abduction with lateral rotation	Leg lose lateral rotation		
	Leg move into flexion	✓	✓
	Pelvis move backwards	✓	✓
	Pelvic hitch	✓	✓
Hip abduction with medial rotation	Leg lose medial rotation		
	Leg move into flexion		
	Pelvis move backwards		✓
	Pelvic hitch	✓	✓

Table 7-6: Left side, HLLMS movement rating pre and post intervention

Screening test	**Movement Criterion**	**Fault pre intervention**	**Fault post intervention**
Small knee bend	Knee move inwards	✓	
	Pelvic hitch	✓	
	Trunk flex		
	Knee past toe	✓	
	Anterior pelvic tilt	✓	
Standing trunk rotation	Pelvis follow trunk	✓	
	Trunk side flex	✓	
	Pelvic hitch	✓	
	Trunk rotate less than 30°		
	Toes claw/loss of balance	✓	✓
	Trunk flex	✓	✓
Standing hip flexion	Pelvis drop		
	Posterior pelvic tilt	✓	✓
	Spine flex		
	Trunk lean backwards		✓
	Weight bearing knee flex		
Sitting hip flexion	Femur fail to get horizontal	✓	✓
	Anterior pelvic tilt		
	Knee move inwards from 2nd toe	✓	✓
	Knee move outwards from 2nd toe		
	Bodyweight shift to one side		
	Axial rotation of pelvis	✓	
Hip abduction with lateral rotation	Pelvis drop		
	Foot fail to align with ankle/knee/hip	✓	✓
	Posterior pelvic tilt	✓	✓
	Spine flexion	✓	✓
Hip abduction with medial rotation	Trunk extension		
	Leg lose lateral rotation		
	Leg move into flexion		✓
	Pelvis move backwards	✓	✓

7.3.4 Kinematics related to the movement criteria from the HLLMS

7.3.4.1 *SKB test*

Peak medial knee displacement averaged over the three trials increased by 5.23mm on the right and 0.62mm on the left from pre to post intervention with the observational rating changing from the participant having knee move inwards fault to not bilaterally (Table 7-7). Large variations were shown in peak medial knee displacement calculated at peak knee flexion compared to the whole trial. An example of the large variation in values is the medial knee deviation for the whole trial of 25.22mm (SD 13.29) versus 14.14mm (SD 13.46) at peak knee flexion for the right side pre-intervention.

Table 7-7: Kinematics related to movement criteria for the SKB test from the HLLMS, pre and post intervention. Mininmal detectable change (MDC) calculated from between day in controls. Shaded criteria indicate those that remain unchanged in the updated HLLMS.

		Pre intervention			Post intervention		
Movement Criterion	**Kinematics**	**Side**	**Fault**	**Mean (SD)**	**Fault**	**Mean (SD)**	**MDC**
Does the knee move inward from the 2nd toe? *Is there an increase in dynamic valgus from the start position?*	Peak medial knee displacement (mm)	Right	yes	25.2 (13.3)	no	30.5 (9.7)	10.8
		Left	yes	29.8 (10.2)	no	30.43 (11.0)	8.9
	Medial knee excursion at peak knee flexion (mm)	Right	yes	14.1 (13.5)	no	14.8 (10.1)	8.0
		Left	yes	24.1 (15.5)	no	27.4 (8.7)	7.6
	Peak knee valgus excursion (°)	Right	yes	-4.8 (5.1)	no	-1.7 (0.9)	4.5
		Left	yes	-4.4 (2.2)	no	-1.0 (0.2)	2.0
Does the pelvis hitch/drop? *Does the pelvis fail to stay level?*	Pelvic anti clockwise (right) clockwise (left) rotation peak excursion (°)	Right	yes	4.4 (2.7)	no	3.7 (2.2)	3.1
		Left	yes	10.1 (1.5)	no	1.2 (0.1)	2.4
Does the knee fail to move 2cm past the toes?	Peak knee flexion excursion (°)	Right	no	77.1 (3.2)	no	55.6 (1.4)	4.9
		Left	no	66.5 (0.0)	no	50.6 (0.0)	5.4
Does the trunk lean forwards?	Peak Trunk flexion excursion (°)	Right	yes	13.3 (1.3)	no	1.5 (1.9)	4.6
		Left	yes	10.9 (5.2)	no	0.8 (0.0)	3.6
Does the pelvis tilt forwards? *Does the pelvis begin in, or tilt forwards (anterior)?*	Peak Anterior pelvic tilt excursion (°)	Right	yes	21.6 (2.2)	no	4.4 (0.5)	5.2
		Left	yes	20.4 (3.5)	no	4.8 (0.1)	3.7

Left side - only 2 trials used as both pre and post intervention had one repition not started in bilateral stance

7.3.4.2 *SKB with Rotation*

The observational rating for criteria from the SKB Rot test all improved from fault to no fault pre to post intervention (Table 7-8). Only the kinematics for the criterion ‘Does the pelvis follow the trunk?’ had corresponding improvements in the kinematics above the MDC for both the left and right side. There were improvements in the kinematics above the MDC corresponding to the change in rating for the criterion ‘Does the trunk lean forwards?’ on the left but not on the right side (Table 7-8).

Table 7-8: Kinematics related to movement criteria for the SKB Rot test from the HLLMS, pre and post intervention. Mininmal detectable change (MDC) calculated from between day in controls. Shaded criteria indicate those that remain unchanged in the updated HLLMS.

			Pre intervention		**Post intervention**		
Movement Criterion	**Kinematics**	**Side**	**Fault**	**Mean (SD)**	**Fault**	**Mean (SD)**	**MDC**
Does the pelvis follow the trunk?	Percentage trunk and pelvis in phase	Right	yes	27.0 (11.3)	no	7.4 (1.9)	8.5
		Left	yes	47.1 (4.5)	no	20.5 (3.2)	8.0
Does the trunk side-bend?	Peak side flexion excursion right plus left (°)	Right	yes	10.8 (2.7)	no	9.6 (1.0)	3.4
		Left	yes	13.9 (5.2)	no	8.1 (1.2)	5.2
Does the pelvis hitch/drop? *Does the pelvis stay level?*	Pelvic anti clockwise/clockwise rotation peak excursion (°)	Right	yes	1.2 (0.9)	no	3.1 (0.9)	4.7
		Left	yes	-1.0 (0.7)	no	-3.0 (0.6)	3.3
Does the trunk lean forwards?	Trunk flexion peak excursion (°)	Right	yes	11.3 (3.3)	no	8.9 (4.7)	4.2
		Left	yes	14.1 (2.6)	no	2.9 (0.4)	4.1

7.3.4.3 *Standing hip flexion test*

The criterion 'Does the spine flex?' was removed from the HLLMS (Appendix E) used in the present study and therefore the kinematics were not assessed. There was only one rating that changed 'Does the trunk lean backwards (extend)?' on the left but only very small change in the kinematics which was considerably below the MDC (Table 7-9).

Table 7-9: Kinematics related to movement criteria for the Standing Hip Flexion test from the HLLMS pre and post intervention. Mininmal detectable change (MDC) calculated from between day in controls. Shaded criteria indicate those that remain unchanged in the updated HLLMS.

		Pre intervention			**Post intervention**		
Movement Criterion	**Kinematics**	**Side**	**Fault**	**Mean (SD)**	**Fault**	**Mean (SD)**	**MDC**
Does the pelvis drop (hitch)?	Pelvic anti clockwise (left)/ clockwise (right) rotation peak excursion	Right	no	7.8 (0.3)	no	8.2 (0.4)	3.0
Does the pelvis fail to stay level?		Left	no	-9.2 (0.3)	no	-11.1 (0.6)	2.9
Does the pelvis tilt backwards (posteriorly)?	Peak pelvic posterior tilt excursion	Right	yes	-17.9 (0.9)	yes	-14.8 (1.5)	3.6
Does the pelvis begin in, or move backwards (posteriorly)?		Left	yes	-16.1 (0.5)	yes	-15.5 (1.3)	5.2
Does the trunk lean backwards (extend)?	Peak trunk extension excursion	Right	no	0.0 (0.0)	no	-0.9 (0.8)	3.3
		Left	no	-0.5 (0.8)	yes	-0.3 (0.3)	2.9
Does the weight bearing knee bend (flex)?	Peak weight bearing knee flexion excursion	Right	no	7.2 (0.8)	no	8.4 (0.8)	4.4
		Left	no	8.8 (2.0)	no	8.3 (1.2)	4.5

7.3.4.4 *Deep Squat*

The criterion ‘Does the knee move outward from 2nd toe?’ and ‘Does the knee move inward from 2nd toe?’ was removed from Version 3 of the HLLMS therefore the kinematics for the knee moving inwards/outwards was not assessed. In addition, data was collected on only one force plate meaning it was not possible to objectively asses the criterion ‘Does the bodyweight shift to one side?’. None of the observational ratings changed from pre to post intervention for any of the criterion that had the kinematics assessed from the deep squat test and similarly there was only small changes in the kinematics (Table 7-10).

Table 7-10: Kinematics related to movement criteria for the Deep Squat test from the HLLMS pre and post intervention. Mininmal detectable change (MDC) calculated from between day in controls. Shaded criteria indicate those that remain unchanged in the updated HLLMS.

			Pre intervention		Post intervention		
Movement Fault	**Kinematic variable**	**Side**	**Fault**	**Mean (SD)**	**Fault**	**Mean (SD)**	**MDC**
Does the pelvis tilt forwards (anteriorly)? *Does the pelvis begin in, or move forwards (anteriorly)?*	Peak excursion pelvis tilt	Left	no	20.9 (2.4)	no	16.1 (1.2)	7.6
Does the thigh (femur) fail to be horizontal with the floor?	Peak excursion of femur flexion	Left	no	82.1 (2.0)	no	89.8 (4.1)	6.5
Does the trunk fail to stay parallel with the shin (tibia)?	Difference between tibia and trunk at peak femur flexion	Left	yes	7.1 (2.0)	yes	7.0 (0.8)	5.0

7.4 Discussion

7.4.1 Hip ROM

The hip flexion passive ROM (115-120 degrees) for the present study is greater than that reported by Nussbaumer et al. (2010) of 103.8 ±15.7 degrees in FAI patients. However, the participants in Nussbaumer et al. (2010) were older (35 ± 11 years) and both sexes which both could had affected their ROM compared to the present study. There was no consistent change in hip ROM from pre to post intervention (Table 7-1) which is similar to the findings reported by Emara et al. (2011). The largest change in ROM from pre to post was only 10 degrees which is within the range in minimal detectable change of 7.8°hip internal rotation to 11.0° hip extension reported by Pua et al. (2008). Although the study by Pua et al. (2008) was on a different population (50-84 year old hip OA patients) it suggests the changes in hip ROM in the present study are not above the measurement error. The ROM from current study were measured using a plurimeter which is potentially more accurate than the goniometer used by Pua et al. (2008). The plurimeter was reported by Croft et al. (1996) to have good repeatable measurement of hip ROM between practitioners. However, although there was no published research known to the author on intra-rater reliability. Nevertheless, even without values for intra-rater reliability, based on the research outlined above the intervention in the present study had little effect on the participant's hip ROM.

7.4.2 HAGOS

The HAGOS values reported in this study are similar to the values reported for FAI group who were scheduled for surgery (Diamond et al., 2014) suggesting the participant had substantial hip and groin symptoms that impacted on their daily life. The large improvement in the HAGOS symptoms sub score from 36% to 61% can be considered a real change as it is above the smallest detectable change (SDC) value at an individual level of 17.7 (95% CI 14.1–23.2) reported by Thorborg et al. (2011). Although Emara et al. (2011) reported a significant ($p<0.01$) improvement in the Harris Hip Score following conservative treatment for mild FAI comparison differences in outcome measure, follow up duration (24 months) and intervention programme (stretches, activity modification) makes comparison with the results from the current study difficult.

The short time period for the intervention for the current study (seven weeks) due to availability of both the participant and author, may have limited the possible change in score. A longer intervention could have led to greater changes, as a 10 week motor control intervention used in shoulder impingement patients by Worsley et al. (2013) reported a significant ($p<0.001$) reduction in the self-reported Shoulder Pain and Disability Index (SPADI). Additionally Thorborg et al. (2011) suggested large SDC values at the individual level are common findings concerning patient-reported questionnaires, indicating that patient-reported questionnaires can be problematic for use at the individual level.

7.4.3 HLLMS observational rating

There was a substantial change in number of observed criteria from 38 to 20 following the intervention (Table 7-3) though, this was mainly due to reduced number of criteria on both the left and right side for the SKB and SKB Rot, eight to zero and 10 to two respectively (Table 7-4). There was little change in the other five tests following the intervention. There are limited studies in the literature to compare the results of this study to. The substantial change in total score in this study appears to be a greater change than the mean pre-test (11.8, SD 1.8) to post test (13.3, SD 1.9) FMS scores reported by Kiesel et al. (2011) for linemen following a standardised seven week off season intervention.

Differences between the FMS and HLLMS in the number of tests and scoring make comparison of the results from this study with Kiesel et al. (2011) difficult. However, the use of a specific exercise programme designed to improve movement patterns used is this study may be more effective than the intervention used by Kiesel et al. (2011) which was mainly based on trigger point treatment, stretches and corrective exercises.

7.4.4 Kinematic validity of observational ratings

7.4.4.1 *SKB test*

The SKB test along with the SKB Rot test the majority of the criteria that the observational rating improved following the intervention (Table 7-4). Based on the results from the current study the kinematic validity to detect change for the observed movement fault of knee moving inwards cannot be supported. For example, right side medial knee displacement increased from 25.22mm (SD 13.29) pre-intervention to 30.45mm (SD 9.72) post intervention (Table 7-7). The increase in medial knee movement was in contrast to the change on observational rating from fault to no movement fault. The high variation as shown by the high SD reported, between the trials may have increased the difficulty in observing for a change from pre to post intervention. A high variation would mean a large change would be needed to identify a real change above the natural variability.

There were substantial differences in knee medial movement between peak for the whole trial (22.64mm) compared to the medial knee movement at maximum knee flexion which was generally lower (6.42mm) (Table 7-7). Ageberg et al. (2010) reported knee kinematics at peak knee flexion which may have underestimated the knee kinematics and suggests measurement of true maximum medial knee should be calculated from the whole trial. Additionally, all changes in medial knee movement kinematics were below the MDC determined from assessing between day kinematics in male students suggest a true change in movement had not occurred.

The results for knee medial knee kinematics suggest that the observational rating is actually observing for something different or the observational rating is not valid at detecting a change in movement. The criterion has been updated to 'Is there an increase in dynamic valgus from the start position?' which the change in valgus kinematics above the MDC suggest the observational rating may be valid in detecting a change on the left but the change in kinematics was below the MDC on the right. On the other hand, adduction of the hip and possible lateral movement of the pelvis may give the impression of medial knee movement (knee valgus) with the knee joint centre not moving medially. The movement pattern suggested above may have led to the lack of correlation between observed movement fault of medial knee movement and the knee kinematics. Further analysis of the thigh and pelvic kinematics relative to the observed ratings for dynamic knee valgus could be worth examining with future studies to identify if the appearance of medial knee movement is more related to thigh relative to pelvis movement than knee movement suggested above.

It was not possible to accurately measure the knee moving 2cm past the toes as there was no marker on the patella or toe to show this. However, measuring maximum knee flexion gives a measure of the consistency of the SKB manoeuvre. There was a substantial reduction in knee flexion from pre to post intervention on both the right and left side which was above the MDC suggesting a true change in movement had occurred. However, there was no change in the observational rating. It is not possible to state if the observational rating is valid at detecting a change or not as the exact kinematics of knee past the toes was not measured. Further work is needed to determine a possible knee flexion angle that correlates with knee past the toes. Furthermore, possibly of more importance is examining the effect of how much knee flexion is needed to detect movement faults. For example, if a participant flexes the knee to 30° they may have less criteria rated as fault compared to if they flex the knee beyond 50°. The results of the study Ageberg et al. (2010) give an indication of a possible minimum knee flexion angle with mean peak knee flexion angles reported of 44.6° (SE 2.2) and 41.9° (SE 1.9) for participants rated as knee over foot and knee medial to foot groups. It is difficult to measure the effect altered knee flexion had on the other kinematics reported from the present study, but future studies should try to reduce the variability in squat depth and investigate the effect of squat depth on movement criteria.

It is difficult to conclude if the observation of the pelvic hitch movement criterion is valid or not due to only a small change in the kinematics relative to a change from fault 4.4mm (SD 2.7) vs no fault 3.7mm (SD 2.2) on the right side.

The participant improved their observational rating for both the 'anterior pelvic tilt' and 'trunk flexion' from pre to post intervention. The improvement in observed movement was supported by substantial decrease in trunk flexion above the MDC suggesting the observational criterion is valid in detecting a change in movement (Table 7-8, Table 7-9). Similarly, anterior pelvic tilt rating improved with corresponding changes in kinematics above the MDC indicating the rating is valid in detecting change (Table 7-8, Table 7-9). The observed fault of trunk flexion and anterior pelvic tilt were the only two from the SKB, which were related with changes in the related kinematics. However, the decrease in anterior pelvic tilt and trunk flexion may be related to the decrease in knee flexion between pre and post intervention and further research is required.

7.4.4.2 *SKB Rot test*

All the observational ratings for the SKB Rot test improved from pre to post intervention, however only the 'Does the pelvis follow the trunk?' had corresponding changes in kinematics above the MDC on both the right and left. These results indicate the criterion is valid in detecting a change in movement. There are conflicting results between the right and left side for the validity to detect change of the observational rating of 'Does the trunk lean forwards?'. The high SD (4.7°) relative to the mean (8.9°) on the right side highlights potential variation between trials in movement patterns and a possible limitation of using the mean from three trials.

7.4.4.3 *Standing hip flexion test*

The exercise intervention appeared to have very little effect on the movement criteria from the standing hip flexion test with small changes in kinematics for all the criteria between pre and post intervention and only one rating changing (trunk extension on the left, no fault to fault). These results suggest the intervention may need adapting if it is to improve the movement patterns from the standing hip flexion test.

7.4.4.4 *Deep squat test*

There were no changes in the observational rating for the criterion that the kinematics were also assessed from the deep squat test (Table 7-10). The criterion ‘Does the pelvis tilt forwards (anteriorly)?’ appears to not have criterion validity as the mean peak excursion of the pelvis was >16° for both pre and post intervention but both rated as no fault. The criterion has been re-worded in the updated HLLMS to ‘Does the pelvis begin in, or move forwards (anteriorly)?’ which will require the kinematic criterion to be adjusted and assessed. However, further investigation is required to examine exactly what movement the raters are observing for as pure anterior pelvic tilt kinematics do not seem to correspond with the rating.

7.5 Limitations

The observational ratings may have been biased, as the rater (NB) designed and delivered the intervention. There is a large potential for the rater to score the participant as having less movement faults post intervention, as they were aware the participant had carried out an intervention to improve their movement control. It is not possible to state how much effect the lack of blinding had on the observational rating, but future studies should try to blind the rater. Rating of the HLLMS without the rater knowing if the participant had carried out any intervention would minimise rater bias.

The participant carried out several HLLMS and therefore the improvements seen in the rating and kinematics may have been due to a learning effect, the intervention or a combination of both. The use of a control group and examining the potential learning effect would allow the assessment of the true effect of the intervention.

7.6 Recommendations and future research

The bespoke intervention used in this case study showed potential to improve movement and reduce symptoms which warrants further investigation with a group of participants including a control group which could allow blinding of the raters. Adherence is key to effectiveness of an exercise intervention (Barengo et al., 2014) which may be reduced if the programme takes too long. Therefore, identification of key exercises which improve movement patterns for all the tests from the HLLMS is needed. Future research could examine the use of an evidence based standardised version of the exercise programme with larger groups of participants and investigate other outcomes of importance such as injury and performance.

7.7 Conclusions

The results of the hip and groin pain case study showed that the exercise intervention reduced the number of movement faults from the HLLMS from 38 to 20, which were mainly from the SKB and SKB Rot tests. Improvement in observational rating for some of the criteria such as the anterior pelvic tilt and trunk flexion from the SKB test corresponded to kinematic changes above the MDC suggested the observational rating was valid at detecting a change. However, some criterion such as the pelvic hitch from the SKB Rot test had improved observational rating which were not supported by the kinematics highlighting criterion than may not be valid. The increase in gluteus medius activation time suggested a neuromuscular adaptation following the exercise intervention but a more robust methodology needs to be developed. The exercise intervention led to an improvement in symptoms measured using the HAGOS, from 36% pre to 61% post intervention which was above the SDC. Further research with the updated criterion from the latest version of the HLLMS is required on a larger number of participants to investigate the potential of exercise interventions to change movement patterns.

Chapter 8: Validity of HLLMS observational ratings: detecting changes in movement following an exercise intervention

8.1 Introduction

Playing football may increase the risk of developing hip OA (Shepard et al., 2003). Movement patterns such as hip internal rotation and adduction may contribute to symptoms of FAI (Austin et al., 2008, Loudon and Reiman, 2014, Wall et al., 2013, Emara et al., 2011). Altered movement patterns of increased hip flexion and poor hip medial rotation control were reported in symptomatic academy footballers diagnosed with FAI, during a small knee bend movement control test (Botha et al., 2014). Additionally, participants with FAI demonstrated decreased squat depth and altered lumbar kinematics during the deep squat compared to healthy controls (Kivlan and Martin, 2012) . However, it is not possible to determine if abnormal movement patterns are the cause or effect but altering these patterns may be beneficial for joint health.

In an attempt to reduce injury through improving movement patterns in footballers, the Fédération Internationale de Football Association (FIFA) designed the FIFA 11+, a specific football injury prevention warm up programme. In a systematic review the FIFA 11+ was found to significantly reduce injury incidence (Barengo et al., 2014). To gain a greater understanding of how programmes such as the FIFA 11+, recently renamed the 11+ Programme', may reduce injury, measuring the change in movement patterns would be beneficial.

As described in earlier chapters (Chapter 1), the HLLMS was developed to identify poor movement patterns associated with FAI in young footballers (Botha et al., 2014, Botha, 2013). Section 1.1.4 of this thesis contains further detail on how movement patterns may be related to FAI. A fellow PhD student (NB) has developed a specific exercise programme to improve footballers' movement patterns. As part of the development of the HLLMS as a valid and reliable tool there is a need to examine its use as an outcome measure. Reliability of the HLLMS was examined in Chapter 4 and criterion validity examined against 3-D motion analysis in Chapter 6. Therefore, examining the ability to the observational rating tool to detect changes in movement control is necessary, i.e. sensitivity to change.

8.2 Aim of the chapter

The aims were to

1: Assess the sensitivity to change of the HLLMS in response to an exercise intervention.

2: Gain a greater understanding of how specific exercises may change movement patterns of the hip and lower limb.

8.2.1 Objectives

1: To examine the changes in the rating of movement criteria from four of the tests from the HLLMS following a 12-week exercise programme designed to improve movement patterns.

2: To examine the validity of the observational rating to detect changes in movement compared to the kinematic data in four of the tests from the HLLMS following a 12-week exercise programme.

8.3 Methodology

8.3.1 Ethics

Ethical approval was granted prior to data collection by the Faculty of Health Sciences, University of Southampton Ethics Committee (Ethics approval numbers 27322) to study male academy footballers.

8.3.2 Participant recruitment and characteristics

A sample of male football players from the South Central region, aged 15-19 years was recruited from football club academies. Further details of footballer recruitment and consent are outlined in section 3.2. The participants for the present study were a subset from the footballers recruited for the intervention study by Nadine Booysen (ethics number 16436).

A sample size of 19 was calculated based on a standardised effect size of 0.5 of the standard deviation, with a power of 0.8 and type 1 error of 0.2 using Stata v13.1 software. The sample size was calculated using the method above as no data were available for the expected differences from pre- to post-intervention. The sample was a reasonable size sample due to the early nature of the research. A final sample size of 21 was decided upon to allow for a 10% drop out rate from pre to post intervention.

Pre-intervention data were collected on 21 academy footballers. However, only seven of the players completed the post intervention testing (mean 17.6 years, range 16-18 years). The substantial drop out rate was mainly due to players leaving the academies and those that were still at the club being unwilling to re test in the laboratory. Additionally, following discussion with, Lee Peacock, the academy head coach, some players were not re-tested due to them not training with the academy so not completing the exercise programme.

8.3.3 Data collection

HLLMS data were collected using the methods outlined in Chapter 3. Participants carried out the HLLMS once pre-intervention and post the 12-week exercise intervention. All data collection including observational rating of the HLLMS was carried out by the present author, as described in section 3.3 and 3.4 of Chapter 3.

8.3.4 Exercise intervention

An exercise intervention programme to improve movement control (Appendix D1) was designed by fellow PhD student Nadine Booysen. This programme gained ethics approval (number 16436) from the Faculty of Health Sciences University of Southampton Ethics Committee. Participants completed the 10-15 minute programme prior to all training sessions and football matches. The programme was designed to improve the motor control of the participant’s lower limbs and lasted 12 weeks. The intervention was based on the 11+ programme with some hip motor control exercises added. The exercises were designed to improve strength, balance and neuromuscular control.

8.3.5 Data analysis

When comparing repeated measures of the kinematics pre and post intervention it is important to get an indication of the amount of change, minimal detectable change (MDC), needed to be confident that the change is due to the intervention and not measurement error (Davidson and Keating, 2014). The MDC for kinematics related to the movement criterion in the present chapter was calculated on the data from 11 male controls, and detailed in section 5.2.4 of Chapter 5.

8.4 Results

Data were analysed from seven participants from four of the tests, SKB, SKB Rot, standing hip flexion and deep squat from the HLLMS. The observational rating for 61 out of 203 ratings changed between the pre and post intervention with 46 of those due to the rating improving. Of the 46 rating that improved, 15 were above the MDC. From the 15 observational ratings that deteriorated, only two were above the MDC.

8.4.1 SKB test

Due to the lack of validity identified in Chapter 6 for medial knee displacement kinematics related to the criterion ‘Does the knee move inward from the 2nd toe?’ only knee valgus kinematics were analysed for the SKB test. Combining the left and right sides from the SKB test, there were 26 out of 70 ratings (right 13, left 13) that changed from pre and post intervention with nine (right 6, left 3) above the MDC (Table 8-1, Table 8-3).

The criterion of ‘Does the knee move inward from the 2nd toe?’ had the most changes in observational rating of all the criteria from the SKB test on the right (6) with three of those having changes in their kinematics greater than the MDC. Similarly, the criterion of trunk flexion had four observational ratings that changed with two of those with corresponding kinematics changes above the MDC. From the 13 observational ratings that changed, only two were for deterioration in rating which were from knee valgus, but the change in kinematics were below the MDC (Table 8-1).

Table 8-1: Right SKB test: changes from pre to post intervention of observational rating, pre minus post intervention kinematics related to each criterion and minimal detectable change (MDC) in academy footballers. Criteria shaded in grey remain unchanged in updated HLLMS.

		Participant							
		1	**2**	**3**	**4**	**5**	**6**	**7**	**>MDC /rating**
Peak knee valgus excursion	Pre – post kinematic change. MDC =4.5 (°)	3.4	0.4	3.5	6.2*	28.8*	26.8 *	-3.8	3/6Δ 0/1#
Does the knee move inward from the 2nd toe?	Rating change	-1	0	1	-1	-1	-1	1	
Peak pelvic lateral rotation excursion anti clockwise (right) clockwise (left)	Pre – post kinematic change MDC =3.1 (°)	-1.3	0.1	4.4*	3.2	-0.3	1.5	-2.3	1/2Δ 0/5#
Does the pelvis hitch/ drop?	Rating change	-1	0	-1	0	0	0	0	
Knee flexion peak excursion	Pre - post kinematic change MDC =4.9 (°)	23.2*	3.3	10.8*	5.4*	-0.3	-5.3*	13.0*	0/0Δ 5/7#
Does the knee fail to move 2cm past the toes?	Rating change	0	0	0	0	0	0	0	
Trunk flexion peak excursion	Pre - post kinematic change MDC =4.6 (°)	5.1*	4.5	4.2	6.1*	-1.7	1.4	8.7*	2/4Δ 1/3#
Does the trunk lean forwards?	Rating change	-1	-1	-1	0	0	0	-1	
Pelvic anterior rotation peak excursion	Pre – post kinematic change MDC =5.2 (°)	4.3	4.6	9.1*	11. 3*	-5.5*	-9.2*	8.7*	1/1Δ 4/6#
Does the pelvis tilt forwards?	Rating change	0	0	-1	0	0	0	0	

Rating change, 0= no change, -1 = fault to no fault, 1 = no fault to fault. *change in kinematics above MDC, Δ – number of participants whose ratings changed # - number of participants whose ratings did not change

The SKB test on the left had three criteria for which the change in rating corresponded with a change in the kinematics greater than the MDC, one for pelvic lateral rotation and two for anterior pelvic tilt. The anterior pelvic tilt was the criterion that had the largest number of participants whose observational rating changed (3) and corresponding kinematic changes were above the MDC (2). The criterion ‘Does the knee move inward from the 2nd toe?’ from the SKB test on the left had four participants with a change in rating but in contrast to the right side none had kinematics changes above the low MDC of 2.0° (Table 8-1, Table 8-3). The criterion ‘Does the pelvis tilt forwards?’ had five participants whose pelvic anterior rotation peak excursion changed above the MDC from pre to post intervention, although, only one had a corresponding change in their observational rating.

Table 8-2: Right SKB test: changes from pre to post intervention for the criterion ‘Does the trunk lean forwards?’ of observational rating and trunk flexion kinematics relative to the threshold for the seven academy footballers.

		Kinematics – changes relative to threshold		
		Improve	No change	Worse
Change in observational rating – pre to post intervention	Improve	4 (TP) [1]	0 (FP)	0 (FP)
	No change	1 (FN) [2]	2 (TN)	0 (FN)
	Worse	0 (FP)	0 (FP)	0 (TP)

TP = True Positive (kinematics change > threshold and observational rating change)
TN = True Negative (kinematics change < threshold and observational rating no change)
FP = False Positive (kinematics change < threshold and observational rating change)
FN = False Negative (kinematics change > threshold and no change in observational rating)
[1] - 2 participants had changes in kinematics > MDC
[2] – 1 participant had changes in kinematics > MDC

A threshold for trunk flexion kinematics from the SKB test on the right was calculated (Figure 6-5) and used to assess the validity to detect a change in the kinematics and compare to the change in observational rating (Table 8-2). Four participants had their observational rating improve and improvements in their kinematics relative to the threshold of 5°. Of those four, two had changes in their kinematics above the MDC. In contrast, one participant had no change in their observational rating, but an improvement in their trunk flexion pre to post intervention, which was also above the MDC.

Table 8-3: Left SKB test: changes from pre to post intervention of observational rating, pre minus post intervention kinematics related to the criterion and minimal detectable change (MDC) in academy footballers. Criteria shaded in grey remain unchanged in updated HLLMS.

		Participant							
		1	**2**	**3**	**4**	**5**	**6**	**7**	**>MDC/ rating**
Does the knee move inward from the 2nd toe?	Pre – post kinematic change MDC =2.0 (°)	0.0	-0.7	0.3	-0.5	-0.4	-0.4	2.1*	0/4Δ 1/3#
Peak knee valgus excursion	Rating change	-1	0	1	-1	-1	0	0	
Peak pelvic lateral rotation excursion anti clockwise (right) clockwise (left)	Pre – post kinematic change MDC =2.4 (°)	2.1	3.8*	3.7*	4.1*	2.3	1.4	0.3	1/3Δ 2/4#
Does the pelvis hitch/drop?	Rating change	-1	0	-1	0	0	0	-1	
Knee flexion peak excursion	Pre – post kinematic change MDC =5.4 (°)	18.7*	-3.1	4.9	3.0	-0.4	12.7*	6.3*	0/0Δ 3/7#
Does the knee fail to move 2cm past the toes?	Rating change	0	0	0	0	0	0	0	
Trunk flexion peak excursion	Pre – post kinematic change MDC =3.6 (°)	0.2	0.9	1.8	7.0*	-0.5	11.6*	7.7*	0/3Δ 3/4#
Does the trunk lean forwards?	Rating change	-1	-1	-1	0	0	0	0	
Pelvic anterior rotation	Pre – post kinematic change MDC =3.7 (°)	4.7*	8.2*	12.7*	13.4*	-3.4	1.8	3.5	2/3Δ 2/4#
Does the pelvis tilt forwards?	Pelvic anterior rotation peak excursion	-1	0	-1	0	0	1	0	

Rating change, 0= no change, -1 = fault to no fault, 1 = no fault to fault
*change in kinematics above MDC
Δ – number of participants whose ratings changed
- number of participants whose ratings did not change

8.4.2 SKB Rot

The SKB Rot test on the right had 10 out of 42 criteria where the ratings changed. The trunk flexion criterion was the only one that had a participant whose change in rating corresponded with a change in kinematics above the MDC (Table 8-4). On the right side 'Does the pelvis follow the trunk?' criterion had only one participant whose observational rating improved, but the change in kinematics was below the MDC of 8.5%. In contrast, of the six participant's whose rating did not change, three of them had changes in their percentage that trunk and pelvis rotation was in phase above the MDC of 8.5%.

Table 8-4: Right SKB Rot test: changes from pre to post intervention of observational rating, pre minus post intervention kinematics related to each criterion and minimal detectable change (MDC) in academy footballers. Criteria shaded in grey remain unchanged in updated HLLMS.

		Participant							
		1	**2**	**3**	**4**	**5**	**6**	**7**	**>MDC /rating**
Percentage trunk and pelvis in phase	Pre – post kinematic change MDC =8.5 (%)	-15.7*	-8.4	9.7*	-4.6	-2.2	10.0*	4.4	0/1Δ 3/6#
Does the pelvis follow the trunk?	Rating change	0	0	0	-1	0	0	0	
Pelvic anti clockwise rotation peak excursion	Pre – post kinematic change MDC =3.2 (°)	2.8	-1.9	5.0*	-3.9*	-0.3	3.7*	0.6	0/0Δ 3/7#
Does the pelvis hitch/drop?	Rating change	0	0	0	0	0	0	0	
Trunk flexion peak excursion	Pre – post kinematic change MDC =4.2 (°)	0.0	17.3*	2.8	-0.6	3.4	3.1	-0.5	1/3Δ 0/4#
Does the trunk lean forwards?	Rating change	1	-1	0	-1	0	0	0	

Rating change, 0= no change, -1 = fault to no fault, 1 = no fault to fault
*change in kinematics above MDC
Δ – number of participants whose ratings changed
- number of participants whose ratings did not change

The SKB Rot test on the left side had five criteria that changed from pre to post intervention but only one of them, trunk flexion for participant two, had a change in kinematics above the MDC (Table 8-5). Similar to the right side, the left side had three participants whose change in percentage trunk and pelvis in phase was above the MDC but no change in their observational rating (Table 8-5).

Table 8-5: Left SKB Rot test: changes from pre to post intervention of observational rating, pre minus post intervention kinematics related each criterion and minimal detectable change (MDC) in academy footballers. Criteria shaded in grey remain unchanged in updated HLLMS.

		Participant							
		1	**2**	**3**	**4**	**5**	**6**	**7**	**>MDC /rating**
Percentage trunk and pelvis in phase	Pre – post kinematic change MDC =8.0 (%)	-11.4*	-27.3*	-0.7	-2.3	-3.1	-11.9*	5.8	0/0Δ 3/7#
Does the pelvis follow the trunk?	Rating change	0	0	0	0	0	0	0	
Pelvic anti clockwise rotation peak excursion	Pre – post kinematic change MDC =3.3 (°)	-0.2	-1.3	-0.3	-1.1	-4.0*	-2.8	3.1	0/2Δ 1/5#
Does the pelvis hitch/drop?	Rating change	-1	0	-1	0	0	0	0	
Trunk flexion peak excursion	Pre – post kinematic change MDC =4.1 (°)	0.0	17.5*	1.7	0.6	2.7	0.4	0.7	1/1Δ 0/6#
Does the trunk lean forwards?	Rating change	0	-1	0	0	0	0	0	

Rating change, 0= no change, -1 = fault to no fault, 1 = no fault to fault
*change in kinematics above MDC
Δ – number of participants whose ratings changed
- number of participants whose ratings did not change

8.4.3 Standing hip flexion

The standing hip flexion test had 18 out of the 70 ratings that changed from pre to post with only five above the MDC (Table 8-6, Table 8-7). The standing hip flexion on the right had two criteria (pelvic posterior tilt and hip flexion) participant each whose each had 1 participant whose rating changed with corresponding changes in kinematics above the MDC (Table 8-6). The criterion ‘Does the hip fail to bend (flex) just beyond 90 degrees (approximate 110 degrees)?’ had six participants whose kinematics changed above the MDC, but only one of those had their observational rating change from pre to post intervention.

Table 8-6: Right standing hip flexion test: changes from pre to post intervention of observational rating, pre minus post intervention kinematics related to each criterion and minimal detectable change (MDC) in academy footballers. Criteria shaded in grey remain unchanged in updated HLLMS.

		Participant							>MDC /rating
		1	**2**	**3**	**4**	**5**	**6**	**7**	
Pelvic anti clockwise/ clockwise rotation peak excursion	Pre – post kinematic change MDC =3.0 (°)	1.4	-0.1	-1.7	3.5*	-2.4	3.3*	2.0	0/0Δ 2/7#
Does the pelvis drop (hitch)?	Rating change	0	0	0	0	0	0	0	
Peak pelvic posterior tilt excursion	Pre – post kinematic change MDC =3.6 (°)	7.9*	15.8*	-0.1	1.3	1.7	-0.6	-5.0*	1/1Δ 2/6#
Does the pelvis tilt backwards (posteriorly)?	Rating change	-1	0	0	0	0	0	0	
Peak hip flexion excursion	Pre – post kinematic change MDC =4.5 (°)	12.9*	13.8*	1.1	12.3*	-5.3*	-10.8*	4.6*	1/1Δ 5/6#
Does the hip fail to bend (flex) just beyond 90 degrees (approximate 110 degrees)?	Rating change	1	0	0	0	0	0	0	
Trunk extension peak excursion	Pre – post kinematic change MDC= 3.3 (°)	1.5	0.7	-0.3	-1.0	3.1	0.3	-8.0*	0/2Δ 1/5#
Does the trunk lean backwards (extend)?	Rating change	-1	0	0	0	0	-1	0	
Peak knee flexion excursion	Pre – post kinematic change MDC = 4.4 (°)	1.0	3.9	2.6	-0.6	-0.5	-2.1	-4.5*	0/2Δ 0/5#
Does the weight bearing knee bend (flex)?	Rating change	-1	0	0	0	0	0	-1	

Rating change, 0= no change, -1 = fault to no fault, 1 = no fault to fault
*change in kinematics above MDC. Δ – number of participants whose ratings changed
- number of participants whose ratings did not change

The standing hip flexion on the left was similar to the right, with the criterion 'Does the hip fail to bend (flex) just beyond 90 degrees (approximate 110 degrees)?' having both participants whose observational rating changed having a corresponding to kinematic changes above the MDC. For both the criteria 'Does the hip fail to bend (flex) just beyond 90 degrees (approximate 110 degrees)?' and 'Does the weight bearing knee bend (flex)?' had five participants whose rating did not change, but three of them had kinematic changes above the MDC. The criteria 'Does the trunk lean backwards (extend)?', 'Does the weight bearing knee bend (flex)?' and 'Does the pelvis tilt backwards (posteriorly)?' all had one participant whose observational rating changed with changes in kinematics above the MDC (Table 8-7).

Table 8-7: Left standing hip flexion test: changes from pre to post intervention of observational rating, pre minus post intervention kinematics related to each criterion and minimal detectable change (MDC) in academy footballers. Criteria shaded in grey remain unchanged in updated HLLMS.

		Participant							>MDC /rating
		1	**2**	**3**	**4**	**5**	**6**	**7**	
Pelvic anti clockwise/ clockwise rotation peak excursion	Pre – post kinematic change MDC =2.9 (°)	-0.1	3.2*	-3.0*	0.0	-1.6	3.5*	-2.2	0/1Δ 3/6#
Does the pelvis drop (hitch)?	Rating change	0	0	0	0	-1	0	0	
Peak pelvic posterior tilt excursion	Pre – post kinematic change MDC =5.2 (°)	13.1*	9.6*	-0.7	-1.1	-2.6	0.6	2.1	1/3Δ 1/4#
Does the pelvis tilt backwards (posteriorly)?	Rating change	-1	0	-1	0	1	0	0	
Peak hip flexion excursion	Pre – post kinematic change MDC= 4.9 (°)	16.0*	-1.4	10.0*	3.8	-9.0*	-8.4*	23.6*	2/2Δ 3/5#
Does the hip fail to bend (flex) just beyond 90 degrees (approximate 110 degrees)?	Rating change	1	0	0	0	-1	0	0	
Trunk extension peak excursion	Pre – post kinematic change MDC =2.9 (°)	4.5*	-0.5	-2.2	-2.8	-3.0*	-0.1	-6.7*	1/3Δ 1/4#
Does the trunk lean backwards (extend)?	Rating change	0	0	1	0	-1	0	1	
Peak knee flexion excursion	Pre – post kinematic change MDC =4.5 (°)	3.2	4.0	7.4*	-1.9	-6.9*	4.7*	4.9*	1/2Δ 3/5#
Does the weight bearing knee bend (flex)?	Rating change	-1	0	0	0	0	0	-1	

Rating change, 0= no change, -1 = fault to no fault, 1 = no fault to fault
*change in kinematics above MDC
Δ – number of participants whose ratings changed
- number of participants whose ratings did not change

8.4.4 Deep squat

There were six out of the possible 21 observational ratings that changed from the deep squat test, with five of those having changes in the kinematics above the MDC. From the 15 observational ratings that did not change, just under half of them (7) had corresponding changes in their kinematics above the MDC (Table 8-8).

Table 8-8: Left deep squat test: changes from pre to post intervention of observational rating, pre minus post intervention kinematics related to each criterion and minimal detectable change (MDC) in academy footballers. Criteria shaded in grey remain unchanged in updated HLLMS.

		Participant 1	2	3	4	5	6	7	>MDC /rating
Difference between tibia and trunk at peak femur flexion	Pre – post kinematic change MDC =6.5 (°)	20.8*	-6.6*	9.1*	-4.4	-5.5	8.0*	3.8	2/2Δ 2/5#
Does the trunk fail to stay parallel with the shin (tibia)?	Rating change	1	0	1	0	0	0	0	
Peak excursion of femur flexion	Pre – post kinematic change MDC =7.6 (°)	-10.9*	-0.3	-12.5*	-1.1	-19.3*	11.9*	0.1	1/1Δ 3/6#
Does the thigh (femur) fail to be horizontal with the floor?	Rating change	0	0	0	0	-1	0	0	
Peak pelvic anterior tilt excursion	Pre – post kinematic change MDC =5.0 (°)	3.2	-2.3	3.4	6.3*	-0.5	6.9*	5.3*	1/3Δ 2/4#
Does the pelvis tilt forwards (anteriorly)?	Rating change	-1	0	-1	0	0	1	0	

Rating change, 0= no change, -1 = fault to no fault, 1 = no fault to fault
*change in kinematics above MDC
Δ – number of participants whose ratings changed
- number of participants whose ratings did not change

8.5 Discussion

In the development of the HLLMS as a valid tool, the ability to accurately detect change in movement patterns using observational rating is important. Criterion validity of the HMLLS as tested against the gold standard of 3D motion analysis was considered in Chapter 6 and was further tested in this experiment, by comparing changes in observational ratings and kinematic data.

The results of the present study suggest that the exercise intervention influenced the movement patterns from the SKB, SKB Rot, standing hip flexion and deep squat tests from the HLLMS, with just over a quarter of the observational ratings changing. From the 61 observational ratings that changed 17 had corresponding kinematics changes above the MDC, indicating that a true change in the movement patterns occurred above the measurement error. Some of the participants had changes in the kinematic above the MDC but no change in their rating possibly indicating that a more refined rating scale other than just fault or no fault may be needed. The sensitivity to detect change validity of the individual criteria from each test will be considered below. There is variation in movement patterns between participants, which may mask some changes if the mean value of the group is considered. Along with the low numbers of participants in this chapter, the discussion below will consider individual cases.

8.5.1 SKB test

The first test to be considered is SKB as the results of the present study showed it had the largest proportion of the overall observational ratings that changed (26/61) and largest number above the MDC (9/17). These results indicate that the intervention had the greatest influence on the movement criteria from the SKB test. Additionally, the SKB manoeuvre is commonly used to assess movement control and studied in the literature (Whatman et al., 2015, Ageberg et al., 2010, Maclachlan et al., 2015).

The validity to detect the change in knee valgus using the HLLMS could be considered important as excessive medial knee displacement presenting as knee valgus is seen as suboptimal and related to injury (Mauntel et al., 2014, Whatman et al., 2015). Considering the individual criteria from the SKB test, knee valgus had the largest number of observational rating changes (10) but only the right side had corresponding changes in the kinematics above the MDC for 3/6 ratings that changed compared to 0/4 for the left side. (Table 8-1, Table 8-3). The low changes in kinematics on the left side of those whose rating changed (<0.5 °) suggest there was no a change in the knee valgus movement. The future use of video recording of the HLLMS would allow a review of the ratings to identify if the lack of change in kinematics on the left side was due to errors in rating or how the kinematics were measured.

As far as the author is aware there are no studies that have looked at validating the observational rating of knee valgus from the SKB to detect changes from pre to post intervention. Studies have showed that knee valgus can be reduced significantly during SKB type movements following an exercise intervention, but they did not examine the change in observational rating (Dawson and Herrington, 2015, Olson et al., 2011). Additionally, the measurement of knee valgus was carried out using a video camera, which means comparison with the results from the present study using 3D motion analysis are limited (Dawson and Herrington, 2015, Olson et al., 2011).

Despite improvements in the observational rating of knee valgus and corresponding changes in kinematics above the MDC on the right there were none on the left. Participants that improved their rating for knee valgus on the left all had changes below the MDC despite its low value compared to the right (left = 2.0°, right = 4.5°). Comparing the low changes in knee valgus kinematics on the left compared to the right from the present study to the literature is limited by some authors only reporting dominant leg (Dawson and Herrington, 2015, Olson et al., 2011). In contrast to the results from the present study Herrington (2010) reported similar changes in right and left knee valgus kinematics following a four week intervention (left reduced by 9.8°, $p = 0.002$; right reduced by 12.3°, $p = 0.0001$). However, substantial differences between Herrington (2010) and the present study including their use of jump movements, females, and video footage to measure knee valgus limit ability to compare the results to the present study. It may be possible that the footballers had better movement control on their left leg as most would use it as their standing leg. Increased control on their left leg may have resulted in lower knee valgus values pre-intervention and less potential to improve post intervention. However, leg dominance was not recorded in the present study. There are several possible causes for the lack of change in knee valgus kinematics relative to the observational rating such as the lack of direct comparison as the kinematics were calculated as a mean of three trials whereas the rating was probably only from one trial. The lack of change in kinematics relative to the observational rating for knee valgus of the left side in the present study warrants further investigation and possibly that right and left, or dominant and non-dominant might need to be considered separately.

When combining the results from the right and left sides for the observational rating for ‘Does the pelvis hitch/drop?’ criterion appears to have both sensitivity to change and criterion validity. Two out of the 5 participants’ whose ratings improved had corresponding changes in the kinematics above the MDC, indicating both sensitivity to change and criterion validity of the movement screen against objective measurement. Also, there were no changes in ratings with changes in the kinematics above the MDC that contradicted the ratings. Similarly, the criterion 'Does the pelvis tilt forwards?' had three out of the four participants whose changes in the rating had concurrent changes in the kinematics above the MDC. Despite there being some large changes in the kinematics above the MDC with the rating remaining as a fault, kinematic values suggest that the participants still had a large amount of anterior pelvic tilt, so the rating was valid. These results highlight that a cut off for how much anterior pelvic tilt is considered a fault would allow further analysis of the ability of the observational rating to detect a change rather than just consider the change relative to the MDC. Furthermore, there may be a case for possibly having a major and minor fault rating so that more subtle changes in movement would be detected by the observational rating which may be clinically important.

The above criteria, knee moving inwards, pelvic hitch and anterior tilt have been re-worded in the updated HLLMS, so the validity of the rating to detect change will need to be re-assessed. The criteria considered below remain unchanged in the updated HLLMS. 'Does the knee fail to move 2cm past the toes?' had no changes in the rating therefore it is not possible to state if it is sensitive or not to detecting changes. 'Does the trunk lean forwards?' appears to be sensitive to change on the right side, with two participants (out of four) improving their rating and kinematics above the MDC and the two others with changes in their kinematics just below the MDC. On the left three participants improved their rating but none had changes above the MDC. The three participants had low pre-intervention mean trunk flexion ranging from 2.8° to 4.3° suggesting they may have had a fault rated incorrectly. However, the large SDs relative to the means, particularly for Participant 3 (mean 3.4° SD 3.58) indicating there were large variations in the kinematics between the trials, which could have led to variation in the rating depending on which trial was rated. These results highlight a potential limitation of not directly comparing the kinematics of each trial with a rating. The large reduction in the trunk flexion of Participant 6 on the left of 11.6° suggests that their rating should have changed. However, their post intervention rating appears correct as they still had a relatively high mean of 7.38° (SD 0.92). Without a set cut off it is not possible to state if Participant 6 should have been rated no fault post intervention, however compared to other participants who rated as no fault the rating is correct and therefore the observational rating is valid (in terms of criterion validity).

Throughout the tests, there were multiple participants whose ratings did not change, but their change in kinematics were above the MDC, suggesting the HLLMS may not be sensitive enough to detect a change in movement. However, it may have been that a participant had substantially less trunk flexion from pre to post intervention, but still flexed their trunk so rated as fault for 'Does the trunk lean forwards?'. The use of a kinematic threshold may be more appropriate method to assess the validity of the observational rating to detect change. Using a kinematic threshold for trunk flexion for the SKB test on the right (Table 8-2) six out of the seven participants' had observational ratings that corresponded to their kinematics. Four participants had corresponding improvements in both their observational rating and kinematics relative to the threshold. Of the four, two had changes above the MDC and two just below the MDC, suggesting a true change in kinematics occurred, above the measurement error. In contrast, one participant improved their trunk flexion beyond the kinematics threshold and above the MDC, but their observational rating did not change. These results suggest there may have been an error in the observational rating, although there was no video footage taken to check the rating. However, cation needs to be applied when using the threshold for trunk flexion above, in that it was calculated on a small number of participants, the mean of three trials were used without knowing if all three were rated the same, as the observational rating for a specific movement fault was only done from one trial.

8.5.2 SKB Rot test

The SKB Rot test had a relatively low number of observational ratings that changed (7/42) which limits the ability to assess the ability of the HLLMS to detect change during this test. The criterion 'Does the pelvis follow the trunk?' may not have criterion validity and thus not sensitive to change. The criterion may not be valid to detecting a change as there were large changes in the kinematics of participants that had no change in their rating on both the right and left side (range -27.3% to 10.0%). It is difficult to state if the criterion if valid at detecting a change as only one participants rating change. However, the kinematic parameters used to assess the validity of the rating, percentage that the trunk and pelvis are in phase may be too sensitive. Utilising appropriate kinematic criteria to validate an observational rating was highlighted by the results of Onate et al. (2010) who scored all 19 participants as having the trunk lateral flexion fault with a very low mean of 1.0 ±0.8cm lateral trunk flexion movement. The low values reported by Onate et al. (2010) suggests that the criterion may be too responsive as it would have probably been impossible for a participant to maintain perfect vertical alignment and subsequently be rated as not having lateral trunk flexion. Similarly, the analysis of pelvic rotation kinematics may be too precise to assess the validity for the criterion 'Does the pelvis follow the trunk?' For example, a fraction of a degree of rotation of the pelvis in the same direction as the trunk would be included in the total percentage of time that the pelvis and trunk are in phase (a fault kinematically) but it would be unlikely to be detected by observational rating. Therefore, the kinematics to assess the validity of the trunk and pelvic rotation criterion may be too precise and not an appropriate measure. Potentially, a more appropriate kinematic criterion may be assessing peak axial rotation in both directions to better match what the rater is looking for. For example, a participant rated as no fault may have lower pelvic axial rotation compared to those rated as having a fault.

The other criterion that remains unchanged in the updated HLLMS, along with the pelvis following the trunk, is 'Does the trunk lean forwards?'. Combining the results from the right and left sides there were four ratings that changed with two of those above the MDC suggesting the criterion may be valid in detecting change. Initial review of the criterion suggests that it may be valid as Participant 2 improved their rating with large reductions in their trunk flexion peak excursion kinematics (right 17.3 °, left 17.5°) considerably above the MDC's (right 4.2°, left 4.1°). However, as previously discussed, there are limitations in using the mean kinematics from three trials to validate the observational rating which is likely to be assessed from only one of the trials. The was underlined by the results of Participant 1 on the right side whose rating deteriorated from pre to post intervention with no change in their kinematics (pre-intervention mean 6.5° SD 8.7; post intervention mean 6.5° SD 5.1). However, there was a considerable variation in the pre-intervention kinematics from 16.4° for trial one to 0.0° for trial three. The no fault rating for pre-intervention was likely due to trial three being rated as the lateral view used to rate trunk flexion occurred after rating the anterior views. These results do not necessarily indicate that the observational rating is not valid but highlight that there may be substantial variation between the trails and hence the importance to use an appropriate kinematic measure.

In contrast to the criteria discussed above the criterion 'Does the pelvis hitch/drop?' has been re-worded in the updated HLLMS to 'Does the pelvis stay level?' Furthermore, it is not possible from the present data to state with any certainly whether this criterion is sensitive to detecting a change, as only two participants' ratings changed, both below the MDC.

8.5.3 Standing hip flexion test

There were three criteria that remained unchanged in the updated HLLMS and these will be considered first. The criterion 'Does the hip fail to bend (flex) just beyond 90 degrees (approximate 110 degrees)?' initially appears to have the ability to detect change and to be valid as all three ratings on the right and left side that changed had kinematic changes above the

MDC. However, it may be more precise to validate the observational rating to detect a change by using a cut off value to reflect what the criterion is assessing. For example, the results of Participant 5 on the left suggest the change in observational rating is validated by the kinematics. However, this criterion was rated as having a fault pre-intervention with a mean of 109.7° (SD 2.1) of peak femur flexion excursion which contrasts with Participant 7 who rated as no fault with a mean femur flexion of 91.0° (SD 12.45) post intervention. These results suggest that there are limitations with using just the change in kinematics to validate the observational rating. Setting a kinematic cut off value of, for example, 100° of femur flexion may be a more accurate method of assessing the validity of the observational rating to detect change in movement.

The criterion 'Does the trunk lean backwards (extend)?' has contrasting results regarding the validity to detect change. One participant's results suggest the criterion is valid with kinematic changes above the MDC supporting the change in rating. However, in contrast two participants had increases in trunk extension above the MDC's (Participant 7 on right 8.0° and Participant 5 on the left 3.0°) but both were rated as no fault post intervention. Both participants had relatively large mean trunk extension (12.5°, SD 2.4; 10.53°, SD 1.71) post intervention, suggesting their observational rating was incorrect. The relatively small ranges of trunk extension and the results above suggest that further work is needed to improve the validity of the trunk extension criterion to detect change.

The kinematics for the criterion 'Does the weight bearing knee bend (flex)?' suggest it is not valid in detecting change due to two participants' kinematic changes above MDC which were in the opposite direction to the changes in observational rating. Furthermore, the large SD compared to the mean for Participant 7 on the right pre-intervention (3.5°, SD 6.0) again highlight a large variation in the kinematics between trials and potential limitations in using a mean of three trials to compare to the observational rating. With relatively small ranges of knee flexion, using the peak excursion from when the non-weight bearing hip angular velocity is >10% of maximum angular velocity may have limitations. For example, a participant may start in slight knee flexion before they move and not increase their knee flexion, so possibly rating as a fault but their peak knee excursion from the start point is minimal. Changing the kinematic criterion to peak knee flexion may be more appropriate to validate the observational rating as currently the observational rating is not valid in detecting changes.

The next two criteria to be considered 'Does the pelvis tilt backwards (posteriorly)?' and 'Does the pelvis drop (hitch)?' have been updated in the latest HLLMS. It is not possible to state if the pelvic drop criterion is valid in detecting a change in kinematics as only one participant rating changed with the change in kinematics below the MDC (Participant 5 on the left). The criterion of posterior pelvic tilt appears valid as two out of the four participants whose rating changed had corresponding changes in the kinematics above the MDC. Despite the large decrease in Participant 2's posterior pelvic tilt of 15.8° with no change in rating, they still had a substantial mean of 7.8° of peak posterior pelvic tilt excursion post intervention, which suggests the fault rating was correct. However, further study is needed with larger numbers of participants.

8.5.4 Deep squat test

The deep squat test only had six out of the 21 possible ratings that changed from pre to post intervention, which limits the ability to judge if the change in observational rating is valid. The results for the criterion 'Does the trunk fail to stay parallel with the shin (tibia)?' indicate that it is not valid due to the two ratings that changed having contradicting changes in their kinematics, which were above the MDC. The lack of validity is also supported by several participants being rated as having a fault with mean differences between trunk and tibia angles of less than 10° but other participants with between 12° and 25° being rated as no fault. The lack of validity of the ratings may be due to the difficulty of judging the relationship between two moving segments.

The criterion 'Does the thigh (femur) fail to be horizontal with the floor?' appears to be valid in regard to the ability to detect change as three ratings changed, and all kinematic changes were above the MDC. However, the kinematic criterion of peak excursion of femur flexion may be limited in assessing the criterion which rates the femur being parallel with the floor. A more applicable kinematic criterion may be setting a cut off by getting an agreement from raters on fault and no fault from video footage and obtaining the femur angles from the corresponding 3D motion analysis data.

The previous two criteria remain unchanged in the updated HLLMS but 'Does the pelvis tilt forwards (anteriorly)?' has been reworded to 'Does the pelvis start in or tilt forwards (anteriorly)?'. The only rating that changed with a kinematic change above the MDC was for Participant 5 whose change in kinematics were contrary to the change in rating, suggesting the criterion in not valid (although this could not be concluded from one observation). The cause of this appears to be an incorrect pre-intervention rating of no fault even though they had the highest mean anterior pelvic tilt (47.2°, SD 0.8) of all the participants, some of whom were rated as fault. Another potential limitation with the validity of criterion which was discussed in section 6.4.4 of Chapter 6, is the high values of anterior pelvic tilt suggesting that all participants should be rated fault. The results indicate the need to identify what the raters are looking for and adapt the kinematics criteria to analyse this as well as ensuring they correspond to the latest wording in the updated HLLMS.

8.6 Limitations

There needs to be some caution in the use of the kinematic MDC as it was calculated on a different, small sample of control participants who may have had differing levels of consistency in their movement compared to the footballers. Also, the MDC was calculated by re testing within a week which could be different to the consistency of movement patterns of the footballers over a 12-week period. At present it is not possible to state if the MDC used in the present study underestimated or overestimated the measurement error for the footballer's pre to post intervention. Despite this limitation, the MDC gives an estimation of the measurement error to assess if a true change in movement has occurred.

Another possible limitation of the study was the lack of blinding of the rater. The rater knew that all participants had carried out the intervention which could have led to a biased rating. However, it would have been unlikely that the rater would have been able to remember the scores of each criterion with at least 12 weeks between ratings.

As discussed previously there is a potentially large limitation in comparing the mean kinematics calculated from three trials to the observational rating which probably was only assessed on one trial. Large variation in the kinematics between trials has been demonstrated for some of the criteria, suggesting that depending on which trial was rated could affected the rating. Therefore, there is a need to directly compare the rating and kinematics for individual trials. This could not be tested through retro- analysis of the present data, as the observational ratings were each made during one of three trials and it is not known which rating was made during which trail.

8.7 Recommendations and future research

There may have been some errors in the assessment of the criteria from the HLLMS due to the rater having to co-ordinate both the laboratory data collection and carry out the observational ratings. Having two researchers, to enable the rater to solely focus on the scoring the HLLMS may improve the accuracy in future studies.

To obtain a more accurate indication of the MDC, future studies should look at using a control group to compare to the intervention group. In addition, having a control group would allow the potential to blind the rater as to whether participants had carried out an intervention or not, reducing the potential bias in the observational ratings.

As explained, the latest version of the HLLMS (Appendix J) has had some of the criteria changed from the version used in the present study, which need to be studied to assess their validity. For some of the criteria, calculating a cut off value rather than just assessing the change in kinematics may be a more accurate way to validate the observational rating. Obtaining the kinematics for trials where an agreement is reached amongst several raters on whether they are rated as a fault or no fault could be used to identify a cut off. For example a receiver operating curve (ROC) was been used by Ageberg et al. (2010) to provide a cut off value to discriminate between those rated as having or not having medial knee movement related to their knee valgus in 2-D.

Participant recruitment was a limitation of the present study. A possible cause of this may be due to some of the players having to travel over an hour to get to the motion analysis laboratory at the university, even though local football clubs were chosen, as they had wide catchment areas. Players would often not have their own transport which would make travel to the laboratory difficult and potentially costly with no funding available to reimburse the participants. To try and improve recruitment of participants, future studies should either consider setting up a mobile motion analysis laboratory at the club or if that was not possible, obtain funding to enable participants to travel.

Future research

I. Update kinematic criterion for the criterion that have been changed in the latest HLLMS (Appendix J) and examine their criterion validity.
II. Review all kinematic criterion for observational criterion that remain unchanged in the updated HLLMS in particular.
    a. ‘Does the pelvis follow the trunk?’ peak pelvic axial rotation in both directions?
    b. ‘Does the weight bearing knee bend (flex)?’ peak knee flexion?
III. Review and possible revision of the ‘Does the trunk fail to stay parallel with the shin (tibia)?’ and to ‘Does the pelvis start in or tilt forwards (anteriorly)?’ from the deep squat test due to poor criterion validity between the rating and kinematics.
IV. Further investigation to determine if there is a difference in peak knee valgus movement between the left and right sides.
V. Compare the observational rating and kinematics directly for each trial.

VI. Examine to potential to determine cut off for if the amount of movement is considered a fault or not especially for the criterion that are a bench mark for example peak hip flexion from the standing hip flexion test.

VII. Consider the potential use of major or minor fault classifications with criterion that have large amounts of movement so that the HLLMS can detect more subtle changes in movement patterns.

VIII. Development of a methodology to explore the relationship between movement patterns from the HLLMS and muscle onset timings using EMG.

8.8 Conclusions

The intervention had the greatest influence on the ratings from the SKB test with 26 ratings changing out of the 61 in total. In contrast the SKB Rot test only had seven ratings that changed, meaning it is difficult to assess the validity to detect change of the observational ratings. The criteria ‘Does the knee move inward from the 2nd toe?’ and ‘Does the pelvis tilt forwards?’ from the SKB test appear to be valid in detecting a change in movement. Similar to criteria from other tests it was difficult to assess the validity to detect change for ‘Does the pelvis hitch/drop?’ even though some of the ratings changed with kinematics changes above the MDC, as there were only a few ratings that changed. It was not possible to assess some of the criteria’s validity to detect change as there was no change in their rating. The limitation of not directly comparing the observational rating to the kinematics was highlighted by some criteria having large variations in the kinematics between the trials which may have led to variation in the observational rating depending on which trial was rated. Additionally, some of the kinematic criteria may not have accurately reflected what the rater was observing. For example, all of the participants from the deep squat test had substantial amounts of anterior pelvic tilt but some were rated as no fault for ‘Does the pelvis tilt forwards (anteriorly)?’.

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Chapter 9: **General Discussion**

There have been a high rate of hip and groin injuries which have been potentially linked to the high rates of OA reported in ex professional footballers (Klünder et al., 1980, Shepard et al., 2003). Furthermore, development of hip OA in footballers is associated with FAI (Sankar et al., 2013, Loudon and Reiman, 2014) and there is a link between abnormal movement and FAI which was detailed in section 1.1.4.1 (Austin et al., 2008, Emara et al., 2011, Loudon and Reiman, 2014). Movement screens are widely used in football (Rusling et al., 2015) and their use is increasing (Whatman et al., 2011, Frohm et al., 2012). However, there is a lack of research on the validity of movement screens to support their use as a robust tool (Whatman et al., 2015). As discussed in Chapter 2 (section 1.1.5), the most widely used screen is the FMS but there may be no justification to use it due to a poor ability to detect injury (Rusling et al., 2015). There has been some research showing good reliability of the observational rating of movement control (see section 2.3.2) but is limited by using the composite score from the FMS (Teyhen et al., 2012, Shultz et al., 2013) and only rating a single criterion mainly using a SKB type movement (Whatman et al., 2015, Ageberg et al., 2010). However, as outlined in section 2.2 there has been little research on the criterion validity of the observational rating assessed against an objective comparison, such as 3D motion analysis. In particular the assessment of the criterion validity for rating multiple criteria of various body segments such as the hip, pelvis and trunk that are commonly analysed in movement screens (Frohm et al., 2012, Mottram and Comerford, 2008, Mischiati et al., 2015). Existing tools were found to be lacking focus on control of hip movement, which affects other joints in the kinetic chain, so the HLLMS was developed (Botha, 2013). As the HLLMS is a relatively new tool, its reliability and validity need to be established during its development, which formed the topic of the present thesis.

The results of this thesis have found some of the criteria from the HLLMS to be reliable and valid, and identified others that further work is needed to improve their reliability and or validity to support their inclusion. This chapter will outline which criteria appear from each test that are valid and reliable and ones that further work is required or possibly should be removed from the HLLMS. A summary of the validity and reliability results from the SKB, SKB Rot, standing hip flexion and deep squat are shown in Table 9-1, which illustrates which tests and criteria were the most robust and those that require further study. Research implications from the findings from this thesis for the movement screening field are detailed in section 9.9, later in this chapter. Some of the criteria had excellent rater agreement but not have criterion validity, highlights the need to assess validity and reliability. The variation in kinematics between trials for some of the criteria highlight the need to directly compare observational rating to the kinematics for each trial and assesses the rating consistency over the trials. Furthermore, poor live rater agreement may have due to the variation in movement between each trial as raters assessed different trials or indicate there is a need for clarification of what constitutes a fault through rating training using images and video footage.

Table 9-1: Summary of the validity and reliability results for the criteria from the SKB, SKB Rot, standing hip flexion and deep squat tests from the HLLMS. Criteria shaded in grey remain unchanged in the latest version of the HLLMS.

		Validity		Observational reliability – right and left mean AC1>0.8			Kinematic Reliability – ICC and CMC > 0.75	
Test	Criterion	p<0.05 difference fault vs no fault kinematics	Detect change	Intra–rater video	Intra-rater between day	Inter-rater footballers	Within session	Between day
SKB	Knee move inwards		✓ Valgus				✓ Valgus	
	Pelvic hitch		✓	✓	✓	✓		
	Knee flexion		¥	✓	✓	✓	✓	✓
	Trunk flexion	✓		✓			✓	✓
	Anterior pelvic tilt	✓	✓			✓	✓	
SKB Rot	Pelvis follow trunk	✓		✓	✓			
	Pelvic hitch			✓			✓	
	Trunk flexion	✓		✓			✓	✓
Standing hip flexion	Pelvic hitch			✓	✓		✓	✓
	Posterior pelvic tilt		✓	✓	✓	✓	✓	✓
	Hip flexion			✓	✓	✓		
	Trunk extension						✓	✓
	WB knee flex	✓						
Deep squat	Trunk parallel tibia			✓			✓	
	Femur horizontal	✓		✓			✓	
	Anterior pelvic tilt						✓	✓

Valgus = knee valgus kinematics, ¥ - not possible to assess due to no ratings changing,

9.1 SKB Test

The results summarised in Table 9-1 suggest that of the two criteria that remain unchanged in updated HLLMS (Appendix J) 'Does the knee fail to move 2cm past the toes?' and 'Does the trunk lean forwards?' have criterion validity and are reliable. Regarding the trunk lean forwards the decrease in trunk flexion above the MDC with corresponding improvement in rating from the hip and groin pain case study, support the validity of the criterion (Table 7-7). For the criterion of knee past the toes, there were no significant differences in fault vs no fault kinematics which was possibly due to the lack of participants rated as having a fault (2 on the right and none on the left) rather than the criterion validity of the observational rating. Additionally, the criterion is more of a bench mark than being assessed for movement control. Clarification of the trunk flexion criterion through training of the rater should lead to improved inter-rater. Also, intra-rater between day agreement could be improved with training, as it had good between day kinematic reliability suggesting the rating rather than changes in movement patterns led to the poor between day rater agreement.

The criteria that have been changed in the updated HLLMS (Appendix J) will be considered next. 'Does the knee move inward from the 2nd toe?' has been reworded to 'Is there an increase in dynamic valgus from the start position?' The rewording of the criterion and training of raters should improve the reliability of the observational rating, as from discussions with the other raters who took part in studies within this thesis, there were differences in what was being looked for. However, in relation to the validity of the difference in kinematics between fault and no fault there were contrasting results between the right and left sides. For example, the non-significant difference in the peak excursion kinematics for fault vs no fault rating on the left side was possibly due to the low knee valgus values on the left side (Table 6-1). As discussed in section 6.4.1 of Chapter 6, it is not clear from the research if there is a difference between left and right movement, but research suggests that knee valgus is valid (Ageberg et al., 2010). A potential alternative to knee valgus kinematics to analyse the knee valgus criterion Barker-Davis (2018) used hip abduction kinematics to assess their criterion of Does the knee move inwards from 2nd toe?'. The authors reasoned that using the hip adduction was easier to interpret than the low values for knee valgus (Barker-Davies et al., 2018). Further study using the update dynamic knee valgus criterion and possibly comparing to both knee valgus and hip adduction kinematics warrants investigation especially if low values for left knee valgus are found similar to the results from this thesis.

The criterion 'Does the pelvis tilt forwards?' and 'Does the pelvis hitch/drop?' have been updated to 'Does the pelvis fail to stay level?' and 'Does the pelvis begin in, or tilt forwards?' These changes in the criteria were aimed at improving the reliability of the observational rating. A lack of validity for the observational rating of pelvic hitch may be due to the low peak excursion values (<3.3°, Table 6-1). To assess the kinematics relative to the reworded criterion, the use of the difference between peak lateral rotation in both directions rather than peak excursion in one direction of lateral tilt could be assessed, which would likely lead to increased kinematic values. In contrast to the pelvic hitch, the anterior pelvic tilt had good criterion validity and validity to detect change from both the footballers and hip and groin case study (Table 7-7). Rewording of the anterior pelvic tilt criterion may lead to increased rater agreement which was not reliable in the present study. However, for both the pelvic hitch and anterior tilt, the combined effect of the reworded criteria on the observational rating and kinematics needs to be examined.

9.2 SKB Rotation test

The criterion 'Does the trunk rotate less than 30°?' is more of a benchmark to ensure the participant moves enough to test their movement control. Furthermore, there are substantial limitations in trying to assess the validity and reliability, as almost all the participants were rated as having no fault. Therefore, similar to the knee flexion criterion from the SKB test at present the results from this thesis support the inclusion of the criterion in the updated HLLMS.

The validity and reliability results from the two other criteria that remain unchanged in the updated HLLMS (Appendix J) 'Does the pelvis follow the trunk?' and 'Does the trunk lean forwards?' support their inclusion in the screen. The results in the thesis for the trunk flexion criterion from the SKB Rot test are similar to the SKB results. Although the criterion for the trunk following the pelvis had good validity and observational reliability, the ICC and CMC values for between day kinematic reliability suggest they were not reliable. However, the ICC values for between day kinematics were just below the 0.75 cut off (ICC = 0.73) and CMC values were above 0.75 (Table 5-6). The results from Table 9-1 suggest the within session kinematics were also not reliable, although this was due to CMC values for trunk and pelvic kinematics being just below the 0.75 cut off (CMC = 0.63 and 0.73, Table 5-2). The kinematic results outlined above for the pelvis following the trunk criterion indicate overall good kinematic reliability but within session waveform variation suggests trunk and pelvic rotation may not be consistent between trials. The variation between trials for trunk and pelvic rotation waveform kinematics may alter the observational rating between the trials and warrants further investigation. Finally, 'Does the pelvis hitch/drop?' has been updated to 'Does the pelvis stay level?' and similar to the criterion from the SKB test further study is required to assess the effect on reliability and validity of the rewording.

9.3 Standing hip flexion test

There are three criteria that remain unchanged in updated HLLMS. The first to be discussed is 'Does the hip fail to bend (flex) just beyond 90 degrees (approximate 110 degrees)?' which the results suggest was not valid and had poor kinematic reliability. However, the criterion is a benchmark which similar to the knee flexion from the SKB test, had the majority of participants being rated as having no fault, which mean assessing validity is limited. As discussed in section 5.4 of Chapter 5, the majority of the measures for hip flexion kinematic reliability were above 0.75, suggesting they are reliable, but the development of a cut off may be useful to further assess the validity. The criterion 'Does the trunk lean backwards (extend)?' was unchanged in the updated HLLMS but the results suggest poor validity and reliability of the observational rating. The low values of mean peak trunk extension excursion used to assess the criterion validity (range -2.3° to -6.3°) for the fault and no fault rating highlight a possible reason for the lack of validity and reliability for the observational rating (Table 6-3). Additionally, the high MDC of 3.3° relative to the mean trunk extension of -3.0° from the between day kinematics in controls indicate there would need to a change greater than the mean to be confident of a true change in movement (Table 5-7). Furthermore, it is probably not possible to observe a difference of only a few degrees of trunk movement. The results from this thesis for trunk extension indicate the criterion should not be included in the HLLMS.

The results presented in this thesis suggest the criterion 'Does the weight bearing knee bend (flex)?' has criterion validity, however the reliability results for kinematic and observational rating highlight areas that need improving. The low CMC for both within and between day knee flexion kinematics (CMC range 0.56 to 0.65, Table 5-7, Table 6-3) suggest variation in the pattern of movement. In contrast the ICC values are all above 0.75 for within and between day (ICC range 0.79 to 0.93, Table 5-7, Table 6-3) suggesting the peak knee flexion excursion is consistent. Although, it could be argued that peak value (good criterion validity) is more important that the consistency in waveform as the peak value probably better reflects what the observer is rating. The poor observational rating of knee flexion criterion clearly needs to be improved/ Further rater training to clarify what is defined as a fault could help improve the rater reliability and needs further investigation.

The criteria considered below have been altered in the updated HLLMS (Appendix J). The criterion 'Does the pelvis drop (hitch)?' has been updated to 'Does the pelvis fail to stay level?'. The present results suggest the criterion has good rater and kinematic reliability but only criterion validity on the right (Table 6-3). Despite the significant difference in the kinematics on the right (p=0.039) both the right and left side had small differences in the mean kinematics for fault and no fault (<2.2°). The small difference in degrees between fault and no fault may not be possible to detect accurately using visual observation. However, as discussed above for the pelvic hitch from other tests, clarification and training for the raters and examination of the reworded criteria need to be undertaken.

The criterion 'Does the pelvis tilt backwards posteriorly)?' has been updated to 'Does the pelvis begin in, or move backwards (posteriorly)?' and similar to the pelvic hitch discussed above, the original criterion had good observational rating and kinematic reliability but only criterion validity on the right (Table 9-1). The criterion validity results were based on substantial imbalance between participants rated as no fault or fault (right 6 vs 29, left 4 vs 31) which limits the confidence in the results (Table 6-3). Additionally, the high mean and SD peak posterior tilt excursion for participants who rated as no fault on the left (-14.3°, SD 8.6) suggests that there should have been more rated as having a fault. These results suggest that posterior pelvic tilt may be present in almost all the participants studied, questioning if it is a true movement fault or rather just normal movement. Further investigation is needed with the updated criterion with clarification on what raters agree is a fault, possibly changing the criterion to excessive posterior pelvic rotation if raters find that all participants have some rotation.

9.4 Deep squat test

The first of the criteria to be considered 'Does the thigh (femur) fail to be horizontal with the floor?' remains unchanged in the updated HLLMS. Table 9-1 illustrates it has criterion validity and within in session reliability but not between day kinematic or observational rating reliability. A possible cause for the lack of between day reliability is an increase in mean femur flexion between session one and two, as indicated by the mean difference of -6.3° in femur flexion (Table 5-8). The increase in mean femur flexion is supported by a decrease in number of participants rated as having a fault from four to one from session one to two. These results suggest there was a learning effect which explains why there was a lack of agreement in observational rating and kinematics between session. Further work is warranted to try and reduce this potential learning effect, possibly by allowing more practice trials.

The effect that the increase in femur flexion from session one to two had on the other kinematics related to the other criteria from the deep squat may be difficult to quantify. The mean difference for the kinematics from the other criteria was <1° suggesting they were not affected by the increase in femur flexion (Table 6-4).

The criterion 'Does the trunk fail to stay parallel with the shin (tibia)?' remains in the updated HLLMS, however, the present validity and reliability results do not support its inclusion. The criterion validity results in Table 6-4 show less than 1° difference between the mean kinematics for participants rated fault or no fault and high SD for both groups which highlight the lack of difference between them and high within group kinematic variation. It may not be possible to accurately observe for the difference between the trunk and tibia segments that are both moving. Without revision of the criterion and subsequent changes in the kinematic parameters the results in this thesis do not support its inclusion in the HLLMS.

The criterion 'Does the pelvis tilt forwards (anteriorly)?' has been updated to 'Does the pelvis begin in, or move forwards (anteriorly)?' Similar to the posterior pelvic tilt from the standing hip flexion test, there were large amounts of anterior pelvic tilt even in those rated as no fault suggesting all should be rated as a fault (Table 6-4). A possible cause of these results is that the raters are not observing pure anterior pelvic tilt, possibly anterior pelvic tilt relative to trunk flexion with corresponding changes in the kinematic criterion. The updated criterion, possibly with a change in the kinematic criterion, needs to be investigated to examine the effect on the validity and reliability. The results from this thesis indicate the criterion is not valid or reliable and therefore should not be included in the HLLMS.

The final criterion to be considered is 'Does the bodyweight shift to one side?' which only had the observational reliability assessed due to being unable use the force platforms. The low intra-rater agreement (AC1 = 0.30) results indicate the criterion should not be in the HLLMS. Further examination with the use of a force platform could clarify if it is possible to use observational rating to consistently identify bodyweight shift or not, and whether it should remain in the HLLMS.

9.5 Sitting hip flexion test

The recommendations for the criteria for the three remaining tests discussed below only have observational rating reliability results due to the 3D motion analysis data not being processed, due to substantial limitations discussed previously in section 3.5.2.6 of Chapter 3. The observational rating reliability results are summarised in Table 9-2.

The sitting hip flexion test had poor reliability results with only the 'Does the hip fail to bend (flex) just beyond 90 degrees (approximate 110 degrees)?' having AC1 values above 0.8 for the right and left sides for all the reliability assessed (Table 9-2). All but 'Does the foot fail to align with the ankle, knee and hip? (rate both legs)' was assessed during standing hip flexion. The similarity of the criteria between the two hip flexion tests and the poor rater agreement for the majority of the criteria could lead to the conclusion that the sitting hip flexion test is removed from the HLLMS.

Table 9-2: Summary of the observational reliability results for the criteria from the sitting hip flexion, hip abduction with lateral rotation and medial rotation from the HLLMS. Criteria shaded in grey remain unchanged in the latest version of the HLLMS.

		Observational reliability – mean right and left AC1>0.8		
Test	**Criterion**	**Intra–rater video**	**Intra-rater between day**	**Inter-rater footballers**
Sitting hip flexion	Pelvic axial rotation ¥		✓	✓
	Pelvic hitch ¥			
	Foot align knee/hip	✓		
	Posterior pelvic tilt			
	Hip flexion	✓	✓	✓
	Trunk extension			
Hip abduction lateral rotation	Leg lose lateral rotation	✓	✓	✓
	Hip flexion	✓	✓	✓
	Pelvis rotate backwards			
	Pelvic hitch	✓		✓
Hip abduction medial rotation	Leg lose medial rotation			
	Hip flexion			
	Pelvis rotate backwards	✓		
	Pelvic hitch			

¥ criteria combined

9.6 Hip abduction with lateral rotation

The two criteria that remain unchanged in the update HLLMS 'Does the leg lose lateral rotation?' and 'Does the hip/knee (leg) move into flexion?' had good rater agreement results in this thesis. However, there needs to be caution with interpretation of the good rater agreement for the leg losing lateral rotation criterion, due to the positive agreement results. Positive agreement was with either N/A meaning that no participant rated as having a fault or 0.00 indicating no participants were rated as having no fault on both ratings for the intra-rater video (Table 4-12) and between day (Table 4-21). The high rater agreement is therefore based primarily on the rating of fault and therefore fault agreement is unknown and a limitation of the results.

The remaining two criteria ‘Does the pelvis move backward?’ and ‘Does the pelvis hitch/drop?’ had limited reliability but have been reworded to ‘Does the pelvis fail to stay vertical (rotate backwards or forwards) and (rotate up or down)?’. Overall the results from this thesis support the inclusion of hip abduction with lateral rotation test in the HLLMS, but the reliability of the updated criteria needs to be assessed. Furthermore, there is a need to develop a 3D motion analysis methodology to assess the kinematic reliability and validity related to the observational criteria.

9.7 Hip abduction with medial rotation

In contrast to the agreement for the hip abduction with lateral rotation, the hip abduction with medial rotation test had poor agreement, with only one criterion ‘Does the pelvis move backward?’ having rater agreement AC1 above 0.8 on both the right and left for intra-rater assessment of video recordings (Table 9-2). The poor agreement results for the criteria in the hip abduction with medial rotation from this thesis suggest that the test should not be included in the HLLMS.

9.8 Study limitations

There are a number of limitations in the studies included in this thesis. The criterion validity was calculated using the kinematics from the mean of the three trials compared to the observational rating which is likely to be based on only one trial. It is not known if each trial would have been rated the same and therefore could lead to errors in assessing the validity of the observational rating.

There were a few of the criteria that had good rater agreement but had no score for either positive or negative agreement meaning all participants were all rated the same. The high rater agreement was based on scoring participants as having the same movement control for example no fault, therefore the level of agreement for fault rating is unknown. This homogeneity in the rating may have led to a high rater agreement that may not reflect the true agreement when there is a balance in participants who rated were rated as having a fault and no fault. The lack of balance between fault and no fault limits the generalisability of the results to other populations.

These results also highlight the limitation of using a single value to report agreement such as AC1 or percentage agreement.

The between day agreement of the observational rating and kinematic reliability was only based on 11 control participants. The small numbers used for the between day study increased the chances that the results in this thesis are not a true reflection of the population between day reliability. Additionally, it is not known if the between day reliability for the controls is the same as for academy footballers.

There is a potential limitation with the same person carrying out the rating of the HLLMS and coordinating the data collection in the laboratory. It is not possible to state the effect on rating when coordinating the data collection in the laboratory at the same time but is likely that the accuracy of the rating would be reduced compared to just rating the HLLMS.

9.9 Research implications

The implications of the results from this thesis are that some of the criteria are valid and reliable such as ‘Does the trunk lean forwards?’ from the SKB and SKB rotation tests. However, despite increasing use of movement screens the results from some of the criteria suggest they are not valid and/ or reliable. This is highlighted by the ‘Does the pelvis hitch/drop?’ from the SKB test which had excellent observational rater agreement but poor criterion validity and kinematic reliability for within in session and between day. The results identify criteria for which further study is required to determine if their validity and reliability can be improved to support their inclusion in the HLLMS.

In relation to the observational reliability of rating multiple criteria and multiple segment movement from the HLLMS, the results from this thesis suggest some criteria are not reliable. For example, the intra-rater video results highlighted the lack reliability for criteria such as ‘Does the pelvis tilt forwards?’ from the SKB test. Along with some poor between day and inter-rater agreement results from this thesis there is a clear need to improve the observational reliability of the HLLMS.

The implications of the poor to good reliability of some of the kinematics related to the observational rating highlights the instability of some of the movement patterns both within session and between day. The variability of the within session kinematics suggests that observational rating may vary depending on which trial is rated and the use of a mean value from the three trials may not be accurate. The within session kinematic reliability was higher than between day, as expected, which indicates the between day needs to be assessed not just within session when trying to determine if a true change in movement has occurred above the natural variation.

In a small sample of academy footballers, a 12-week exercise intervention was able to change the observational rating of some of the criteria from the HLLMS. Changes in observational rating for knee valgus and anterior pelvic tilt from the SKB was supported by corresponding kinematics changes, suggesting the criterion are valid in detecting a change in movement.

9.10 Novelty

There were several aspects of this thesis that were novel and have advanced knowledge in relation to the reliability and validity of the observational rating of movement screening, specifically the HLLMS.

9.10.1 Validity

The criterion validity of the observational rating from movement screens in the literature has been limited to primarily the SKB test and usually only rating one criterion at a time with medial knee movement commonly assessed (Whatman et al., 2011, Whatman et al., 2015, Ageberg et al., 2010). Several of the present criteria assessed from the SKB, SKB Rot, standing hip flexion and deep squat had significant differences in the kinematics between those rated as fault or no fault, suggesting the observational rating had criterion validity.

9.10.2 Exercise intervention changing movement and symptoms- demonstrating sensitivity of the HLLMS to change.

Abnormal movement patterns have been associated with FAI (Austin et al., 2008, Botha, 2013) but there is limited evidence of changing of those movement patterns. The results from the studies in this thesis on academy footballers and an ex footballer with hip and groin pain indicate an exercise intervention can improve abnormal movement patterns of the pelvis, hip and knee. Changes in movement patterns have been associated with decreased symptoms in shoulder pain patients (Worsley et al., 2013) but no research on the lower limb. The exercise intervention not only changed some of the movement patterns in the ex-footballer with hip and groin pain but also reduced their symptoms score from the HAGOS, above the smallest detectable change.

9.10.3 Reliability of kinematics

The reliability of the kinematics related to movements assessed in movement screening have been examined in the literature but mainly only ICC s of peak values for within session for the SKB test (Whatman et al., 2011, Alenezi et al., 2014). There is limited research on the between day reliability and analysis of the kinematic waveform for both within and between day reliability. The results from this thesis indicate that the within session peak excursion kinematics and kinematic waveform for the majority of the criteria are reliable (Table 9-1). The between day kinematic reliability was lower than within session with just under half of the criteria had good reliability.

Chapter 10: **Conclusions and future work**

10.1 Conclusions

The conclusions below relate to the whether the validity and reliability results from the studies in this thesis support the inclusion of the criteria in developing a robust HLLMS.

10.1.1 SKB test

The criteria 'Does the knee fail to move 2cm past the toes?' and 'Does the trunk lean forwards?' have good criterion validity and reliability in regard to their kinematics and observational rating. Further examination of the reworded versions of the criteria 'Does the knee move inward from the 2nd toe?', 'Does the pelvis hitch/drop?' and 'Does the pelvis tilt forwards?' is required due to them not having both good criterion validity and reliability results.

10.1.2 SKB Rot test

The validity and reliability results from this thesis support the inclusion of the criteria 'Does the pelvis follow the trunk?' and 'Does the trunk lean forwards?'. It is difficult to assess the criterion 'Does the trunk rotate less than 30°?' as almost all participants rated as no fault. Similar to the results from the SKB the 'Does the pelvis hitch/drop?' criterion has been reworded and further investigation is required to state if it is robust and should be included in the HLLMS.

10.1.3 Standing hip flexion test

The criteria 'Does the hip fail to bend (flex) just beyond 90 degrees (approximate 110 degrees)?', 'Does the weight bearing knee bend (flex)?', 'Does the pelvis drop (hitch)?' and 'Does the pelvis tilt backwards posteriorly)?' had variable validity and reliability and further investigation is needed. The results in this thesis of poor observational reliability, lack of criterion validity and small amounts of movement suggest that the 'Does the trunk lean backwards (extend)?' is removed from the HLLMS.

10.1.4 Deep squat test

The criterion 'Does the thigh (femur) fail to be horizontal with the floor?' had criterion validity and intra-rater video reliability but the apparent learning effect for between session needs to be addressed. The criterion 'Does the trunk fail to stay parallel with the shin (tibia)?' needs to be revised as results do not support its inclusion. The criterion 'Does the bodyweight shift to one side?' had low observational reliability and further study with the use of force platforms is required to determine if a valid and reliable criterion can be developed.

10.1.5 Hip abduction with lateral rotation

The criterion appears to have good observational agreement, but this may be related to the large majority all being rated as having the same movement. Further research is required to establish the criterion validity and the reassessment of the reworded criteria that had poor observational rating reliability.

10.1.6 Sitting hip flexion and hip abduction with medial rotation tests

Based on the poor observational reliability results from this thesis for the criteria from the sitting hip flexion and hip abduction with medial rotation tests indicate that they should not be included in the HLLMS.

10.2 Future work

The studies in this thesis are part of the development of a reliable and valid HLLMS. In relation to the findings of this thesis the recommendations for future work are outlined in relation to the latest version of the HLLMS (Appendix J).

I. Development of training material for raters including photos and video footage to improve observational rating consistency within and between raters.
II. Update kinematic criterion for the criterion that have been changed and those that were not valid but remain unchanged in the latest HLLMS and examine their criterion validity.
III. Further investigation to determine if there is a difference in peak knee valgus movement between the left and right sides.
IV. Compare the observational rating and kinematics directly for each trial.

V. Examine to potential to determine cut off for the amount of movement that is considered a fault or no fault, especially for the criterion that are a bench mark for example peak hip flexion from the standing hip flexion test.

VI. Consider the potential use of major or minor fault classifications with criterion that have large amounts of movement so that the HLLMS can detect more subtle changes in movement patterns.

VII. Development of a methodology to explore the relationship between movement patterns from the HLLMS and muscle onset timings using EMG to gain a greater understanding of the mechanisms of movement control.

VIII. Consider collecting data on more than three trails to ensure have three good quality trials.

IX. Design a reflective marker configuration that allows the validity of the sitting hip flexion and hip abduction test to be investigated.

10.3 Publications

Wilson, D.A., Booysen, N., Dainese, P., Heller, M.O., Stokes, M. and Warner M.B. (2018) Accuracy of movement quality screening to document effects of neuromuscular control retraining exercises in a young ex-footballer with hip and groin symptoms: a proof of concept case study. Medical Hypotheses, Volume 120, November 2018, Pages 116-120. (Appendix Q)

Appendices

Appendix A Footballer PIS

PARTICIPANT INFORMATION SHEET (Footballers)

Study Title: Exercise programmes for hip control to protect lower limb joints during exercise: effects on muscle activation and biomechanics in male adolescent academy footballers.

Lay Title: How exercises affect movements of the legs in young footballers.

Researcher: David Wilson **Ethics number**: 18656

Collaborator: Nadine Botha

Before agreeing to take part, it is important that you read this form and speak to your parent/guardian if you are aged 15-17 years.

You are being asked to take part in a research study because we want to learn about the effects of a warm-up exercise programme. Intensive sports activities may cause hip and groin pain and affect the way you move. The warm-up exercise programme is designed to prevent or reduce the pain you may feel in the hip and groin area.

<u>What is the research about?</u>

My name is David Wilson and I am a Physiotherapist studying for a PhD at the University of Southampton. I am doing this study to see if a warm-up exercise programme can improve movements around the hip and pelvis to protect the hip joint which may prevent pain and injury. I am working alongside Nadine Botha and will be making accurate measurements of movement to see how the warm-up exercise programme changes movement patterns.

Footballers may be more at risk of injury because of the high physical demands placed on your hips, through sprinting, jumping and kicking. This may be a result of how you move. By correcting the movement of the pelvis, hip and leg through a warm-up exercise programme we may be able to prevent or reduce pain and injury.

<u>Why have I been chosen?</u>

You are a footballer between 15-19 years old and play for a football academy team. Your club trains at least twice a week in addition to matches, with 15-30 matches being played during a season. We are looking for players with or without hip and groin pain.

What will happen to me if I take part?

My part of the study will take place in the movement laboratory at the University of Southampton. The warm-up exercise programme will take place at the football club where you do your training and you will not need to do any exercises at home. There will be three parts to the study; 1) baseline measurements, 2) the warm-up exercise programme over 12 weeks, and 3) follow-up measurements.

Giving permission:

Before the start of the study you will be told about the project and assessment methods at your club with written information. If you are aged 15-17 years you will go through the information pack with your parents/guardian. If you want to take part after reading the information you will be asked to give verbal permission (ages 15-17) and sign a form (ages 15-19) consenting to the study. Your parent/guardian will sign a consent form to also give permission for you to be in the study if you are aged 15-17.

Players will only be included into the study if they agree to take part.

Baseline measurements:

The researcher will arrange a date and time with your club to undertake the first assessment measures which should take approximately 1 hour. A second baseline measurement will be take place more than two days after the first baseline measurement. The baseline measurements will take place before the 12 week exercise programme.

Assessment measures will involve collecting information in the form of questionnaires, physiotherapy assessment on the hip and everyday movements. The assessment will involve measuring the amount of movement of your legs. This involves the investigator moving your leg in different directions and recording how much your leg moves. To measure your movement reflective makers and sensors that measure muscle activity will be placed on your trunk

and legs. To prepare the skin for the small pads to measure muscle activity an area approximately 3cm by 3cm will be shaved and cleaned with an alcohol swab to reduce the skin resistance. Positioning of markers and EMG sensors are illustrated in the photograph below.

The investigator will then ask you to perform a series of movements which include squatting on one leg, squatting on two legs and lying on your side and lifting your leg. During these movements the investigator will ask you to maintain certain positions (e.g. keep the chest upright). The investigator will make an assessment of how well you move and note down whether you are able to maintain the positions and perform the movements. Your movement during the testing will be recorded on video. The video will include your face, but only the researchers will have access to these videos. Any videos used for presentation purposes will have your face and any other identifiable characteristics (e.g. Tattoos) obscured from the video so the participants will remain anonymous.

You will be wearing shorts during the physiotherapy and movement assessments and an adult will be present at all times, who will either be a representative from your football club, a researcher from the University or one of your parents/guardian. You will do some stretches as a warm-up and you will be given instructions of the movement measurements. One example of the movement is to perform a squat which the researcher will teach you and give you a chance to practice before the assessment.

Warm-up exercise programme:

The exercise programme will be led by your coach and/or team captain. The coaches/captain may use a smartphone app with videos of the exercises which they can access on the pitch to ensure the exercises are done correctly. The exercise programme will take 10-15 minutes, forming part of your warm-up programme. The exercises will be done for 12 weeks before all your training sessions and games. You will not need to do any exercises on your own at home.

Nadine Botha (another physiotherapist from the University) will visit the club every to make sure the exercises are done correctly.

Follow-up measurements:

After 12 weeks when the exercise programme finishes your movement will be measured again in the movement laboratory at the University of Southampton the same as for the baseline measures outlined above.

Are there any risks involved?

The tests are not expected to cause any pain. If you feel any pain or discomfort during any of the assessment the test would be stopped as soon as you tell the researcher. There is a small risk of your skin reacting to the tape or electrodes that measure muscle activity. We will monitor your skin closely and stop the testing if there is any sign of a reaction. There is a small risk of injury during the movement assessment but these are not as demanding as football training drills. We will try to avoid any risk by doing warm-up stretches and taking break times between the assessments if you feel tired. There may be a small risk of injury during the exercise programme but the programme will be performed under the supervision of your coach or team captain to ensure the movements are performed correctly to minimise the risk. The exercises will form part of your usual warm-up programme so if you do get injured you will follow the usual practice at the club. The coach will contact the researcher if any problems specifically associated with the exercise occur but the risk is much lower than injury from actual training or playing football.

Do you have to be in this research study?

No. You do not have to be in this study. We are asking you if you would like to be in the study but if you say no, no one will be upset with you. You can also say yes now and if you change your mind later. You can leave the study at any time without giving a reason.

Please talk this over with your parents/guardian if you are aged 15-17 before you decide whether or not to take part. Your parents/guardian will be asked to give their permission for you to be in the study. Even though they have said it is all right with them, you can still say 'No'.

If you decide not to take part we will not collect any assessment measures from you. The club may continue delivering the exercise programme and you may still be asked to take part in the exercises as normal football practice.

What else do you need to know?

The results of this research may also be presented at meetings or in research journals, but your name would not be used. You will be given an ID number so that your information will be anonymous. Research study records that identify you will be kept private which we also call confidential. It won't be possible to keep your involvement in the study completely confidential, as it will be obvious if you're doing the exercises with the group or not. If you decide not to be part of the study you may still be asked to continue the exercise programme which will form part of normal football practice. Also, you might talk to each other about the study and exercises.

What about your privacy?

The researchers will not talk about you with anyone else except the people working on the study unless you give me your permission. If I think you are not safe then I will have to tell somebody else.

Are there any payment?

There will be no payment to be part of the study.

What happens if there is a problem?

If you are not happy about how your child has been approached or treated during the study then please contact the Research Governance Office at the University of Southampton, Building 37, Highfield, Southampton, SO17 1BJ (Tel: +44 (0)23 8059 5058) or Email: rgoinfo@soton.ac.uk.

Where can I get more information?

If you have any more questions about this study after reading this information sheet please contact David Wilson, email dw1y13@soton.ac.uk or Professor Maria Stokes (m.stokes@soton.ac.uk) on 023 80596868 or Dr Martin Warner (m.warner@soton.ac.uk) on 023 80598990.

If you want to be in this study, please tell your parent/guardian if you are 15-17 years old and they will let us know. If you are 18 or 19 years old you can just let us know. Thank you for taking the time to read this information.

Appendix B Footballer Consent Forms

CONSENT FORM Age 18-19 years (*Version 2*)

Study title: Exercise programmes for hip control to protect lower limb joints during exercise: effects on muscle activation and biomechanics in male adolescent academy footballers.

Lay Title: How exercises affect movements of the legs in young footballers.

Researcher name: David Wilson
Collaborator: Nadine Botha

Ethics reference: FoHS_ETHICS_18656

Please initial the box(es) if you agree with the statement(s):

I have read and understood the information sheet (18/1/16 Version 2 of participant information sheet) and have had the opportunity to ask questions about the study.	☐
I agree to take part in this research project and agree for my data to be used for the purpose of this study.	☐
I understand my participation is voluntary and I may withdraw at any time without my legal rights being affected.	☐
I agree to be video recorded for the purposes of the research study. I understand that these videos will not be anonymous, but only the researchers will have access to these videos.	☐
I agree that video footage of myself with my face and any identifying characteristics obscured, can be used for presentation purposes and demonstrating in future studies.	☐

Data Protection
I understand that information collected about me during his participation in this study will be stored on a password protected computer and that this information will only be used for the purpose of this study. All files containing any personal data will be made anonymous.

Name of participant (print name)…………………………………………………………………

Signature Participant………………………………………………
Date…………………………

Name of Researcher…………………………………………………………………………………

Signature of Researcher……………………………………………
Date………………………..

CONSENT FORM Parent/Guardian (*Version 2*)

Study title: Exercise programmes for hip control to protect lower limb joints during exercise: effects on muscle activation and biomechanics in male adolescent academy footballers.

Lay Title: How exercises affect movements of the legs in young footballers.

Researcher name: David Wilson
Collaborator: Nadine Botha

Ethics reference: FoHS_ETHICS_ 18656

Please initial the box(es) if you agree with the statement(s):

I have read and understood the information sheet (18/1/16 Version 2 of Parent/Guardian participant information sheet) and have had the opportunity to ask questions about the study.	☐
I agree for my child to take part in this research project and agree for his data to be used for the purpose of this study.	☐
I understand that my Childs participation is voluntary and he may withdraw at any time, without giving any reason, without his legal rights being affected.	☐
I agree to my child being video recorded for the purposes of the research study. I understand that these videos will not be anonymous, but only the researchers will have access to these videos.	☐
I agree that video footage of my child with their face and any identifying characteristics obscured, can be used for presentation purposes and demonstrating in future studies.	☐

Data Protection
I understand that information collected about my child during his participation in this study will be stored on a password protected computer and that this information will only be used for the purpose of this study. All files containing any personal data will be made anonymous.

Name of participant (print name)…………………………………………………………………

Name of Parent/Guardian (print name)…………………………………………………………...

Signature of Parent/Guardian…………………………………….
Date………………………….
Name of Researcher…………………………………………………………………………………

Signature of Researcher…………………………………………….
Date……………………….…

Verbal Assent Age 15-17 years (*Version 2*)

Study title: Exercise programmes for hip control to protect lower limb joints during exercise: effects on muscle activation and biomechanics in male adolescent academy footballers.

Lay Title: How exercises affect movements of the legs in young footballers.

Researcher name: David Wilson
Collaborator: Nadine Botha

Ethics reference: FoHS_ETHICS_18656

Name of participant (print name)………………………………………………
has given verbal permission to take part in the research study.

Before giving verbal assent the participant:

- Read the participant information sheet
- Has talked with the researcher and his parents/guardian about the study
- Had all his questions answered and said that he wanted to take part in the study
- Understands he can say yes now and if he changes his mind later he can withdraw from the study and no one will be upset with him.
- He can call the researcher any time if he has any questions.
- Understands that besides his parents/guardian his information will only be shared with the researchers and supervisors.

Signature of Participant………………………………………………………….

Name of Researcher………………………………………………………………..

Signature of Researcher………………………………
Date…………………….

Name of Witness ……………………………………………………………..........

Appendix C Control PIS

Study Title:
Validation and reliability of 3D motion analysis and muscle electrical activity during hip screening and gait in young male adults

Lead Researcher: David Wilson **Ethics number**: 14083
Collaborator: Lavinia-Alexandra Otescu

Please read this information carefully before deciding to take part in this research. If you are happy to participate you will be asked to sign a consent form.

What is the research about?
Taking part in sports such as football has health benefits but there is also an increased injury risk including hip and groin injury, known as Femoroacetabular impingement (FAI), which is a change in the bony structure of the hip. FAI may lead to osteoarthritis (OA), which is pain and stiffness in the joints. The changes in footballers' hips may be due to the way they move (their movement patterns). There is some evidence that specific exercises can improve abnormal movement patterns and muscle activity, which could reduce the risk of developing injury, FAI and OA.

A hip screening tool has been designed to detect players whose movement pattern may lead to hip and groin injury, which is linked to FAI. Changes in movement patterns (kinematics), can be accurately obtaining using equipment that measures movement in three dimensions (called 3D motion analysis). Electromyography (EMG) can be used to measure the electrical activity of muscle. To detect if a true change in movement pattern or muscle activity has occurred, it is important to know how much these measurements vary from day-to-day, without any treatment or exercise.

Movement patterns may be different in the laboratory compared to on the field, so wireless sensors can be used to analyse movement outdoors. However, it is unknown how accurate and practical it is to use these sensors.

The present study will determine if the methods for measuring movement are accurate and reliable enough to use in studies. This work will then lead to a better understanding how movement can be changed to reduce injury risk and improve the long term health of hip joints.

Why have I been chosen?
We are interested in the movement patterns of young males who are unlikely to have developed any structural hip abnormalities, to compare to the young footballers who will be analysed in a later study.

If you have any of the following you will not be able to take part in the study: any lower limb pain; diagnosed with lower limb disorder; any muscle or bone problems; lower limb or spinal fractures or allergic to tape/plasters. If you are not between the ages of 18 to 29 years old you will not be able to take part.

What will happen to me if I take part?
The testing will take place in the biomechanics laboratory in building 45 of the Faculty of Health Sciences at the University of Southampton. The second part of the session will take place in the Highfield Botanical Garden. The date and time at which the testing will take place will be agreed between you and the researchers. The researchers will explain what you will be asked to do and you will have the opportunity to ask any questions before testing begins. If you agree to take part in the study we will ask you to sign the consent form.

You will be asked to wear shorts for testing in the laboratory and loose fitting clothing for the testing outdoors, which will not restrict your movement in any way. The testing will begin with measuring your height, weight and your ankle and knee widths. To prepare the skin for the small pads to measure muscle activity the areas will be shaved and cleaned with an alcohol swab to reduce the skin resistance. Reflective markers and small pads to measure muscle activity will be attached to the skin on your thorax and legs using double sided tape.

Matchbox sized wireless sensors will be attached to your lower back, thighs and lower legs with the tape. You will then be asked to carry out movements of your legs in standing, sitting and lying. You will be asked to perform movements such as squatting and lying on your side then lifting the uppermost leg towards the ceiling that form a 'Hip screening tool', which has been designed to identify footballers that may have problems or may develop problems with their hip joints. Your movement will be recorded using the markers, remote sensors and video cameras. Another PhD student (Nadine Botha) will be present to rate your movement during the hip screening assessment alongside David Wilson. You will also walk up and down the laboratory while recordings are made.

At the end of the laboratory session, the reflective markers and electrodes will be removed, leaving only the remote sensors attached, for testing by another PhD student (Lavinia Otescu). You will be asked to walk to the outdoor venue (a few minutes walk) together with the researchers for the second part of the session. You will repeat a few selected movements, which you will have already performed in the laboratory and you will be asked to walk up and down a footpath 3 times. The entire time including both sessions should take less than 90 minutes.

A second set of sessions will be carried out at least two days later, so we can see how similar the results are.

Are there any benefits in my taking part?
There are no direct benefits to taking part in this study. The information gained from this study will help further study on measuring movement patterns and how these may be changed to decrease injury risk.

Are there any risks involved?
There are minimal risks to taking part in this study. The sensors, markers and electrodes will not cause any pain or discomfort. Removal of the markers may cause momentary discomfort similar to removing a small plaster. The tasks you will perform only require a low level of physical effort.

Some people may have a skin irritation in response to the sticky tape used attached the markers and sensors to the skin. If you have a known skin allergy or sensitivity to sticky tape, we ask you not to take part in the study.

Will my participation be confidential?
Yes, all data collected will be kept confidential in compliance with the Data Protection Act and University of Southampton data protection policy. To keep data confidential all written data will be stored in a locked filing cabinet and all electronic data will be stored on password protected computers that only the researchers have access. Your data will be anonymised by assigning a unique ID number to your data. No one, other than the researchers, will be able to link your name with the unique ID number. Data that will be published in journal articles, conferences or meetings will not report any names or unique ID numbers to maintain the anonymity of the data. All data will be kept for 10 years.

Video footage will be transferred from an encrypted memory card and stored on a password protected University of Southampton Research Drive. Participants will be asked for consent for their videos to be used in the future to enable different assessors in the team to compare how they rate performance of the tests. This is known as inter-rater reliability. Written consent would be obtained from participants whose video footage may be used to demonstrate test movements in future studies.

What happens if I change my mind?
Participation in the study is entirely voluntary and you may withdraw at any point during the study, without giving a reason for doing so and without affecting your rights.

What happens if something goes wrong?
In the unlikely event that you wish to make a complaint, or express any concerns, you should contact: Diana Galpin (Head of Intellectual Property, Contracts and Policy) Address: Building 37, University of Southampton, University Road, Southampton, SO17 1BJ. Email: d.galpin@soton.ac.uk Telephone: 023 8059 8673

Where can I get more information?
If you require any further information or have any questions regarding taking part in this study please contact David Wilson on the details below

David Wilson – PhD Student
Senior Physiotherapist
Faculty of Health Sciences, Building 45, University of Southampton
Highfield Campus, Southampton, SO17 1BJ, Tel 02380 594332
Email: dw1y13@soton.ac.uk

Thank you for considering participating and for taking time to read this sheet.

Appendix D **Control Consent**

CONSENT FORM (v1)

Accuracy and reliability of measuring muscle activity and hip movement in 3D in young males.

Researcher name: David Wilson **Ethics reference**: 14083

Please initial the box(es) if you agree with the statement(s):

I have read and understood the information sheet (7th July 2015, V4). of participant information sheet) and have had the opportunity to ask questions about the study. ☐

I agree to take part in this research project and agree for my data to be used for the purpose of this study ☐

I understand my participation is voluntary and I may withdraw at any time without my legal rights being affected ☐

I agree to be video recorded whilst performing functional movements, in order for my performance to be analysed at a later stage ☐

I agree that the data collected can be used for further research that may be undertaken by a student or other researchers at the University of Southampton ☐

I agree that video footage of myself can be used for presentation purposes and demonstrating in future studies. ☐

I am happy to be contacted regarding other unspecified research projects. I therefore consent to the University retaining my personal details on a database, kept separately from the research data detailed above. The 'validity' of my consent is conditional upon the University complying with the Data Protection Act and I understand that I can request my details be removed from this database at any time. ☐

I understand that information collected about me during my participation in this study will be stored on a password protected computer and that this information will only be used for the purpose of this study. All files containing any personal data will be made anonymous.

Name of participant (print name)…………………………………………………

Signature of participant……………………………………………………………..

Signature of researcher (David Wilson) ………………………………………………………..

Date………………………………………………………………………………

Appendix E **HLLMS Version 2 used for golfer and case studies**

Movement Control Test				
Test	Verbal Instruction	Outcome		
SKB Test	• Stand on one leg with your foot pointing forward. • Place the unsupported foot behind you by bending your knee 90°. • While keeping your body upright, keeping your pelvis and heel in position, bend your knee so that your knee is in line with your 2nd toe and moves past it until you can no longer see the tape line. • Do you understand the instructions?	Does the knee move inward from the 2nd toe? Does the pelvis hitch/drop? Does the knee fail to move 2cm past the toes? Does the trunk lean forwards? Does the pelvis tilt anterior?	Right Y=1 N=0 Y=1 N=0 Y=1 N=0 Y=1 N=0 Y=1 N=0	Left Y=1 N=0 Y=1 N=0 Y=1 N=0 Y=1 N=0 Y=1 N=0
		Total Score		
SKB with Trunk Rotation Test	• Stand on one leg with your foot pointing forward. • Place the unsupported foot behind you by bending your knee 90°. • While keeping your body upright, keeping your pelvis and heel in position, bend your knee so that your knee aligns along your 2nd toe. • While holding this position turn your upper body to the left and right looking over your shoulder 30° • Do you understand the instructions?	Does the pelvis follow the trunk? Does the trunk side-bend? Does the pelvis hitch/drop? Does the trunk rotate less than 30°? Do the toes claw or any loss of balance? Does the trunk lean forwards?	Right Y=1 N=0 Y=1 N=0 Y=1 N=0 Y=1 N=0 Y=1 N=0 Y=1 N=0	Left Y=1 N=0 Y=1 N=0 Y=1 N=0 Y=1 N=0 Y=1 N=0 Y=1 N=0
		Total Score		
Standing Hip Flexion Test	• Stand with your feet approximately hip width apart and the toes pointing forward. • Place your arms across your chest. • While keeping your body upright, keeping your pelvis steady and	Does the pelvis hitch/drop? Does the pelvis tilt posterior? Does the spine flex?	Right Y=1 N=0 Y=1 N=0 Y=1 N=0	Left Y=1 N=0 Y=1 N=0 Y=1 N=0

	knee locked, raise the opposite leg, bending your hip up to 110°. •Do you understand the instructions? Rating weight bearing leg	Does the trunk lean backwards? Does the weight bearing knee flex?	Y=1 N=0 Y=1 N=0	Y=1 N=0 Y=1 N=0
		Total Score		
Deep Squat	• Stand with your feet approximately shoulder width apart and the toes pointing forward. •Place your arms forward. •While keeping your body upright, keeping your heels in position and your weight equal, move down as deep as possible aligning your knee to your 2nd toe. Your upper thigh needs to be horizontal with the floor. •Do you understand the instructions?	Does the trunk fail to stay parallel with the tibia? Does the femur fail to reach horizontal level with the floor? Does the pelvis tilt anterior? Does the knee move inward from 2nd toe? Does the knee move outward from 2nd toe? Does the bodyweight shift to one side?	Y=1 N=0 Y=1 N=0 Y=1 N=0 Y=1 N=0 Y=1 N=0 Y=1 N=0	
		Total Score		
Sitting Hip Flexion Test	• Sit with your arms across your chest. • While keeping your body upright, keeping your pelvis steady raise the opposite leg, bending your hip to 110°, making sure to maintain your foot alignment with the ankle, knee and hip. • Do you understand the instructions?	Is there axial rotation of the pelvis? Does the pelvis hitch/drop? Does the foot fail to align with the ankle, knee and hip? Does the pelvis tilt posterior? Does the spine flex? Does the trunk lean backwards?	<u>Right</u> Y=1 N=0 Y=1 N=0 Y=1 N=0 Y=1 N=0 Y=1 N=0 Y=1 N=0	<u>Left</u> Y=1 N=0 Y=1 N=0 Y=1 N=0 Y=1 N=0 Y=1 N=0 Y=1 N=0
		Total Score		
Hip Abduction lateral rotators Test	•Lie on your side with your bottom leg bent for support. •While maintaining the leg straight, with the upper body straight and your leg turned outward, lift your leg	Does the leg lose lateral rotation? Does the hip/knee (leg) move into flexion?	<u>Right</u> Y=1 N=0 Y=1 N=0	<u>Left</u> Y=1 N=0 Y=1 N=0

	towards the ceiling 45° while keeping your pelvis steady. •Do you understand the instructions?	Does the pelvis move backward? Does the pelvis hitch/drop?	Y=1 N=0 Y=1 N=0	Y=1 N=0 Y=1 N=0
		Total Score		
Hip Abduction medial rotators Test	• Lie on your side with your bottom leg flexed for support. • While maintaining leg extension, a straight back and your leg turned downward, lift your leg towards the ceiling while keeping your pelvis steady. • Do you understand the •Do you understand the instructions?	 Does the leg lose medial rotation? Does the leg move into flexion? Does the pelvis move backward/vertical? Does the pelvis hitch/drop?	Right Y=1 N=0 Y=1 N=0 Y=1 N=0 Y=1 N=0	Left Y=1 N=0 Y=1 N=0 Y=1 N=0 Y=1 N=0
		Total Score		

Appendix F **Golfer Kappa data**

Table 10-1: Inter-rater percentage agreement and Kappa for the SKB test in male professional golfers (n=45)

Movement criteria	**Side**	**Kappa value (95%CI)**	**Inter-rater percentage agreement**	**Mean percentage agreement for each fault**
Does the knee move inward from the 2nd toe?	Right	0.40 (0.12 - 0.68)	73	68
	Left	0.19 (-0.06 -0.44)	62	
Does the pelvis hitch/drop?	Right	0.28 (-0.10 -0.67)	84	84
	Left	0.19 (-0.13 -0.51)	84	
Does the knee fail to move 2cm past the toes?	Right	0.79 (0.39 - 1.19)	98	98
	Left	*	98	
Does the trunk lean forwards?	Right	0.55 (0.33 - 0.77)	80	81
	Left	0.68 (0.46 - 0.90)	84	
Overall agreement			83	

*= no Kappa score as one scorer rated all participants as either all passing/failing the criterion

Table 10-2: Inter-rater percentage agreement and Kappa for the SKB with rotation test in male professional golfers (n=45)

Movement criteria	**Side**	**Kappa value (95%CI)**	**Inter-rater percentage agreement**	**Mean percentage agreement for each fault**
Does the pelvis follow the trunk?	Right	0.64 (0.43 - 0.86)	82	74
	Left	0.38 (0.16 - 0.60)	67	
Does the trunk side-bend?	Right	0.33 (-0.09 - 0.74)	87	87
	Left	0.18 (-0.24 - 0.60)	87	
Does the pelvis hitch/drop?	Right	0.33 (0.07 - 0.58)	76	78
	Left	0.43 (0.16 - 0.71)	80	
Does the trunk rotate less than 30°?	Right	-0.23 (-0.54 - 0.08)	96	97
	Left	*	98	
Do the toes claw or any loss of balance?	Right	0.21 (-0.09 - 0.51)	69	72
	Left	0.20 (-0.13 - 0.54)	76	
	Right	0.41 (0.17 - 0.66)	73	68

Does the trunk lean forwards?	Left	0.29 (0.08 - 0.50)	62
Overall agreement			79

*= no Kappa score as one scorer only scored true or false for all participants

Table 10-3: Inter-rater percentage agreement and Kappa for the standing hip flexion test in male professional golfers (n=45)

Movement criteria	**Side**	**Kappa value (95%CI)**	**Inter-rater percentage agreement**	**Mean percentage agreement for each fault**
Does the pelvis drop (hitch)?	Right	0.48 (0.32-0.62)	96	93
	Left	-0.05 (0.02-0.05)	91	
Does the pelvis tilt backwards (posteriorly)?	Right	0.29 (0.14-0.28)	64	70
	Left	0.52 (0.12-0.24)	76	
Does the spine flex?	Right	0.32 (0.15-0.28)	69	70
	Left	0.41 (0.13-0.26)	71	
Does the trunk lean backwards (extend)?	Right	*	87	90
	Left	-0.03 (0.02-0.04)	93	
Does the weight bearing knee bend (flex)?	Right	0.52 (0.12-0.24)	76	80
	Left	0.67 (0.11-0.22)	84	
Overall agreement			81	

*= no Kappa score as one scorer only scored true or false for all participants

Table 10-4: Inter-rater percentage agreement and Kappa for the deep squat test in male professional golfers (n=45)

Movement criteria	**Kappa value (95%CI)**	**Inter-rater percentage agreement**
Does the trunk fail to stay parallel with the shin (tibia)?	0.66 (0.42-0.91)	87
Does the thigh (femur) fail to be horizontal with the floor?	0.74 (0.51-0.98)	91
Does the pelvis tilt forwards (anteriorly)?	0.18 (-0.12-0.47)	64
Does the knee move inward from the 2nd toe?	*	98

Does the knee move outward from the 2nd toe?	*	98
Does the bodyweight shift to one side?	*	93
Overall agreement		89

Table 10-5: Inter-rater percentage agreement and Kappa for the hip abduction with lateral rotatoin test in male professional golfers (n=45)

Movement criteria	**Side**	**Kappa values (95% CI)**	**Inter-rater percentage agreement**	**Mean percentage agreement for each criterion**
Does the leg lose lateral rotation?	Right	0.24 (-0.21 -0.68)	89	88
	Left	0.33 (-0.08 -0.74)	87	
Does the hip/knee (leg) move into flexion?	Right	0.23 (-0.14 - 0.61)	82	89
	Left	0.55 (0.17 - 0.94)	91	
Does the pelvis move backward?	Right	0.55 (0.27 -0.82)	84	84
	Left	0.57 (0.30 - 0.85)	84	
Does the pelvis hitch/drop?	Right	0.49 (0.11 - 0.87)	89	91
	Left	0.31 (-0.16 - 0.77)	91	
Overall agreement			87	

Appendix G **Hip and Lower Limb Movement Screen (Version 3) – Footballer/Controls**

Participant code: _________ Age: _______ Date: _______

Movement Control Test				
Test	Verbal Instruction	Outcome		
SKB Test	• Stand on one leg with your foot pointing forward. • Place the unsupported foot behind you by bending your knee 90°. • While keeping your body upright, keeping your pelvis and heel in position, bend your knee so that your knee is in line with your 2nd toe and moves past it until you can no longer see the tape line. • Do you understand the instructions?		Right	Left
		Does the knee move inward from the 2nd toe?	Y=1 N=0	Y=1 N=0
		Does the pelvis hitch?	Y=1 N=0	Y=1 N=0
		Does the knee fail to move 2cm past the toes?	Y=1 N=0	Y=1 N=0
		Does the trunk lean forwards?	Y=1 N=0	Y=1 N=0
		Does the pelvis tilt anterior?	Y=1 N=0	Y=1 N=0
		Total Score		
SKB with Trunk Rotation Test	• Stand on one leg with your foot pointing forward. • Place the unsupported foot behind you by bending your knee 90°. • While keeping your body upright, keeping your pelvis and heel in position, bend your knee so that your knee aligns along your 2nd toe. • While holding this position turn your upper body to the left and right looking over your shoulder 30° • Do you understand the instructions?		Right	Left
		Does the hip and pelvis follow the trunk?	Y=1 N=0	Y=1 N=0
		Does the trunk side-bend?	Y=1 N=0	Y=1 N=0
		Does the pelvis hitch?	Y=1 N=0	Y=1 N=0
		Does the trunk fail to rotate more than 30°?	Y=1 N=0	Y=1 N=0
		Do the toes claw or any loss of balance?	Y=1 N=0	Y=1 N=0
		Does the trunk lean forwards?	Y=1 N=0	Y=1 N=0
		Total Score		

Standing Hip Flexion Test	• Stand with your feet approximately hip width apart and the toes pointing forward. • Place your arms across your chest. • While keeping your body upright, keeping your pelvis steady and knee locked. Raise the opposite leg, bending your hip up to 110°. •Do you understand the instructions?	Does the pelvis hitch? Does the pelvis tilt posterior? Does the spine flex? Does the trunk lean backwards? Does the weight bearing knee flex?	Right Y=1 N=0 Y=1 N=0 Y=1 N=0 Y=1 N=0 Y=1 N=0	Left Y=1 N=0 Y=1 N=0 Y=1 N=0 Y=1 N=0 Y=1 N=0
		Total Score		
Deep Squat	• Stand with your feet approximately shoulder width apart and the toes pointing forward. •Place your arms forward. •While keeping your body upright, keeping your heels in position and your weight equal, move down as deep as possible aligning your knee to your 2nd toe. Your upper thigh needs to be horizontal with the floor. •Do you understand the instructions?	Does the trunk fail to stay vertical or parallel with the tibia? Does the femur fail to be horizontal with the floor? Does the pelvis anterior tilt? Does the knee move inward from 2nd toe? Does the knee move outward from 2nd toe? Does the bodyweight shift to one side?	Y=1 N=0 Y=1 N=0 Y=1 N=0 Y=1 N=0 Y=1 N=0 Y=1 N=0	
		Total Score		
Sitting Hip Flexion Test	• Sit with your arms across your chest. • While keeping your body upright, keeping your pelvis steady raise the opposite leg, bending your hip to 110°, making sure to maintain your foot alignment with the ankle, knee and hip. • Do you understand the instructions?	Is there axial rotation of the pelvis? Does the pelvis hitch? Does the foot fail to align with the ankle, knee and hip? Does the pelvis tilt posterior? Does the spine flex? Does the trunk lean backwards?	Right Y=1 N=0 Y=1 N=0 Y=1 N=0 Y=1 N=0 Y=1 N=0 Y=1 N=0	Left Y=1 N=0 Y=1 N=0 Y=1 N=0 Y=1 N=0 Y=1 N=0 Y=1 N=0
		Total Score		

Hip Abduction lateral rotators Test	•Lie on your side with your bottom leg bent for support. •While maintaining the leg straight, with the upper body straight and your leg turned outward, lift your leg towards the ceiling 45° while keeping your pelvis steady. •Do you understand the instructions?	Does the leg lose lateral rotation? Does the leg move into flexion? Does the pelvis move backward? Does the pelvis hitch?	<u>Right</u> Y=1 N=0 Y=1 N=0 Y=1 N=0 Y=1 N=0	<u>Left</u> Y=1 N=0 Y=1 N=0 Y=1 N=0 Y=1 N=0
		Total Score		
Hip Abduction medial rotators Test	• Lie on your side with your bottom leg flexed for support. • While maintaining leg extension, a straight back and your leg turned downward, lift your leg towards the ceiling while keeping your pelvis steady. • Do you understand the •Do you understand the instructions?	Does the leg lose medial rotation? Does the leg move into flexion? Does the pelvis move backward? Does the pelvis hitch?	<u>Right</u> Y=1 N=0 Y=1 N=0 Y=1 N=0 Y=1 N=0	<u>Left</u> Y=1 N=0 Y=1 N=0 Y=1 N=0 Y=1 N=0
		Total Score		

Appendix H **Golfers Participant Information Sheet**

Hip Pain in Professional Golfers

Chief Investigator: Dr Edward Dickenson

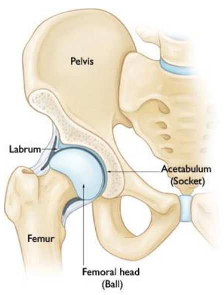
Patient Information Sheet

You are invited to take part in our research study. Before you decide whether to take part we would like you to understand why the study is being done and what it would involve for you. Once you have had a chance to read information sheet and if you are happy to participate we would ask that you complete the enclosed consent form and questionnaire.

What is the purpose of this study?
We are interested in finding out about causes of hip pain in professional golfers, previous work suggests a fifth of golfers suffer significant hip pain.

Background Information
Your hip joint has two bones that fit together like a ball in a socket, see figure 1.

- Figure 1 – Normal Hip Joint



In some people these bones have a slightly different shape. As these different shaped hips move the bones may be able to abnormally press against each other earlier than would otherwise occur. The muscles around the hip are also important in controlling hip movements and preventing abnormal contact.
Hip impingement, or the medical term femoroacetabular impingement (FAI for short), is a condition caused by different hip shapes and abnormal hip muscle function. FAI results in the bones contacting each other prematurely resulting in pain. Hip impingement has only been discovered in the last 15 years and we do not understand how common the condition is. There is evidence to suggest FAI is more common in professional athletes. During a golf swing there is a rapid movement of the hips and therefore golfers may be more prone to developing FAI than non golfers.

Why have I been invited to take part in the study?
We are inviting professional golfers to participate in the study.

Appendix

Do I have to do to take part?
You participation is entirely voluntary and it is up to you to decide whether to take part.

What will happen to me if I take part?
We ask that you complete the enclosed questionnaire, undergo a hip examination by an orthopaedic surgeon and physiotherapist and have an MRI scan of your hips. If you consent we will video part of your hip examination to allow other specialist to observe your hip movements. These videos will not be shared and would only be used by the research team. The MRI scan will take 20 minutes; you would be required to lie still in the scanner, which is a confined space.

What are the possible risks of taking part?
By taking part there are no risks to you health.

Will my taking part in this study be kept confidential?

All information which is collected about you from the study will be kept anonymised and strictly confidential. The information will not be shared with anyone outside of your direct care team. The data we collect (non identifiable) will be kept on record for 10 years. If we identify any abnormalities in your hips we will inform you, and if you wish the European tour medical team. Any video recordings will be kept confidential.

What will happen to the results of the research study?

At the end of the study we will publish the findings in medical journals and at medical conferences. You will not be identified in any reports or publications resulting from the study. If you would like to obtain a copy of the published results, please use the contact details shown below.

Who is funding the Research?

This research is the result of collaboration between Southampton University, The European Tour Performance Institute and Warwick University. The University of Warwick sponsors the research. The MRI scans are being funded by a research grant from Royal College of Radiologists.

Who has reviewed this project?

This study has been reviewed by the BSREC committee at the University of Warwick 16/6/15

What if there is a problem?
This study is covered by the University of Warwick's insurance and indemnity cover. If you have an issue, please contact the Chief Investigator of the study:
Edward Dickenson, CSRI, University Hospital Coventry and Warwickshire, Clifford Bridge Rd, Coventry CV2 2DX.

Who should I contact if I wish to make a complaint?
Any complaint about the way you have been dealt with during the study or any possible harm you might have suffered will be addressed. Please address your complaint to the person below, who is a senior University of Warwick official entirely independent of this study:
Director of Delivery Assurance
Registrar's Office, University House, University of Warwick, Coventry, CV4 8UW
Complaints@Warwick.ac.uk 024 7657 4774

Contacts for further information

If you have any questions about the study or would like further information, contact:

Edward Dickenson, CSRL CSB, University Hospital Coventry and Warwickshire, Clifford Bridge Rd, Coventry CV2 2DX.
Tel; 02746 968623 Email: e.j.dickenson@warwick.ac.uk

Appendix I **Golfer Consent**

Study Number:

Patient Identification Number for this study:

Title of Project: Hip Pain in Professional Golfers

Chief Investigator: Dr Edward Dickenson

Please initial all boxes

1. I confirm that I have read and understand the information sheet dated 15/5/2015 for the above study. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily. ☐
2. I understand that my participation is voluntary and that I am free to withdraw at any time without giving any reason, without my medical care being affected. ☐
3. I understand that data collected during the study may be looked at by individuals from the University of Warwick, the University of Southampton, the European Tour Medical Team and from regulatory authorities, where it is relevant to my taking part in this research. I give permission for these individuals to have access to my data. ☐
4. I give permission for the video recording of my hip examination. ☐
5. I agree to undergo an MRI scan of my hips. ☐
6. I agree to take part in the above study. ☐

________________	________________	________________
Name of Participant	Date	Signature

________________	________________	________________
Name of Person taking consent	Date	Signature

-

Appendix J **Updated HLLMS (Version 4)**

The Hip and Lower Limb Movement Screening Tool

Participant code: _________Test start side: L / R   Dominant side: L / R   Date: _________

Test	Verbal Instruction	Outcome		
			Right	Left
SKB Test	• Stand on one leg with your foot pointing forward. • Place the unsupported foot behind you by bending your knee 90°. • While keeping your body upright, keeping your pelvis and heel in position, bend your knee so that your knee is in line with your 2nd toe and moves past it until you can no longer see the tape line. • Do you understand the instructions?	Does the knee fail to move 2cm past the toes?	Y=1 N=0	Y=1 N=0
		Does the pelvis begin in, or tilt forwards (anterior)?	Y=1 N=0	Y=1 N=0
		Does the trunk lean forwards (flex)?	Y=1 N=0	Y=1 N=0
		Is there an increase in dynamic valgus from the start position?	Y=1 N=0	Y=1 N=0
		Does the pelvis fail to stay level?	Y=1 N=0	Y=1 N=0
		Total Score		
		Failed test		
			Right	Left
SKB with Trunk Rotation Test	• Stand on one leg with your foot pointing forward. • Place the unsupported foot behind you by bending your knee 90°. • While keeping your body upright, keeping your pelvis and heel in position, bend your knee so that your knee aligns along your 2nd toe. • While holding this position turn your upper body to the left and right looking over your shoulder 30° • Do you understand the instructions?	Does the trunk rotate less than 30°?	Y=1 N=0	Y=1 N=0
		Does the pelvis fail to stay level?	Y=1 N=0	Y=1 N=0
		Does the pelvis follow the trunk rotation?	Y=1 N=0	Y=1 N=0
		Does the trunk lean forwards (flex)?	Y=1 N=0	Y=1 N=0
		Total score		
		Failed test		
			Right	Left
Standing Hip Flexion Test	• Stand with your feet approximately hip width apart and the toes pointing forward. • Place your arms across your chest. • While keeping your body upright, keeping your pelvis steady and knee locked. Raise the opposite leg, bending your hip up to 110°. •Do you understand the instructions?	Does the hip fail to bend (flex) just beyond 90 degrees (approximate 110 degrees)?	Y=1 N=0	Y=1 N=0
		Does the trunk lean backwards (extend)?	Y=1 N=0	Y=1 N=0
		Does the pelvis begin in, or move backwards (posteriorly)?	Y=1 N=0	Y=1 N=0
		Does the weight-bearing knee bend (flex)?	Y=1 N=0	Y=1 N=0
		Does the pelvis fail to stay level?	Y=1 N=0	Y=1 N=0
		Total Score		
		Failed test		
Deep Squat	• Stand with your feet approximately shoulder width apart and the toes pointing forward. •Place your arms forward.	Does the thigh (femur) fail to be horizontal with the floor?	Y=1 N=0	
		Does the pelvis begin in, or move forwards (anteriorly)?	Y=1 N=0	

	•While keeping your body upright, keeping your heels in position and your weight equal, move down as deep as possible aligning your knee to your 2nd toe. Your upper thigh needs to be horizontal with the floor. •Do you understand the instructions?	Does the trunk fail to stay parallel with the shin (tibia)? Does the bodyweight shift to one side?	Y=1 N=0 Y=1 N=0	
		Total Score		
		Failed test		
Sitting Hip Flexion Test	• Sit with your arms across your chest, feet not touching the floor. • While keeping your body upright, keeping your pelvis steady raise the opposite leg, bending your hip to 110°, making sure to maintain your foot alignment with the ankle, knee and hip. • Do you understand the instructions?	Does the hip fail to bend (flex) just beyond 90 degrees (approximate 110 degrees)? Does the pelvis begin in, or move backwards (posteriorly)? Does the trunk lean backwards (extend)? Does the pelvis rotate (axial plane) or hitch/hike (frontal plane)? Does the foot fail to align with the ankle, knee and hip?	Right Y=1 N=0 Y=1 N=0 Y=1 N=0 Y=1 N=0 Y=1 N=0 (R / L)	Left Y=1 N=0 Y=1 N=0 Y=1 N=0 Y=1 N=0 Y=1 N=0 (R / L)
		Total Score		
		Failed test		
Hip Abduction lateral rotators Test	•Lie on your side with your bottom leg bent for support. •While maintaining the leg straight, with the upper body straight and your leg turned outward, lift your leg towards the ceiling 45° while keeping your pelvis steady. •Do you understand the instructions?	Does the hip fail to abduct to 45 degrees? Does the pelvis fail to stay vertical (rotate up or down)? Does the leg lose outwards (lateral) rotation? Does the hip/knee (leg) move forwards (flexion)? Does the pelvis fail to stay vertical (rotate backwards or forwards)?	Right Y=1 N=0 Y=1 N=0 Y=1 N=0 Y=1 N=0 Y=1 N=0	Left Y=1 N=0 Y=1 N=0 Y=1 N=0 Y=1 N=0 Y=1 N=0
		Total Score		
		Failed test		
Hip Abduction medial rotators Test	• Lie on your side with your bottom leg flexed for support. • While maintaining leg extension, a straight back and your leg turned downward, lift your leg towards the ceiling while keeping your pelvis steady. • Do you understand the •Do you understand the instructions?	Does the hip fail to abduct to 35 degrees? Does the pelvis fail to stay vertical (rotate up or down)? Does the leg lose downward (medial) rotation? Does the hip/knee (leg) move forwards(flexion)? Does the pelvis fail to stay vertical (rotate backwards or forwards)?	Right Y=1 N=0 Y=1 N=0 Y=1 N=0 Y=1 N=0 Y=1 N=0	Left Y=1 N=0 Y=1 N=0 Y=1 N=0 Y=1 N=0 Y=1 N=0
		Total Score		
		Failed test		

Appendix K **Rater agreement summary**

Intra-rater video, intra-rater real time and inter-rater footballers AC1 agreement scores the SKB with rotation test.

		AC1		
Movement criteria	**Side**	**Intra-rater video (n=20)**	**Intra-rater between day (n=11)**	**Inter-rater footballers (n=20)**
Does the pelvis follow the trunk?	Right	0.87	0.74	0.79
	Left	0.93	1.00	0.31
Does the trunk side-bend? *	Right	0.94	0.70	0.68
	Left	0.79	0.64	0.60
Does the pelvis hitch/drop?	Right	0.73	0.47	0.51
Does the pelvis stay level?	Left	0.92	0.20	0.81
Does the trunk rotate less than 30°?	Right	0.95	1.00	0.95
	Left	0.95	1.00	1.00
Do the toes claw or any loss of balance? *	Right	0.71	0.48	0.52
	Left	0.56	0.86	0.66
Does the trunk lean forwards?	Right	0.70	0.20	0.51
	Left	0.90	0.32	0.53

Table 10-6. Intra-rater video, intra-rater real time and inter-rater footballers AC1 agreement scores for the standing hip flexion test.

		AC1		
Movement criteria	**Side**	**Intra-rater video (n=20)**	**Intra-rater between day (n=11)**	**Inter-rater footballers (n=20)**
Does the pelvis drop (hitch)?	Right	0.81	0.86	0.62
Does the pelvis fail to stay level?	Left	0.89	0.86	0.51
Does the pelvis tilt backwards (posteriorly)?	Right	0.93	1.00	0.94
Does the pelvis begin in, or move backwards (posteriorly)?	Left	0.87	0.86	0.95
Does the pelvis begin in, or move backwards (posteriorly)?	Right	1.00	1.00	0.87
	Left	1.00	1.00	0.94
Does the hip fail to bend (flex) just beyond 90 degrees (approximate 110 degrees)?	Right	0.66	0.86	0.68
	Left	0.73	0.58	0.45
Does the trunk lean backwards (extend)?	Right	0.71	0.45	0.50
	Left	0.60	0.52	0.41

Intra-rater video, intra-rater real time and inter-rater footballers AC1 agreement scores for the deep squat.

	AC1		
Movement criteria	**Intra-rater video (n=20)**	**Intra-rater between day (n=11)**	**Inter-rater footballers (n=20)**
Does the trunk fail to stay parallel with the shin (tibia)?	1.00	0.70	0.63
Does the thigh (femur) fail to be horizontal with the floor?	0.83	0.74	0.66
Does the pelvis tilt forwards (anteriorly)? *Does the pelvis begin in, or move forwards (anteriorly)?*	0.36	0.58	0.10
Does the bodyweight shift to one side?	0.90	0.30	0.21

Intra-rater video, intra-rater real time and inter-rater footballers AC1 agreement scores for criteria that are below 0.8 for the sitting hip flexion test.

Movement criteria	Side	AC1		
		Intra-rater video (n=20)	**Intra-rater between day (n=11)**	**Inter-rater footballers (n=20)**
Is there axial rotation of the pelvis? ¥	Right	0.50	0.66	0.76
	Left	0.70	1.00	0.89
Does the pelvis hitch? #	Right	0.94	0.12	-0.40
	Left	0.51	-0.08	-0.47
Does the foot fail to align with the ankle, knee and hip?	Right	0.87	0.32	0.38
Does the foot fail to align with the ankle, knee and hip? (rate both legs)	Left	0.84	0.58	0.48
Does the pelvis tilt backwards (posteriorly)?	Right	0.60	0.66	0.62
Does the pelvis begin in, or move backwards (posteriorly)?	Left	0.70	0.64	0.56
Does the hip fail to bend (flex) just beyond 90 degrees (approximate 110 degrees)?	Right	1.00	1.00	0.83
	Left	1.00	0.90	0.81
Does the trunk lean backwards (extend)?	Right	0.80	0.45	0.32
	Left	0.72	0.66	0.12

¥ and # criteria combined in updated HLLMS

Intra-rater video, intra-rater real time and inter-rater footballers AC1 agreement scores for the hip abduction with lateral rotation test.

Movement criteria	**Side**	**AC1** **Intra-rater video (n=20)**	**Intra-rater between day (n=11)**	**Inter-rater footballers (n=20)**
Does the leg lose lateral rotation?	Right	1.00	0.90	0.89
	Left	0.95	0.90	0.76
Does the hip/knee (leg) move into flexion?	Right	0.94	0.74	1.00
	Left	0.81	0.90	0.89
Does the pelvis move backward?	Right	0.71	0.48	0.68
Does the pelvis fail to stay vertical (rotate backwards or forwards)?	Left	0.84	0.74	0.76
Does the pelvis hitch/drop?	Right	0.88	0.20	0.89
Does the pelvis fail to stay vertical (rotate up or down)?	Left	0.94	0.30	1.00

Intra-rater video, intra-rater real time and inter-rater footballers AC1 agreement scores for the hip abduction with medial rotation test.

Movement criteria	**Side**	**AC1** **Intra-rater video (n=20)**	**Intra-rater between day (n=11)**	**Inter-rater footballers (n=20)**
Does the leg lose medial rotation?	Right	0.66	0.30	-0.08
	Left	0.45	0.86	-0.39
Does the hip/knee (leg) move into flexion?	Right	0.63	0.32	0.48
	Left	0.68	0.47	0.42
Does the pelvis move backward?	Right	0.89	0.52	0.30
Does the pelvis fail to stay vertical (rotate backwards or forwards)?	Left	0.95	0.52	0.60
Does the pelvis hitch/drop?	Right	0.85	0.20	0.83
Does the pelvis fail to stay vertical (rotate up or down)?	Left	0.58	0.32	0.60

Appendix L **Kinematic Reliability Tables**

Within session ICC, mean, SEM, for the kinematics related to the faults from the SKB test in footballers (n=21) and controls (n=11). Faults highlighted in grey remain unchanged in the updated HLLMS.

Movement criteria	**Kinematic variable**	**Right**					
		Controls					
		Session 1		**Session 2**		**Footballers**	
		ICC	**Mean (SEM)**	**ICC**	**Mean (SEM)**	**ICC**	**Mean (SEM)**
Does the knee move inward from the 2nd toe? *Is there an increase in dynamic valgus from the start position?*	Peak medial knee displacement (mm)	0.81	25.6 (6.19)	0.82	26.6 (5.59)	0.75	20.3 (5.79)
	Medial knee excursion at peak knee flexion (mm)	0.77	18.5 (8.51)	0.75	19.3 (8.84)	0.63	12.3 (9.83)
	Peak knee valgus excursion (°)	0.96	-6.8 (1.10)	0.74	-2.0 (2.07)	0.96	-12.2 (2.60)
Does the pelvis hitch/drop? *Does the pelvis fail to stay level?*	Pelvic anti clockwise (right) clockwise (left) rotation peak excursion (°)	0.27	-2.0 (1.72)	0.63	-1.6 (1.05)	0.91	-3.5 (0.84)
Does the knee fail to move 2cm past the toes?	Knee flexion peak excursion (°)	0.97	57.2 (2.04)	0.98	59.3 (1.72)	0.95	56.3 (2.70)
Does the trunk lean forwards?	Trunk flexion peak excursion (°)	0.93	9.5 (1.69)	0.98	10.5 (1.00)	0.87	8.6 (1.97)
Does the pelvis tilt forwards?	Pelvic anterior rotation peak excursion (°)	0.89	12.0 (2.08)	0.95	13.5 (1.48)	0.97	13.2 (1.35)

Within session ICC, mean, SEM, for the kinematics related to the faults from the SKB test in footballers (n=21) and controls (n=11). Faults highlighted in grey remain unchanged in the updated HLLMS.							
Movement criteria	**Kinematic variable**	**Left**					
		Controls					
		Session 1		**Session 2**		**Footballers**	
		ICC	**Mean (SEM)**	**ICC**	**Mean (SEM)**	**ICC**	**Mean (SEM)**
Does the knee move inward from the 2nd toe? *Is there an increase in dynamic valgus from the start position?*	Peak medial knee displacement (mm)	0.89	-29.0 (6.08)	0.86	-29.4 (7.55)	0.80	-27.3 (8.20)
	Medial knee excursion at peak knee flexion (mm)	0.84	-19.8 (9.07)	0.91	-22.5 (6.88)	0.86	-19.3 (7.49)
	Peak knee valgus excursion (°)	0.72	2.1 (0.93)	0.96	1.6 (0.30)	0.59	3.3 (2.83)
Does the pelvis hitch/drop? *Does the pelvis fail to stay level?*	Pelvic anti clockwise (right) clockwise (left) rotation peak excursion (°)	0.90	1.6 (0.59)	0.81	1.6 (0.95)	0.86	3.6 (1.20)
Does the knee fail to move 2cm past the toes?	Knee flexion peak excursion (°)	0.94	61.0 (2.13)	0.94	60.5 (2.17)	0.93	58.1 (3.31)
Does the trunk lean forwards?	Trunk flexion peak excursion (°)	0.95	10.0 (1.22)	0.94	9.1 (1.46)	0.93	7.9 (1.87)
Does the pelvis tilt forwards?	Pelvic anterior rotation peak excursion (°)	0.97	13.1 (1.02)	0.99	12.7 (0.86)	0.95	12.4 (1.64)

CMC and waveform error for within session for the kinematics related to the faults from the SKB test in male academy footballers (n=21). Faults highlighted in grey remain unchanged in the updated HLLMS.					
Movement criteria	**Kinematic variable**	**Right**		**Left**	
		CMC	**waveform**	**CMC**	**waveform**
Does the knee move inward from the 2nd toe?	Medial knee displacement (mm)	0.52 (0.24)	9.49 (7.36)	0.57 (0.20)	9.63 (5.41)
	Knee valgus (°)	0.63 (0.24)	2.78 (3.49)	0.59 (0.23)	2.03 (1.42)
Does the pelvis hitch/drop?	Pelvic lateral rotation (°)	0.61 (0.20)	1.49 (0.71)	0.59 (0.20)	1.65 (0.83)
Does the knee fail to move 2cm past the toes?	Knee flexion (°)	0.81 (0.18)	8.62 (4.97)	0.86 (0.16)	6.31 (3.77)
Does the trunk lean forwards?	Trunk flexion (°)	0.66 (0.22)	2.76 (1.45)	0.61 (0.25)	2.51 (1.08)
Does the pelvis tilt forwards?	Pelvic anterior rotation (°)	0.72 (0.20)	3.11 (3.01)	0.68 (0.22)	2.50 (1.20)

Within session ICC, mean, SEM and MDC for the kinematics related to the faults from the SKB Rot test in footballers (n=21) and controls (n=11). Faults highlighted in grey remain unchanged in the updated HLLMS.							
Movement criteria	**Kinematic variable**	**Right**					
		Controls					
		Session 1		**Session 2**		**Footballers**	
		ICC	**Mean (SEM)**	**ICC**	**Mean (SEM)**	**ICC**	**Mean (SEM)**
Does the pelvis follow the trunk?	Percentage trunk and pelvis in phase (%)	0.93	66.8 (5.22)	0.94	62.2 (4.53)	0.92	53.3 (4.72)
Does the trunk side-bend? *	Peak side flexion excursion right plus left (°)	0.63	9.9 (2.82)	0.75	10.8 (2.54)	0.56	10.4 (4.58)
Does the pelvis hitch/drop?	Pelvic anti clockwise/clockwise rotation peak excursion (°)	0.92	7.0 (0.91)	0.77	7.2 (1.70)	0.75	5.5 (1.81)
Does the trunk lean forwards?	Trunk flexion peak excursion (°)	0.90	11.3 (1.66)	0.95	10.2 (1.34)	0.95	9.6 (1.65)
*fault removed from updated HLLMS							

Within session ICC, mean, SEM for the kinematics related to the faults from the SKB Rot test in footballers (n=21) and controls (n=11). Faults highlighted in grey remain unchanged in the updated HLLMS.

Movement criteria	Kinematic variable	Left					
		Controls					
		Session 1		Session 2		Footballers	
		ICC	Mean (SEM)	ICC	Mean (SEM)	ICC	Mean (SEM)
Does the pelvis follow the trunk?	Percentage trunk and pelvis in phase (%)	0.93	64.3 (4.99)	0.95	61.2 (4.37)	0.91	53.1 (5.71)
Does the trunk side-bend? *	Peak side flexion excursion right plus left (°)	0.74	9.6 (3.34)	0.79	10.6 (1.77)	0.58	8.5 (2.84)
Does the pelvis hitch/drop?	Pelvic anti clockwise/ clockwise rotation peak excursion (°)	0.61	-7.1 (2.59)	0.42	-5.8 (1.86)	0.86	-4.9 (1.14)
Does the trunk lean forwards?	Trunk flexion peak excursion (°)	0.91	10.7 (1.54)	0.91	9.0 (1.47)	0.94	9.7 (1.79)

*fault removed from updated HLLMS

CMC and waveform for within session for the kinematics related to the faults from the SKB Rot test in male academy footballers (n=21). Faults highlighted in grey remain unchanged in the updated HLLMS.

Movement criteria	Kinematic variable	Right		Left	
		CMC	waveform	CMC	waveform
Does the pelvis follow the trunk?	Trunk axial rotation (°)	0.72 (0.13)	1.81 (0.71)	0.74 (0.18)	1.51 (0.53)
	Pelvic axial rotation (°)	0.73 (0.34)	1.93 (1.11)	0.64 (0.22)	1.95 (0.64)
Does the trunk side-bend?*	Trunk lateral flexion (°)	0.65 (0.19)	3.78 (1.83)	0.79 (0.16)	3.49 (1.33)
Does the pelvis hitch/drop?	Pelvic lateral rotation (°)	0.70 (0.35)	6.46 (3.10)	0.66 (0.21)	5.98 (2.54)
Does the trunk lean forwards?	Trunk flexion (°)	0.72 (0.35)	2.14 (0.92)	0.42 (0.19)	1.76 (0.61)

*fault removed from updated HLLMS

CMC and waveform error (WE) for within session intervention for the kinematics related to the faults from the SKB Rot test in controls. Faults highlighted in grey remain unchanged in the updated HLLMS.									
		Session 1 (n=14)				**Session 2 (n=11)**			
Movement criteria	**Kinematic variable**	**Right**		**Left (n=**		**Right**		**Left**	
		CMC	**WE**	**CMC**	**WE**	**CMC**	**WE**	**CMC**	**WE**
Does the pelvis follow the trunk?	Trunk axial rotation (°)	0.63 (0.20)	1.81 (0.59)	0.73 (0.21)	1.39 (0.43)	0.69 (0.24)	1.70 (0.82)	0.67 (0.27)	1.60 (0.82)
	Pelvic axial rotation (°)	0.72 (0.19)	1.99 (0.84)	0.75 (0.18)	1.75 (0.45)	0.76 (0.11)	1.71 (0.60)	0.70 (0.26)	1.46 (0.39)
Does the trunk side-bend?*	Trunk lateral flexion (°)	0.78 (0.16)	3.84 (1.14)	0.89 (0.07)	2.92 (0.98)	0.81 (0.12)	3.12 (1.06)	0.80 (0.19)	3.39 (1.67)
Does the pelvis hitch/drop?	Pelvic lateral rotation (°)	0.75 (0.19)	5.79 (2.48)	0.78 (0.17)	4.32 (1.29)	0.79 (0.11)	5.16 (1.91)	0.76 (0.25)	5.99 (3.64)
Does the trunk lean forwards?	Trunk flexion (°)	0.48 (0.20)	1.88 (0.67)	0.54 (0.19)	1.78 (0.82)	0.57 (0.21)	2.02 (0.80)	0.65 (0.21)	1.85 (0.64)
*fault removed from updated HLLMS									

Within session ICC, mean, SEM and MDC for the kinematics on right side related to the faults from the standing hip flexion test in footballers (n=21) and controls (n=11). Faults highlighted in grey remain unchanged in the updated HLLMS.							
Movement criteria	**Kinematic variable**	**Right**					
		Controls					
		Session 1		**Session 2**		**Footballers**	
		ICC	**Mean (SEM)**	**ICC**	**Mean (SEM)**	**ICC**	**Mean (SEM)**
Does the pelvis drop (hitch)?	Pelvic anti clockwise/ clockwise rotation peak excursion(°)	0.91	9.7 (0.94)	0.95	9.8 (0.83)	0.89	10.2 (0.92)
Does the pelvis tilt backwards (posteriorly)?	Peak pelvic posterior tilt excursion (°)	0.95	-13.1 (0.91)	0.97	-12.6 (0.49)	0.92	-15.6 (1.45)
Does the hip fail to bend (flex) just beyond 90 degrees (approximate 110 degrees)?	Peak hip flexion excursion(°)	0.46	110.1 (4.76)	0.96	112.5 (1.28)	0.77	106.1 (4.05)
Does the trunk lean backwards (extend)?	Trunk extension peak excursion(°)	0.89	-3.7 (0.89)	0.92	-3.0 (0.91)	0.81	-4.4 (1.29)
Does the weight bearing knee bend (flex)?	Peak knee flexion excursion(°)	0.93	6.9 (1.56)	0.95	8.5 (1.28)	0.84	7.9 (2.44)

Within session ICC, mean, SEM and MDC for the kinematics related to the faults from the standing hip flexion test in footballers (n=21) and controls (n=11). Faults highlighted in grey remain unchanged in the updated HLLMS.							
Movement criteria	**Kinematic variable**	**Left**					
		Controls					
		Session 1		**Session 2**		**Footballers**	
		ICC	**Mean (SEM)**	**ICC**	**Mean (SEM)**	**ICC**	**Mean (SEM)**
Does the pelvis drop (hitch)?	Pelvic anti clockwise/ clockwise rotation peak excursion(°)	0.96	-11.4 (0.78)	0.98	-11.1 (0.71)	0.95	-10.9 (0.68)
Does the pelvis tilt backwards (posteriorly)?	Peak pelvic posterior tilt excursion (°)	0.97	-14.3 (0.86)	0.99	-12.8 (0.64)	0.90	-16.2 (1.48)
Does the hip fail to bend (flex) just beyond 90 degrees (approximate 110 degrees)?	Peak hip flexion excursion (°)	0.96	111.8 (1.50)	0.97	112.7 (1.60)	0.61	108.5 (4.04)
Does the trunk lean backwards (extend)?	Trunk extension peak excursion (°)	0.81	-2.8 (1.10)	0.89	-2.7 (0.85)	0.64	-4.4 (1.69)
Does the weight bearing knee bend (flex)?	Peak knee flexion excursion(°)	0.88	6.7 (1.79)	0.88	7.5 (2.37)	0.91	8.6 (1.55)

Appendix

Within session CMC and WE for the kinematics related to the faults from the Standing Hip Flexion Rot test in controls (n=11). Faults highlighted in grey remain unchanged in the updated HLLMS.									
		Session 1				**Session 2**			
Movement criteria	**Kinematic variable**	**Right**		**Left**		**Right**		**Left**	
		CMC	**WE**	**CMC**	**WE**	**CMC**	**WE**	**CMC**	**WE**
Does the pelvis drop (hitch)?	Pelvic lateral rotation (°)	0.83 (0.18)	1.33 (0.57)	0.88 (0.12)	1.17 (0.40)	0.91 (0.08)	1.06 (0.63)	0.91 (0.07)	1.12 (0.38)
Does the pelvis tilt backwards (posteriorly)?	Pelvic posterior tilt (°)	0.90 (0.06)	1.85 (0.73)	0.90 (0.08)	1.82 (0.62)	0.93 (0.03)	1.36 (0.47)	0.88 (0.11)	1.75 (0.80)
Does the hip fail to bend (flex) just beyond 90 degrees (approximate 110 degrees)?	Femur flexion(°)	0.65 (0.17)	2.01 (0.92)	0.66 (0.27)	1.78 (0.92)	0.70 (0.26)	1.82 (0.70)	0.62 (0.19)	1.96 (0.98)
Does the trunk lean backwards (extend)?	Trunk extension (°)	0.95 (0.05)	8.68 (3.82)	0.97 (0.02)	7.57 (2.98)	0.99 (0.01)	4.07 (2.20)	0.96 (0.04)	7.42 (3.48)
Does the weight bearing knee bend (flex)?	Knee flexion (°)	0.64 (0.18)	1.60 (0.88)	0.57 (0.23)	1.58 (0.74)	0.74 (0.12)	1.15 (0.59)	0.59 (0.19)	1.25 (0.59)

Within session CMC and waveform for the kinematics related to the faults from the Standing Hip Flexion Rot test in male academy footballers (n=21). Faults highlighted in grey remain unchanged in the updated HLLMS.					
Movement criteria	**Kinematic variable**	**Right**		**Left**	
		CMC	**waveform**	**CMC**	**waveform**
Does the pelvis drop (hitch)?	Pelvic lateral rotation (°)	0.85 (0.16)	1.26 (0.47)	0.87 (0.10)	1.36 (0.65)
Does the pelvis tilt backwards (posteriorly)?	Pelvic posterior tilt(°)	0.84 (0.18)	2.22 (1.00)	0.86 (0.10)	2.25 (0.95)
Does the hip fail to bend (flex) just beyond 90 degrees (approximate 110 degrees)?	Femur flexion (°)	0.93 (0.09)	9.81 (3.73)	0.93 (0.08)	10.28 (4.97)
Does the trunk lean backwards (extend)?	Trunk extension (°)	0.51 (0.23)	1.78 (1.00)	0.91 (0.10)	1.58 (0.74)
Does the weight bearing knee bend (flex)?	Knee flexion (°)	0.56 (0.26)	2.39 (1.24)	0.59 (0.25)	2.37 (1.32)

Within session ICC, mean, SEM for the kinematics related to the faults from the deep squat test in controls (n=11) and academy footballers (n=21) for the left side. Faults highlighted in grey remain unchanged in the updated HLLMS.							
Movement criteria	Kinematic variable	Controls				Footballers	
		Session 1		Session 2			
		ICC	Mean (SEM)	ICC	Mean (SEM)	ICC	Mean (SEM)
Does the thigh (femur) fail to be horizontal with the floor?	Peak excursion of femur flexion (°)	0.83	76.0 (5.57)	0.95	82.3 (1.60)	0.95	76.0 (3.04)
Does the trunk fail to stay parallel with the shin (tibia)?	Difference between tibia and trunk at peak femur flexion(°)	0.91	9.2 (1.76)	0.98	9.8 (1.51)	0.90	9.5 (1.83)
Does the pelvis tilt forwards (anteriorly)?	Peak pelvis flexion excursion(°)	0.92	23.3 (2.93)	0.97	24.2 (1.34)	0.61	22.9 (6.56)

Within session CMC and WE for within session for the kinematics related to the faults deep squat test in controls Left side only as side rated from (n=11). Faults highlighted in grey remain unchanged in the updated HLLMS.							
		Controls				Footballers	
		Session 1		Session 2			
Movement criteria	Kinematic variable	CMC (SD)	Waveform (SD)	CMC (SD)	Waveform (SD)	CMC (SD)	Waveform (SD)
Does the thigh (femur) fail to be horizontal with the floor?	Femur flexion (°)	0.92 (0.21)	5.89 (5.39)	0.98 (0.01)	4.65 (1.67)	0.96 (0.04)	4.97 (2.63)
Does the trunk fail to stay parallel with the shin (tibia)?	Trunk flexion (°)	0.90 (0.15)	3.54 (1.75)	0.96 (0.02)	2.75 (0.72)	0.89 (0.19)	3.76 (2.45)
	Tibia flexion (°)	0.91 (0.21)	2.35 (2.37)	0.97 (0.02)	1.78 (0.47)	0.93 (0.06)	2.11 (0.63)
Does the pelvis tilt forwards (anteriorly)?	Pelvic anterior tilt (°)	0.87 (0.16)	2.57 (1.22)	0.94 (0.05)	2.05 (0.56)	0.91 (0.09)	2.74 (0.99)

Appendix

Between session ICC, mean, SEM and MDC for the kinematics related to the faults SKB test in controls (n=11). Faults highlighted in grey remain unchanged in the updated HLLMS.							
Movement criteria	**Kinematic variable**	**Right**			**Left**		
		ICC	**Mean (SEM)**	**MDC**	**ICC**	**Mean (SEM)**	**MDC**
Does the knee move inward from the 2nd toe?	Peak medial knee displacement (mm)	0.64	26.1 (15.09)	10.8	0.64	-29.2 (10.35)	8.9
	Medial knee excursion at peak knee flexion (mm)	0.67	18.9 (8.29)	7.98	0.86	-21.1 (7.47)	7.58
	Peak knee valgus excursion	0.60	-6.8 (2.67)	4.53	0.86	1.8 (0.52)	2.00
Does the pelvis hitch/drop?	Pelvic rotation peak excursion (°)	0.07	-1.8 (1.24)	3.08	0.82	1.6 (0.76)	2.42
Does the knee fail to move 2cm past the toes?	Knee flexion peak excursion (°)	0.91	58.3 (3.10)	4.88	0.82	60.8 (3.86)	5.44
Does the trunk lean forwards?	Trunk flexion peak excursion ()	0.83	10.0 (2.73)	4.58	0.91	9.5 (1.69)	3.61
Does the pelvis tilt forwards?	Pelvic anterior rotation peak excursion (°)	0.67	12.8 (3.50)	5.19	0.92	12.9 (1.74)	3.65

CMC and waveform error for between session for the kinematics related to the faults SKB test in controls (n=11). Faults highlighted in grey remain unchanged in the updated HLLMS.					
Movement criteria	**Kinematic variable**	**Right**		**Left**	
		CMC (SD)	**Waveform (SD)**	**CMC (SD)**	**Waveform (SD)**
Does the knee move inward from the 2nd toe?	Medial knee displacement (mm)	0.69 (0.13)	9.79 (2.14)	0.69 (0.13)	9.79 (2.14)
	Knee valgus (°)	0.68 (0.20)	1.77 (0.50)	0.68 (0.20)	1.77 (0.50)
Does the pelvis hitch/drop?	Pelvic lateral rotation (°)	0.65 (0.14)	1.38 (0.38)	0.65 (0.14)	1.38 (0.38)
Does the knee fail to move 2cm past the toes?	Knee flexion (°)	0.91 (0.11)	7.97 (6.98)	0.91 (0.11)	7.97 (6.98)
Does the trunk lean forwards?	Trunk flexion (°)	0.69 (0.21)	2.62 (1.14)	0.69 (0.21)	2.62 (1.14)
Does the pelvis tilt forwards?	Pelvic anterior rotation (°)	0.81 (0.20)	2.32 (0.79)	0.81 (0.20)	2.32 (0.79)

Between session ICC, mean, SEM and MDC for the kinematics related to the faults SKB Rot test in controls (n=11). Faults highlighted in grey remain unchanged in the updated HLLMS.							
Movement criteria	**Kinematic variable**	**Right**			**Left**		
		ICC	**Mean (SEM)**	**MDC**	**ICC**	**Mean (SEM)**	**MDC**
Does the pelvis follow the trunk?	Percentage trunk and pelvis in phase (%)	0.73	63.9 (9.43)	8.5	0.80	64.5 (8.27)	8.0
Does the trunk side-bend? *	Peak side flexion excursion right plus left (°)	0.85	10.4 (1.56)	3.46	0.27	10.1 (3.47)	5.17
Does the pelvis hitch/drop?	Pelvic anti clockwise/clockwise rotation peak excursion (°)	0.79	7.3 (1.30)	3.15	0.65	-6.6 (1.38)	3.25
Does the trunk lean forwards?	Trunk flexion peak excursion	0.81	11.1 (2.24)	4.15	0.76	9.8 (2.19)	4.10
*fault removed from updated HLLMS							

CMC and waveform error for between session for the kinematics related to the faults SKB Rot test in controls (n=11). Faults highlighted in grey remain unchanged in the updated HLLMS.					
Movement criteria	**Kinematic variable**	**Right**		**Left**	
		CMC (SD)	**Waveform (SD)**	**CMC (SD)**	**Waveform (SD)**
Does the pelvis follow the trunk?	Trunk axial rotation (°)	0.85 (0.10)	6.46 (1.62)	0.83 (0.22)	6.51 (2.66)
	Pelvic axial rotation (°)	0.79 (0.15)	4.34 (1.44)	0.79 (0.18)	4.10 (1.25)
Does the trunk side-bend? *	Trunk lateral flexion (°)	0.55 (0.14)	2.09 (0.62)	0.50 (0.18)	2.13 (0.65)
Does the pelvis hitch/drop?	Pelvic lateral rotation (°)	0.67 (0.15)	2.10 (0.78)	0.71 (0.25)	1.60 (0.56)
Does the trunk lean forwards?	Trunk flexion (°)	0.69 (0.15)	2.65 (1.25)	0.64 (0.18)	2.80 (1.57)
*fault removed from updated HLLMS					

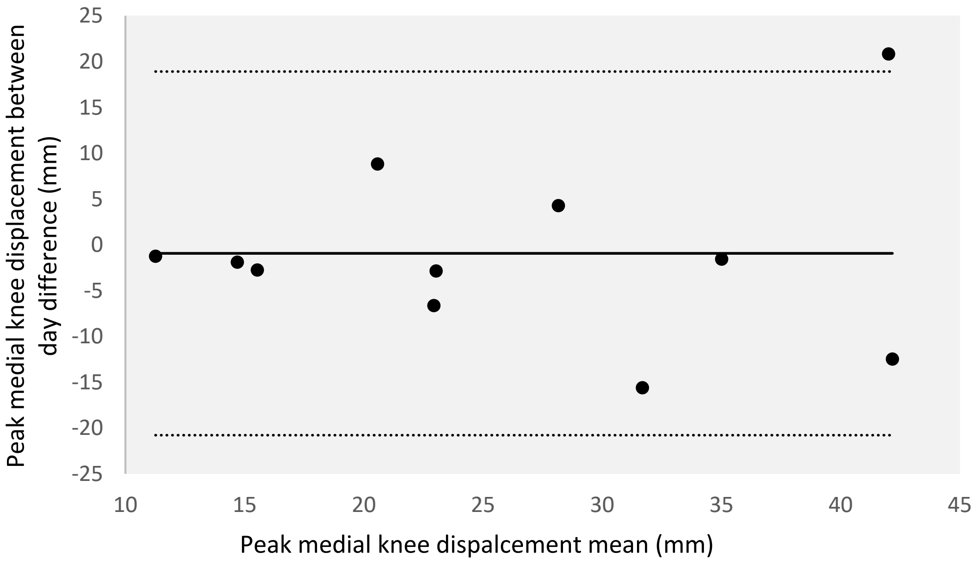
Appendix

ICC, mean, SEM and MDC for between session for the kinematics related to the faults Standing Hip Flexion test in controls (n=11). Faults highlighted in grey remain unchanged in the updated HLLMS.							
Movement criteria	**Kinematic variable**	**Right**			**Left**		
		ICC	**Mean (SEM)**	**MDC**	**ICC**	**Mean (SEM)**	**MDC**
Does the pelvis drop (hitch)?	Pelvic anti clockwise/clockwise rotation peak excursion (°)	0.87	9.7 (1.14)	3.0	0.93	-11.3 (1.11)	2.9
Does the pelvis tilt backwards (posteriorly)?	Peak pelvic posterior tilt excursion (°)	0.89	-12.9 (1.65)	3.56	0.54	-13.4 (3.45)	5.15
Does the hip fail to bend (flex) just beyond 90 degrees (approximate 110 degrees)?	Peak hip flexion excursion (°)	0.74	112.5 (2.65)	4.51	0.85	112.3 (3.06)	4.85
Does the trunk lean backwards (extend)?	Trunk extension peak excursion (°)	0.75	-3.0 (1.39)	3.27	0.75	-2.8 (1.11)	2.92
Does the weight bearing knee bend (flex)?	Peak knee flexion excursion (°)	0.79	8.5 (2.53)	4.41	0.75	7.1 (2.68)	4.54

Between session CMC and WE the kinematics related to the faults Standing Hip Flexion test in controls (n=11). Faults highlighted in grey remain unchanged in the updated HLLMS.					
Movement criteria	**Kinematic variable**	**Right**		**Left**	
		CMC (SD)	**Waveform (SD)**	**CMC (SD)**	**Waveform (SD)**
Does the pelvis drop (hitch)?	Pelvic lateral rotation (°)	0.85 (0.09)	1.57 (0.54)	0.90 (0.06)	1.42 (0.47)
Does the pelvis tilt backwards (posteriorly)?	Pelvic posterior tilt (°)	0.82 (0.11)	2.95 (1.55)	0.78 (0.15)	3.41 (1.75)
Does the hip fail to bend (flex) just beyond 90 degrees (approximate 110 degrees)?	Femur flexion (°)	0.96 (0.03)	9.01 (3.38)	0.96 (0.02)	9.37 (2.75)
Does the trunk lean backwards (extend)?	Trunk extension (°)	0.61 (0.15)	2.05 (1.14)	0.42 (0.15)	2.19 (0.86)
Does the weight bearing knee bend (flex)?	Knee flexion (°)	0.64 (0.24)	2.42 (1.00)	0.52 (0.22)	3.23 (1.95)

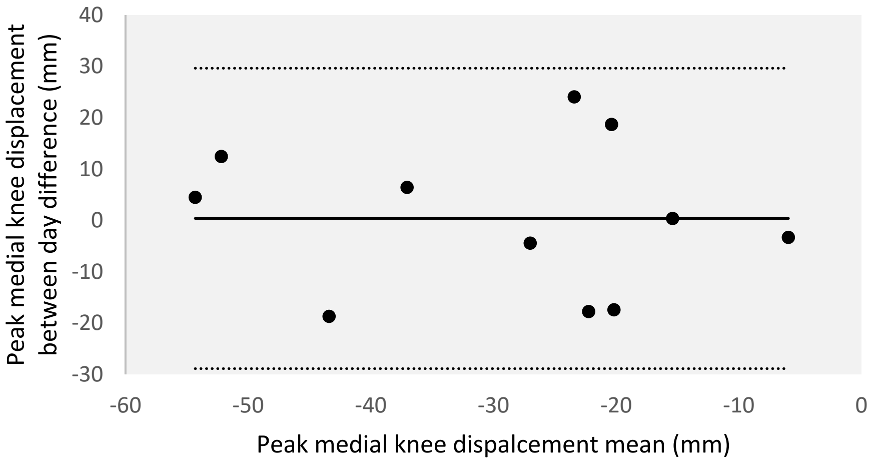
Appendix M Between day Bland and Altman plots

Small Knee Bend Test

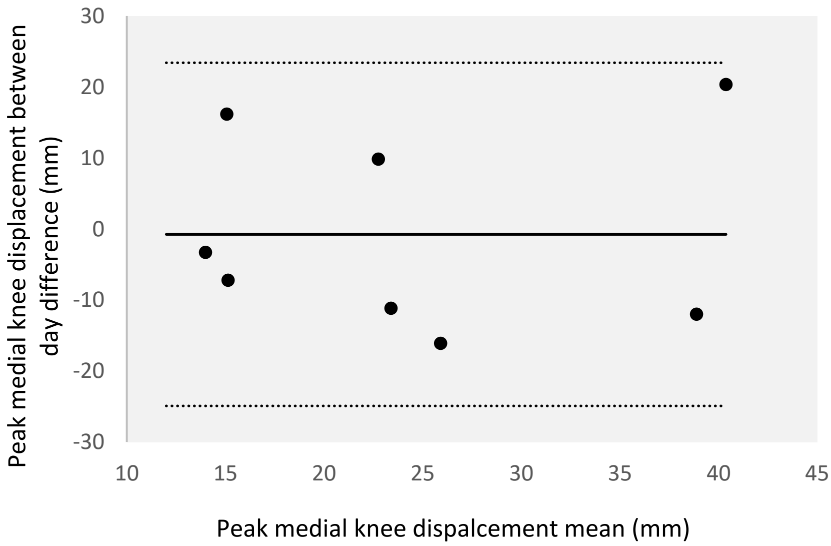


Right SKB test, peak medial knee displacement: Bland and Altman distribution plots showing the mean measurement (day one mean + day two mean / 2) against the differences between measurements (day one minus day two). The middle horizontal line represents the mean value of the difference between the score on day one minus day two. The other two horizontal lines represent the lower and upper levels of agreement (mean day difference ± 2 standard deviation).

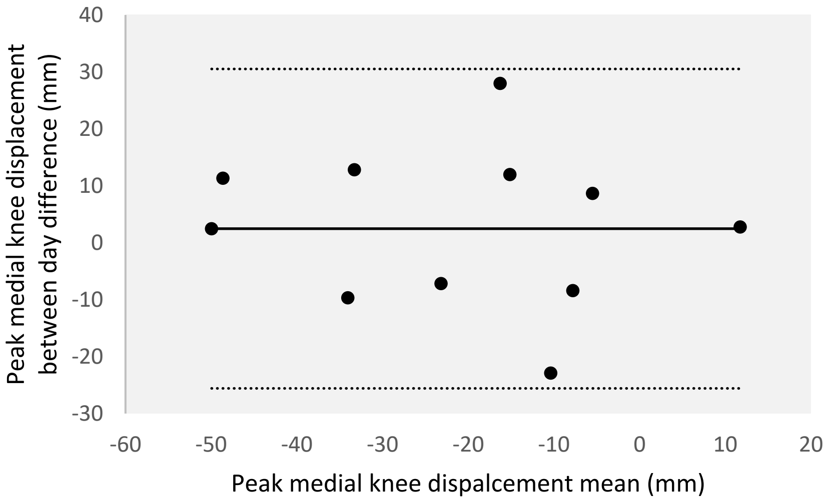
Appendix



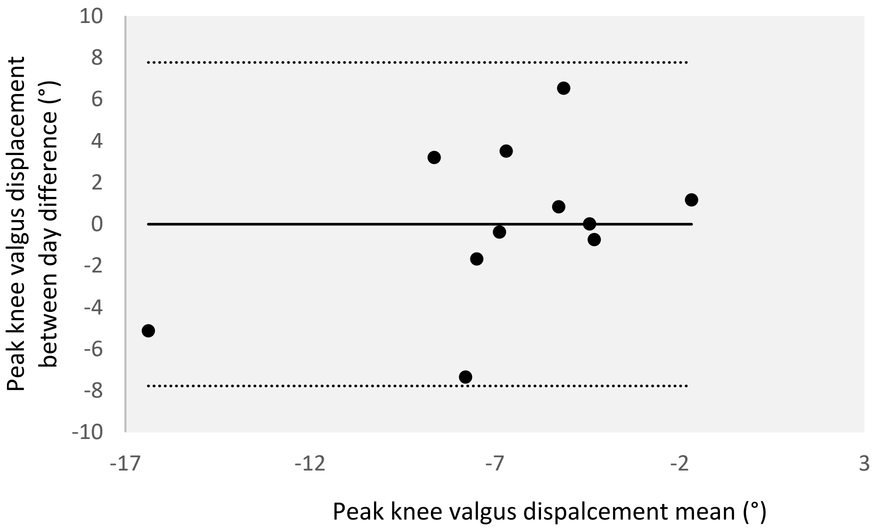
Left SKB test, peak medial knee displacement: Bland and Altman distribution plots showing the mean measurement (day one mean + day two mean / 2) against the differences between measurements (day one minus day two). The middle horizontal line represents the mean value of the difference between the score on day one minus day two. The other two horizontal lines represent the lower and upper levels of agreement (mean day difference ± 2 standard deviation).



Right SKB test, peak medial knee displacement at peak knee flexion: Bland and Altman distribution plots showing the mean measurement (day one mean + day two mean / 2) against the differences between measurements (day one minus day two). The middle horizontal line represents the mean value of the difference between the score on day one minus day two. The other two horizontal lines represent the lower and upper levels of agreement (mean day difference ± 2 standard deviation).

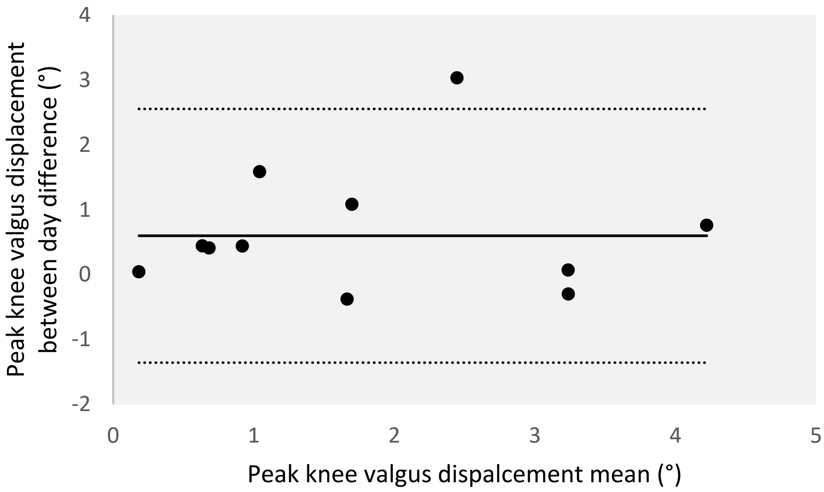


Left SKB test, peak medial knee displacement at peak knee flexion: Bland and Altman distribution plots showing the mean measurement (day one mean + day two mean / 2) against the differences between measurements (day one minus day two). The middle horizontal line represents the mean value of the difference between the score on day one minus day two. The other two horizontal lines represent the lower and upper levels of agreement (mean day difference ± 2 standard deviation).

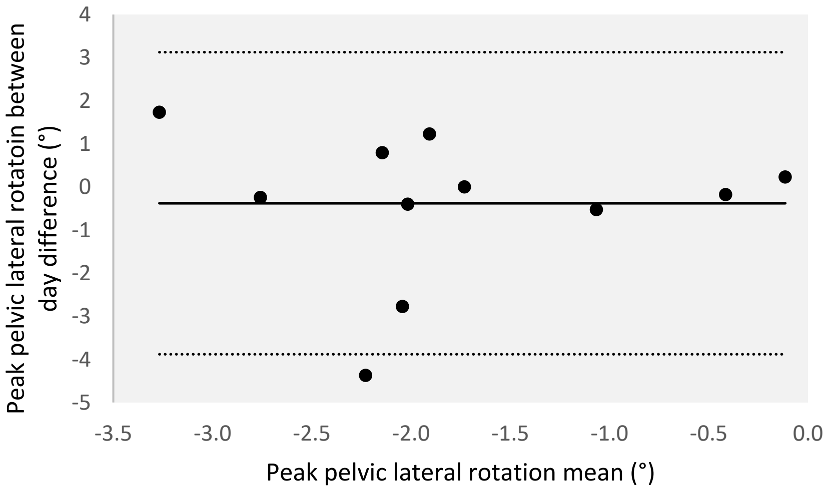


Right SKB test, peak knee valgus displacement: Bland and Altman distribution plots showing the mean measurement (day one mean + day two mean / 2) against the differences between measurements (day one minus day two). The middle horizontal line represents the mean value of the difference between the score on day one minus day two. The other two horizontal lines represent the lower and upper levels of agreement (mean day difference ± 2 standard deviation).

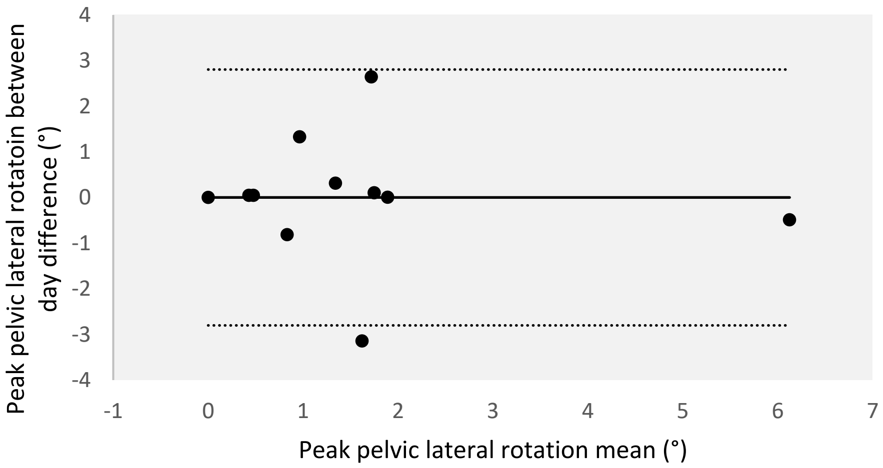
Appendix



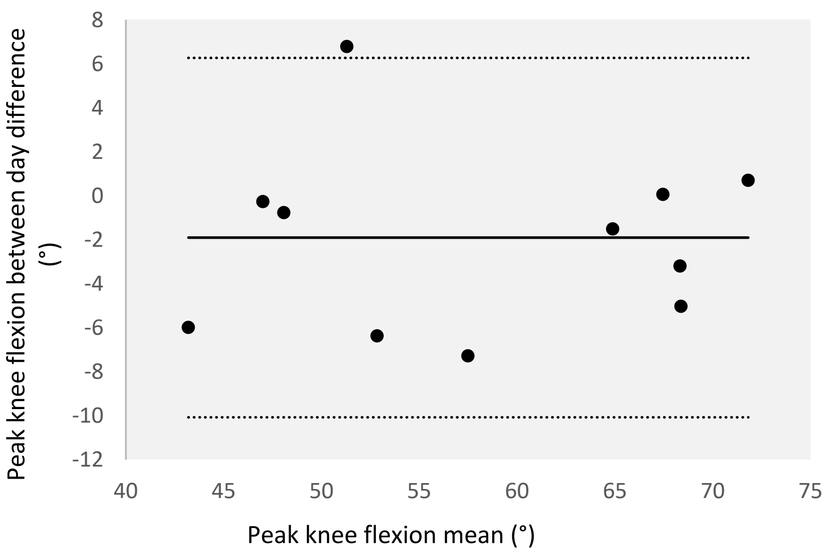
Left SKB test, peak knee valgus displacement: Bland and Altman distribution plots showing the mean measurement (day one mean + day two mean / 2) against the differences between measurements (day one minus day two). The middle horizontal line represents the mean value of the difference between the score on day one minus day two. The other two horizontal lines represent the lower and upper levels of agreement (mean day difference ± 2 standard deviation).



Right SKB test, peak pelvic lateral rotation: Bland and Altman distribution plots showing the mean measurement (day one mean + day two mean / 2) against the differences between measurements (day one minus day two). The middle horizontal line represents the mean value of the difference between the score on day one minus day two. The other two horizontal lines represent the lower and upper levels of agreement (mean day difference ± 2 standard deviation).

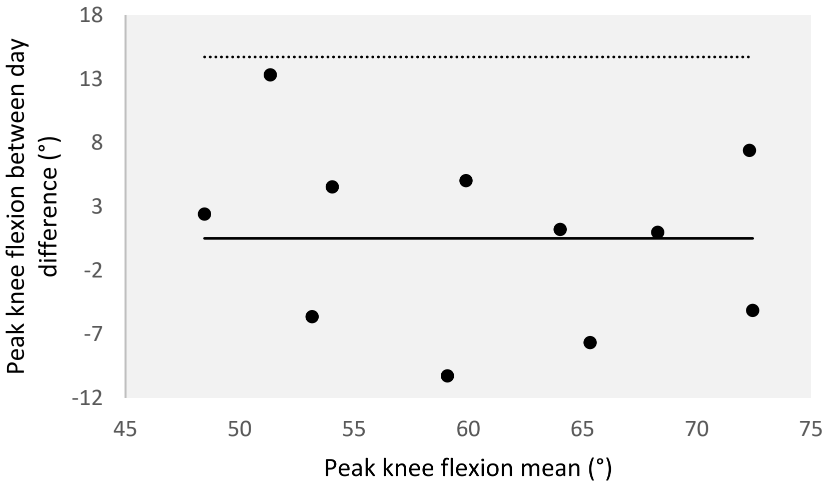


Left SKB test, peak pelvic lateral rotation: Bland and Altman distribution plots showing the mean measurement (day one mean + day two mean / 2) against the differences between measurements (day one minus day two). The middle horizontal line represents the mean value of the difference between the score on day one minus day two. The other two horizontal lines represent the lower and upper levels of agreement (mean day difference ± 2 standard deviation).

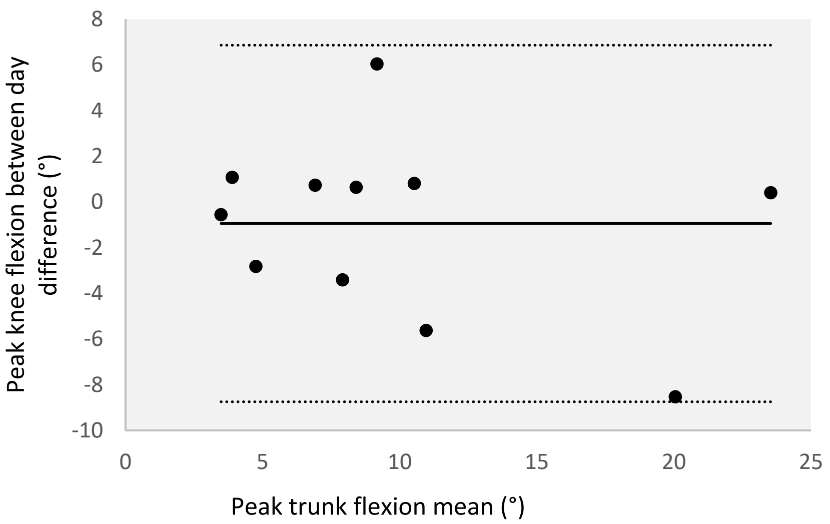


Right SKB test, peak knee flexion: Bland and Altman distribution plots showing the mean measurement (day one mean + day two mean / 2) against the differences between measurements (day one minus day two). The middle horizontal line represents the mean value of the difference between the score on day one minus day two. The other two horizontal lines represent the lower and upper levels of agreement (mean day difference ± 2 standard deviation).

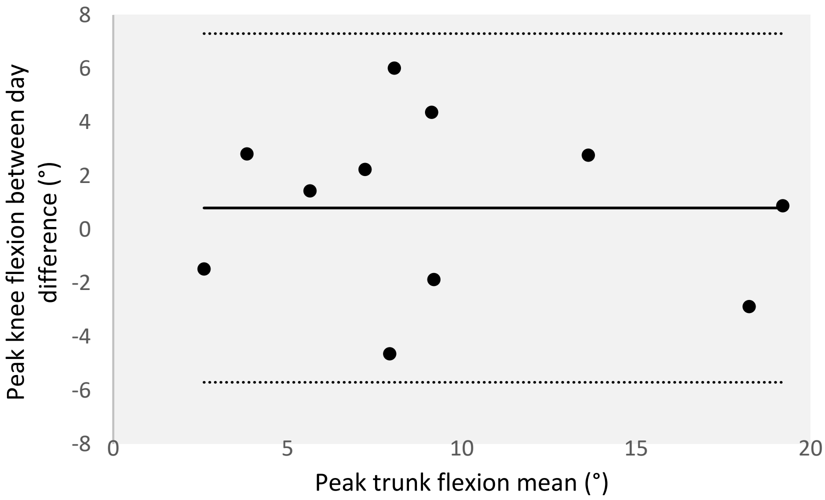
Appendix



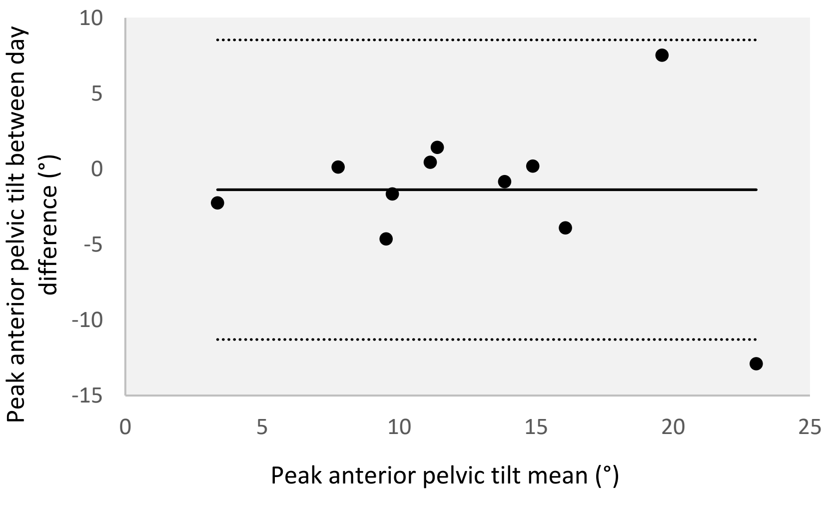
Left SKB test, peak knee flexion: Bland and Altman distribution plots showing the mean measurement (day one mean + day two mean / 2) against the differences between measurements (day one minus day two). The middle horizontal line represents the mean value of the difference between the score on day one minus day two. The other two horizontal lines represent the lower and upper levels of agreement (mean day difference ± 2 standard deviation).



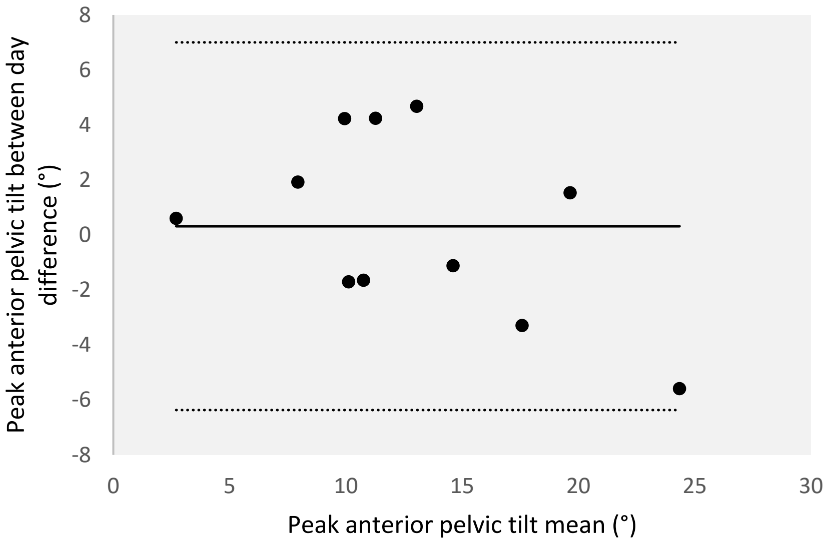
Right SKB test, peak trunk flexion: Bland and Altman distribution plots showing the mean measurement (day one mean + day two mean / 2) against the differences between measurements (day one minus day two). The middle horizontal line represents the mean value of the difference between the score on day one minus day two. The other two horizontal lines represent the lower and upper levels of agreement (mean day difference ± 2 standard deviation).



Left SKB test, peak trunk flexion: Bland and Altman distribution plots showing the mean measurement (day one mean + day two mean / 2) against the differences between measurements (day one minus day two). The middle horizontal line represents the mean value of the difference between the score on day one minus day two. The other two horizontal lines represent the lower and upper levels of agreement (mean day difference ± 2 standard deviation).

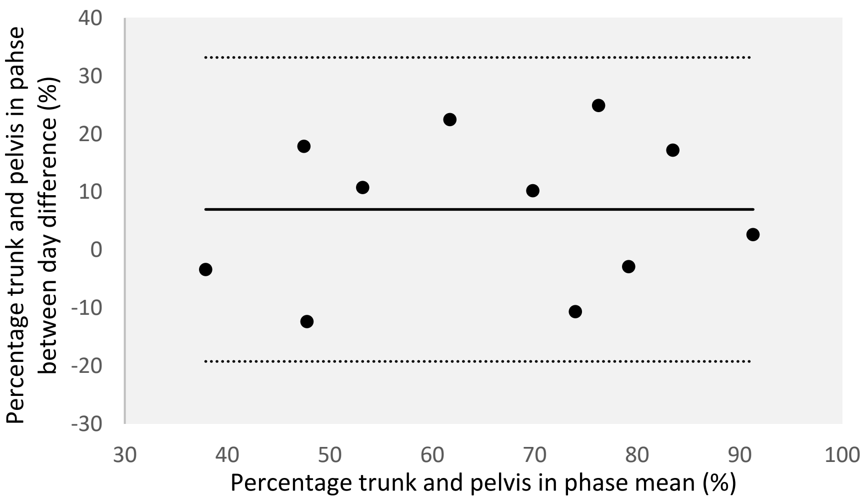


Right SKB test, peak anterior pelvic tilt: Bland and Altman distribution plots showing the mean measurement (day one mean + day two mean / 2) against the differences between measurements (day one minus day two). The middle horizontal line represents the mean value of the difference between the score on day one minus day two. The other two horizontal lines represent the lower and upper levels of agreement (mean day difference ± 2 standard deviation).

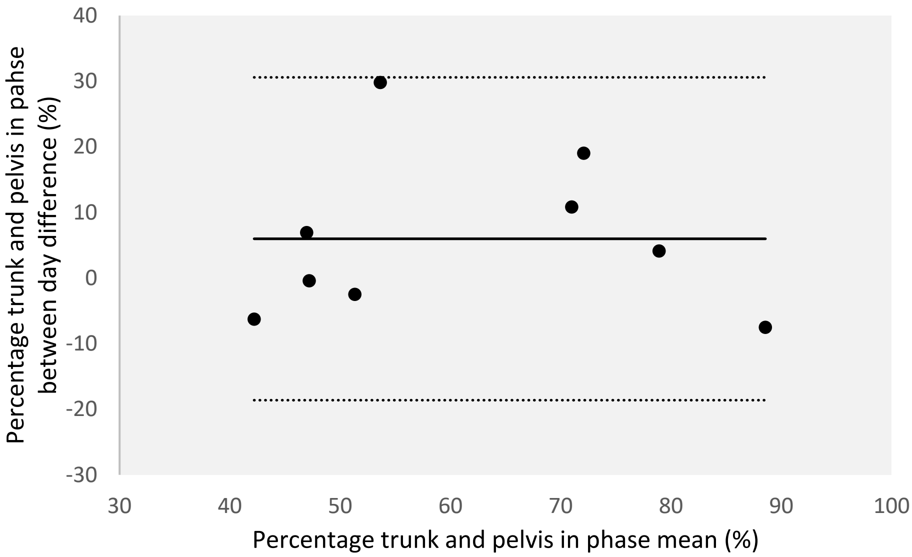


Left SKB test, peak anterior pelvic tilt: Bland and Altman distribution plots showing the mean measurement (day one mean + day two mean / 2) against the differences between measurements (day one minus day two). The middle horizontal line represents the mean value of the difference between the score on day one minus day two. The other two horizontal lines represent the lower and upper levels of agreement (mean day difference ± 2 standard deviation).

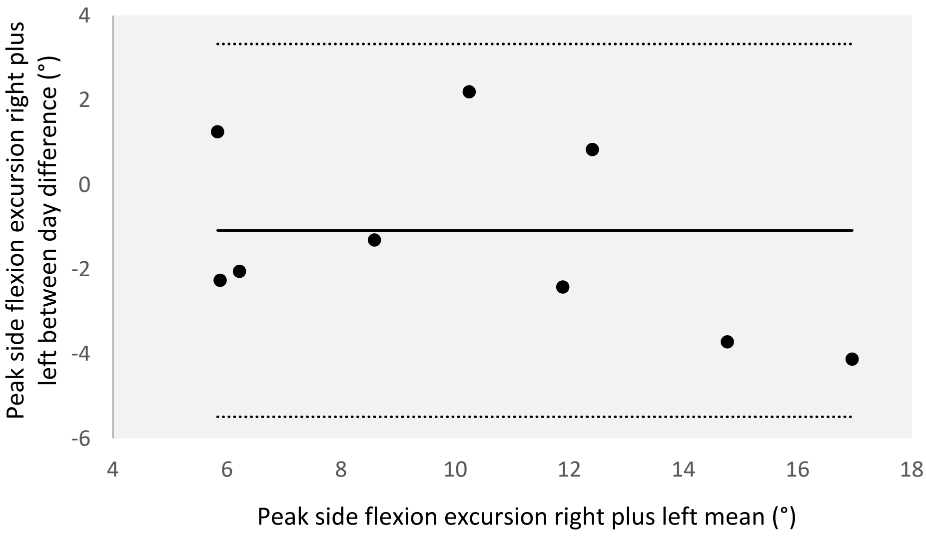
Small Knee Bend with Rotation Test



Right SKB Rot test, percentage trunk and pelvis is phase: Bland and Altman distribution plots showing the mean measurement (day one mean + day two mean / 2) against the differences between measurements (day one minus day two). The middle horizontal line represents the mean value of the difference between the score on day one minus day two. The other two horizontal lines represent the lower and upper levels of agreement (mean day difference ± 2 standard deviation).

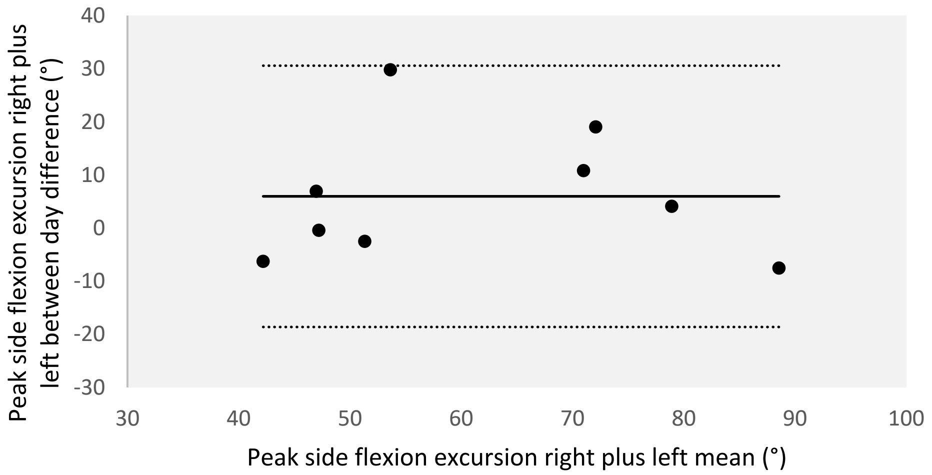


Left SKB Rot test, peak anterior pelvic tilt: Bland and Altman distribution plots showing the mean measurement (day one mean + day two mean / 2) against the differences between measurements (day one minus day two). The middle horizontal line represents the mean value of the difference between the score on day one minus day two. The other two horizontal lines represent the lower and upper levels of agreement (mean day difference ± 2 standard deviation).

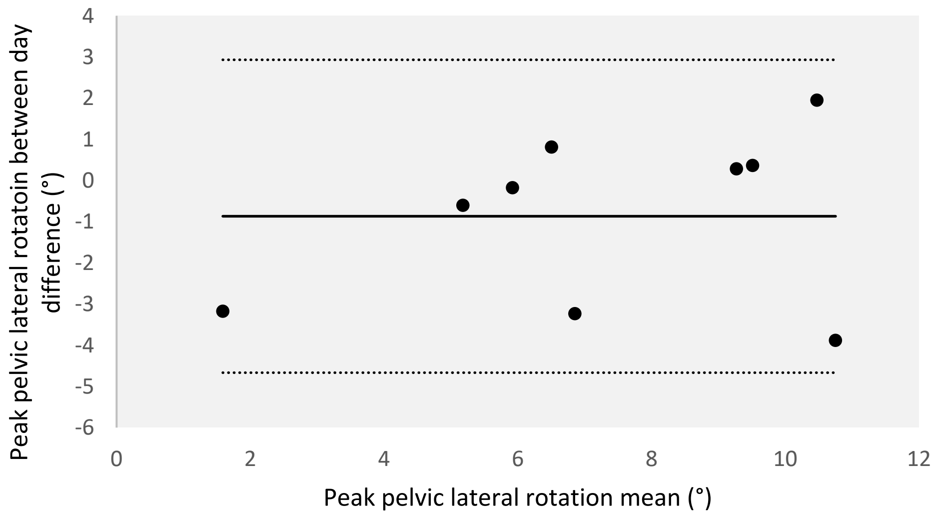


Right SKB Rot test, peak side flexion excursion right plus left: Bland and Altman distribution plots showing the mean measurement (day one mean + day two mean / 2) against the differences between measurements (day one minus day two). The middle horizontal line represents the mean value of the difference between the score on day one minus day two. The other two horizontal lines represent the lower and upper levels of agreement (mean day difference ± 2 standard deviation).

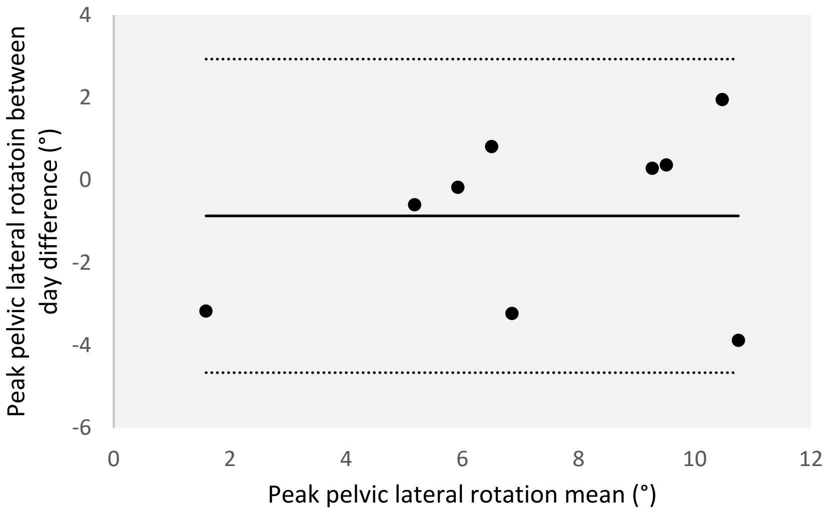
Appendix



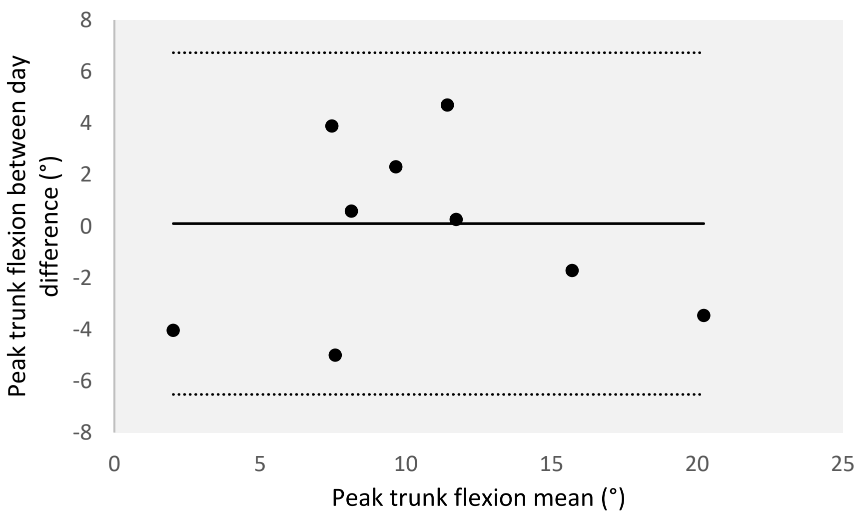
Left SKB Rot test, peak side flexion excursion right plus left: Bland and Altman distribution plots showing the mean measurement (day one mean + day two mean / 2) against the differences between measurements (day one minus day two). The middle horizontal line represents the mean value of the difference between the score on day one minus day two. The other two horizontal lines represent the lower and upper levels of agreement (mean day difference ± 2 standard deviation).



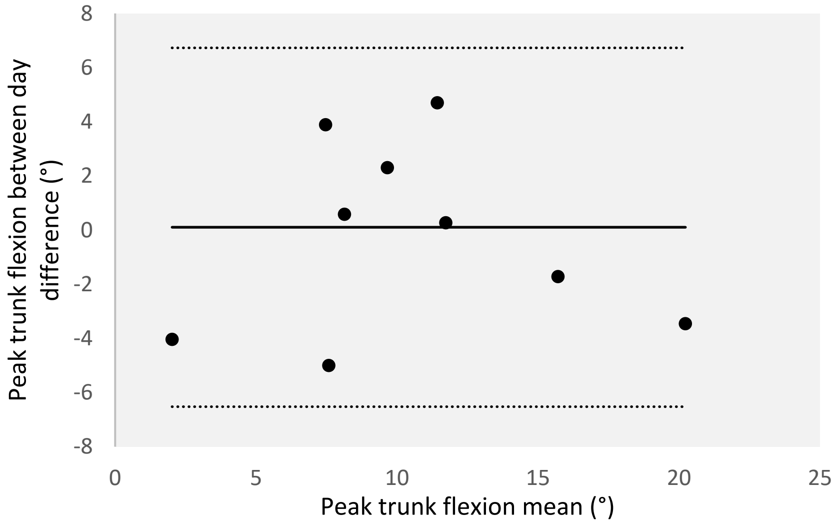
Right SKB Rot test, peak pelvic lateral rotation: Bland and Altman distribution plots showing the mean measurement (day one mean + day two mean / 2) against the differences between measurements (day one minus day two). The middle horizontal line represents the mean value of the difference between the score on day one minus day two. The other two horizontal lines represent the lower and upper levels of agreement (mean day difference ± 2 standard deviation).



Left SKB Rot test, peak pelvic lateral rotation: Bland and Altman distribution plots showing the mean measurement (day one mean + day two mean / 2) against the differences between measurements (day one minus day two). The middle horizontal line represents the mean value of the difference between the score on day one minus day two. The other two horizontal lines represent the lower and upper levels of agreement (mean day difference ± 2 standard deviation).

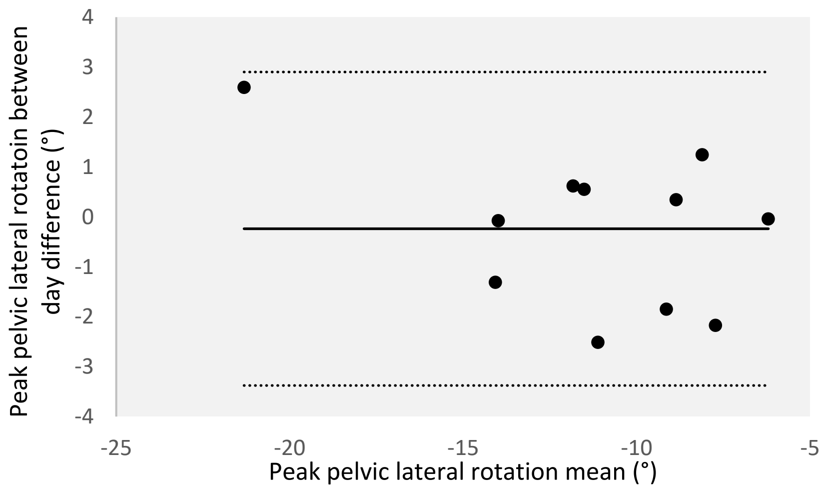


Right SKB Rot test, peak trunk flexion: Bland and Altman distribution plots showing the mean measurement (day one mean + day two mean / 2) against the differences between measurements (day one minus day two). The middle horizontal line represents the mean value of the difference between the score on day one minus day two. The other two horizontal lines represent the lower and upper levels of agreement (mean day difference ± 2 standard deviation).

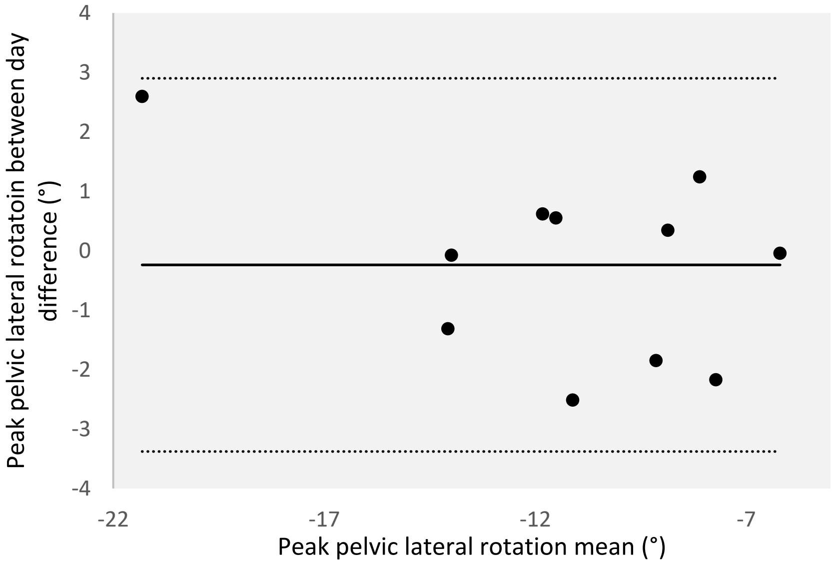


Left SKB Rot test, peak trunk flexion: Bland and Altman distribution plots showing the mean measurement (day one mean + day two mean / 2) against the differences between measurements (day one minus day two). The middle horizontal line represents the mean value of the difference between the score on day one minus day two. The other two horizontal lines represent the lower and upper levels of agreement (mean day difference ± 2 standard deviation).

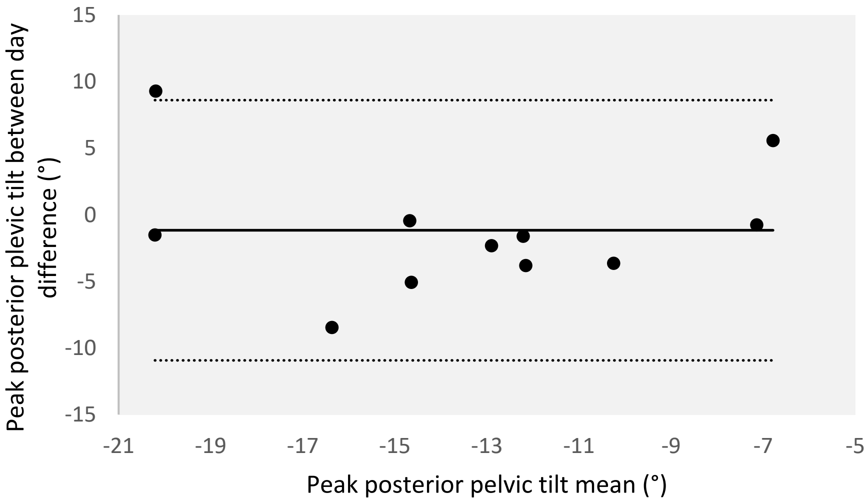
Standing Hip Flexion Test



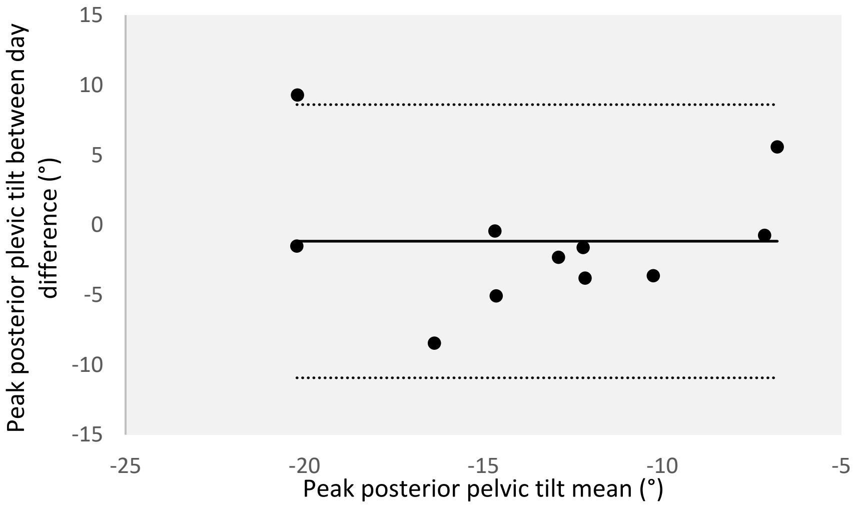
Right standing hip flexion test, peak pelvic lateral rotation: Bland and Altman distribution plots showing the mean measurement (day one mean + day two mean / 2) against the differences between measurements (day one minus day two). The middle horizontal line represents the mean value of the difference between the score on day one minus day two. The other two horizontal lines represent the lower and upper levels of agreement (mean day difference ± 2 standard deviation).



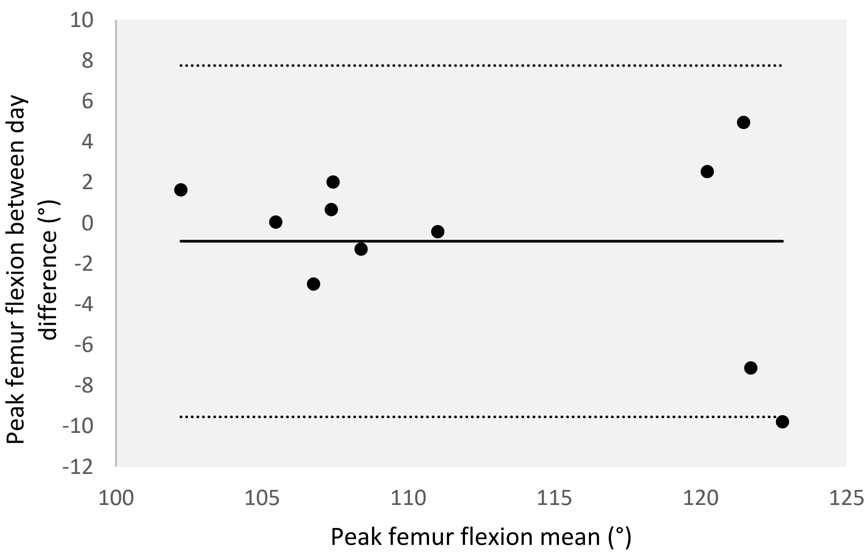
Left standing hip flexion test, peak pelvic lateral rotation: Bland and Altman distribution plots showing the mean measurement (day one mean + day two mean / 2) against the differences between measurements (day one minus day two). The middle horizontal line represents the mean value of the difference between the score on day one minus day two. The other two horizontal lines represent the lower and upper levels of agreement (mean day difference ± 2 standard deviation).



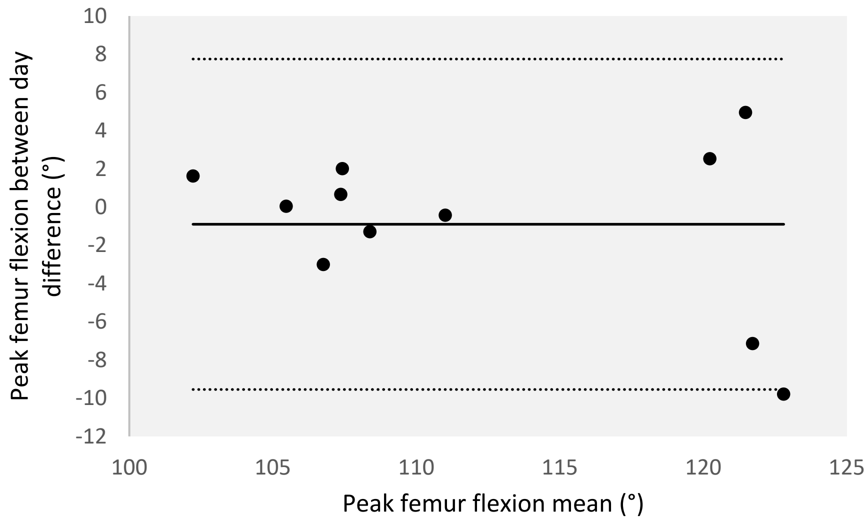
Right standing hip flexion test, posterior pelvic tilt: Bland and Altman distribution plots showing the mean measurement (day one mean + day two mean / 2) against the differences between measurements (day one minus day two). The middle horizontal line represents the mean value of the difference between the score on day one minus day two. The other two horizontal lines represent the lower and upper levels of agreement (mean day difference ± 2 standard deviation).



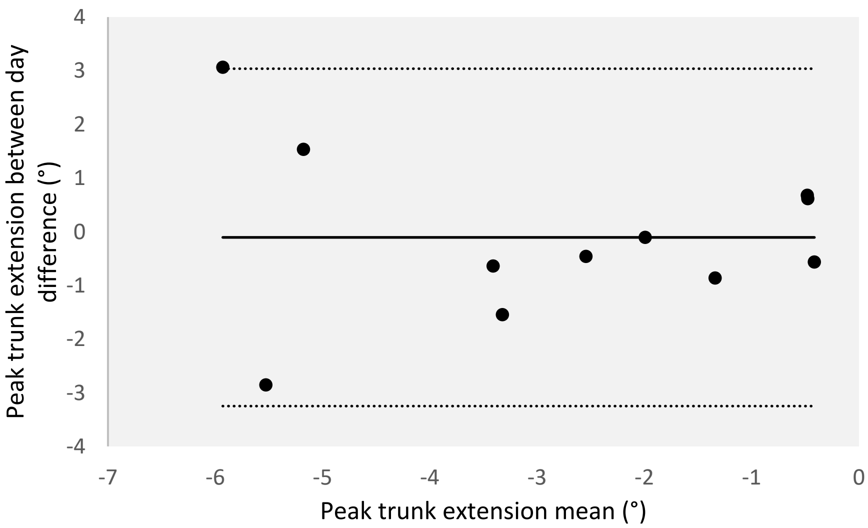
Left standing hip flexion test, posterior pelvic tilt: Bland and Altman distribution plots showing the mean measurement (day one mean + day two mean / 2) against the differences between measurements (day one minus day two). The middle horizontal line represents the mean value of the difference between the score on day one minus day two. The other two horizontal lines represent the lower and upper levels of agreement (mean day difference ± 2 standard deviation).



Right standing hip flexion test, peak femur flexion: Bland and Altman distribution plots showing the mean measurement (day one mean + day two mean / 2) against the differences between measurements (day one minus day two). The middle horizontal line represents the mean value of the difference between the score on day one minus day two. The other two horizontal lines represent the lower and upper levels of agreement (mean day difference ± 2 standard deviation).

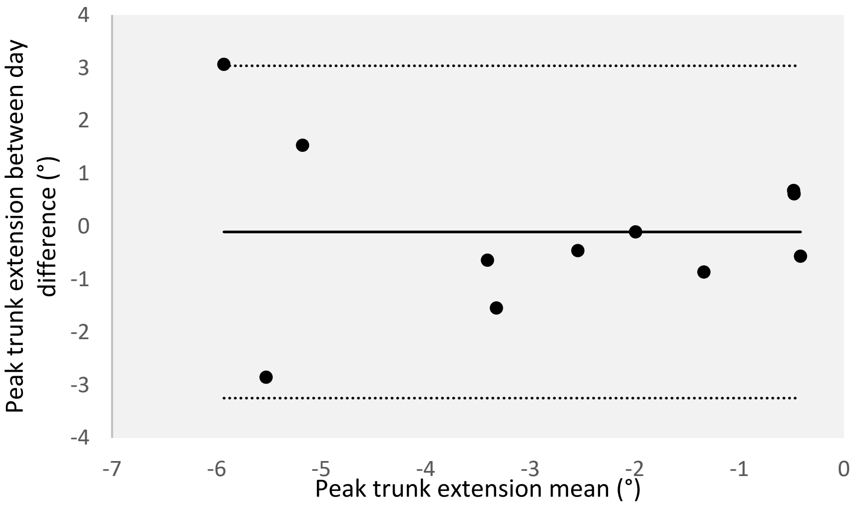


Left standing hip flexion test, peak femur flexion: Bland and Altman distribution plots showing the mean measurement (day one mean + day two mean / 2) against the differences between measurements (day one minus day two). The middle horizontal line represents the mean value of the difference between the score on day one minus day two. The other two horizontal lines represent the lower and upper levels of agreement (mean day difference ± 2 standard deviation).

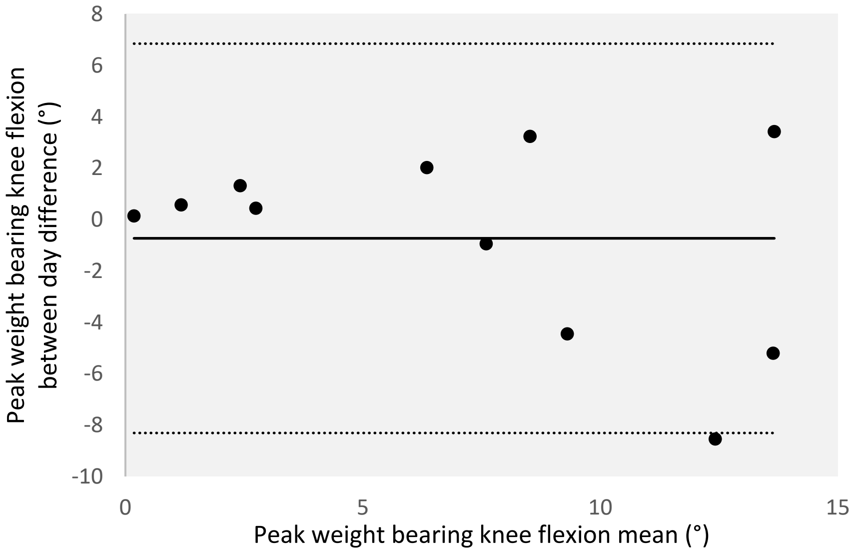


Right standing hip flexion test, peak trunk extension: Bland and Altman distribution plots showing the mean measurement (day one mean + day two mean / 2) against the differences between measurements (day one minus day two). The middle horizontal line represents the mean value of the difference between the score on day one minus day two. The other two horizontal lines represent the lower and upper levels of agreement (mean day difference ± 2 standard deviation).

Appendix

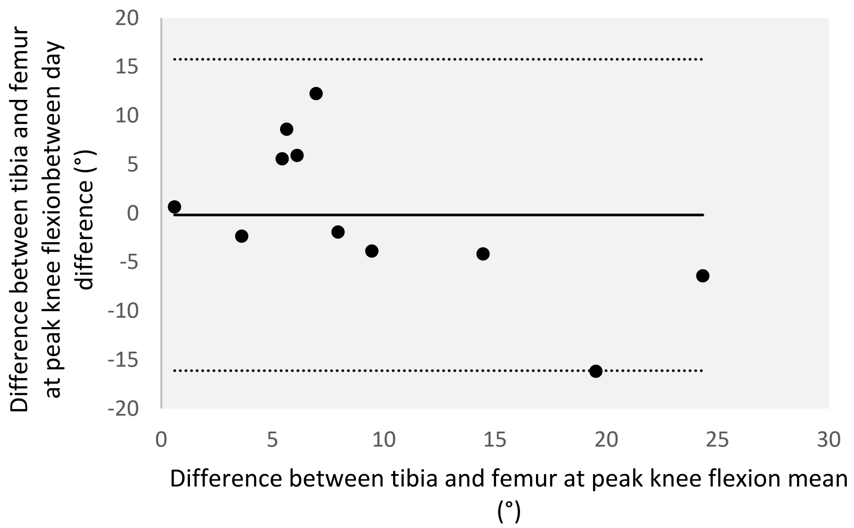


Left standing hip flexion test, peak trunk extension: Bland and Altman distribution plots showing the mean measurement (day one mean + day two mean / 2) against the differences between measurements (day one minus day two). The middle horizontal line represents the mean value of the difference between the score on day one minus day two. The other two horizontal lines represent the lower and upper levels of agreement (mean day difference ± 2 standard deviation).

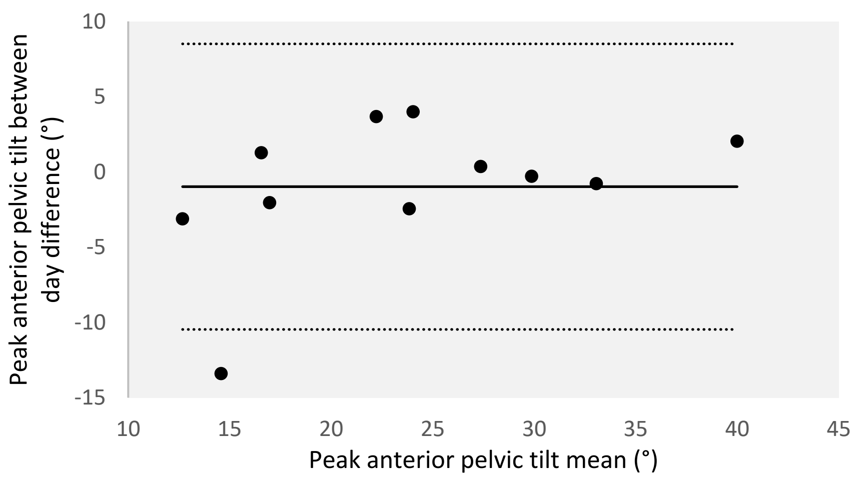


Left standing hip flexion test, peak weight bearing knee flexion: Bland and Altman distribution plots showing the mean measurement (day one mean + day two mean / 2) against the differences between measurements (day one minus day two). The middle horizontal line represents the mean value of the difference between the score on day one minus day two. The other two horizontal lines represent the lower and upper levels of agreement (mean day difference ± 2 standard deviation).

Deep Squat

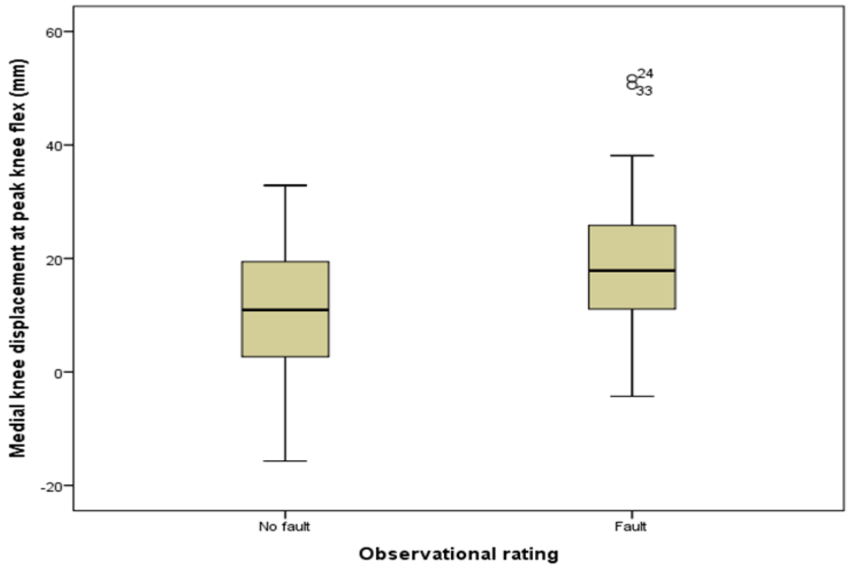


Deep squat test, difference between femur and tibia at peak knee flexion: Bland and Altman distribution plots showing the mean measurement (day one mean + day two mean / 2) against the differences between measurements (day one minus day two). The middle horizontal line represents the mean value of the difference between the score on day one minus day two. The other two horizontal lines represent the lower and upper levels of agreement (mean day difference ± 2 standard deviation).

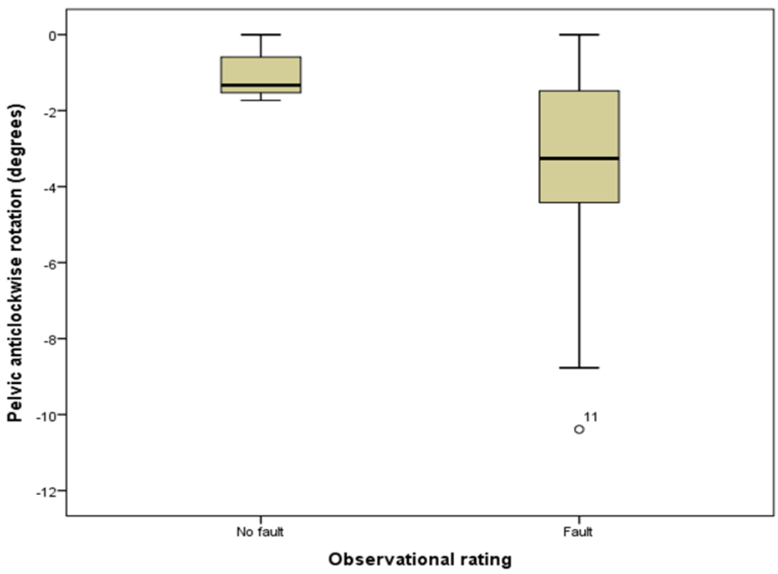


Deep squat test, peak anterior pelvic tilt: Bland and Altman distribution plots showing the mean measurement (day one mean + day two mean / 2) against the differences between measurements (day one minus day two). The middle horizontal line represents the mean value of the difference between the score on day one minus day two. The other two horizontal lines represent the lower and upper levels of agreement (mean day difference ± 2 standard deviation).

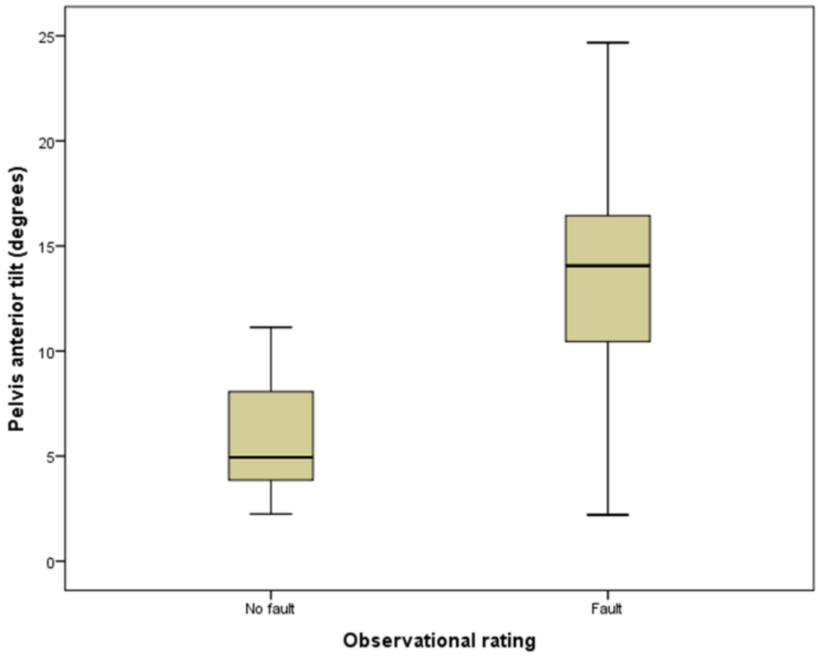
Appendix N**Box plots: criterion validity**



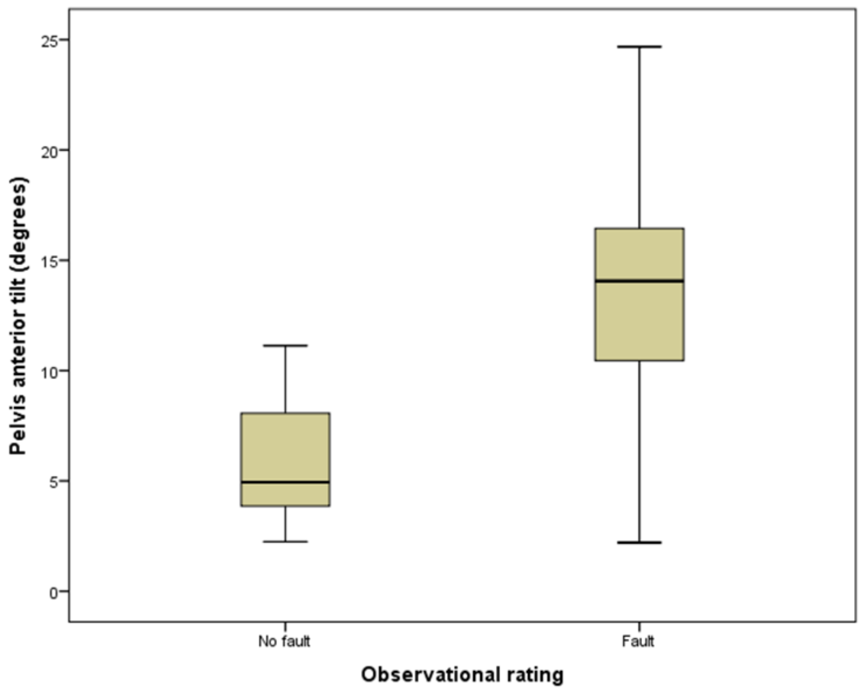
Box plots showing median, interquartile range, maximum, minimum and outliers for the peak excursion of medial knee displacement at peak knee flexion for fault and no fault from the SKB test on the right side.



Box plots showing median, interquartile range, maximum, minimum and outliers for the peak excursion of pelvic anticlockwise rotation for fault and no fault from the SKB test on the right side.

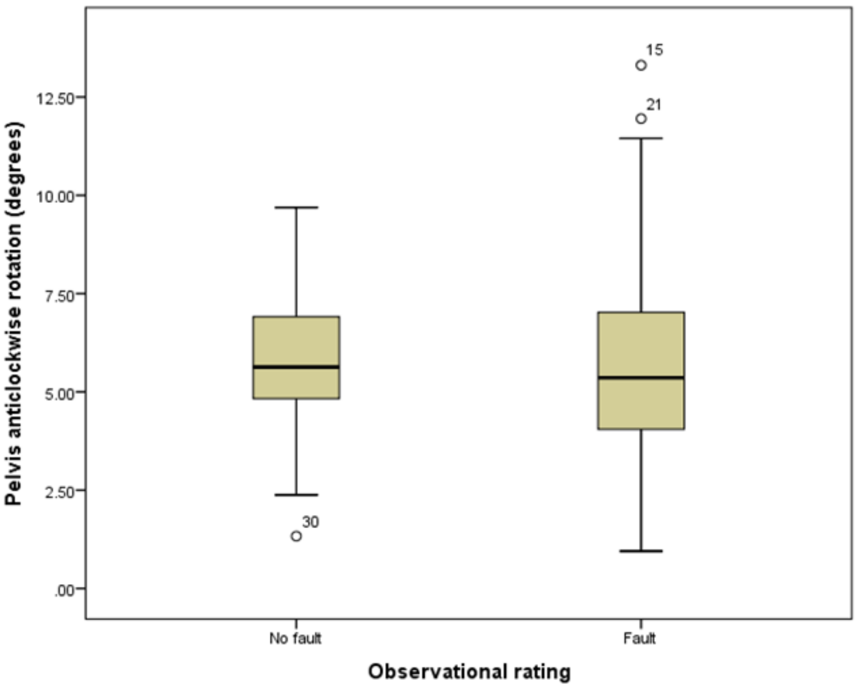


Box plots showing median, interquartile range, maximum, minimum and outliers for the peak excursion of pelvic anterior tilt for fault and no fault from the SKB test on the right side.

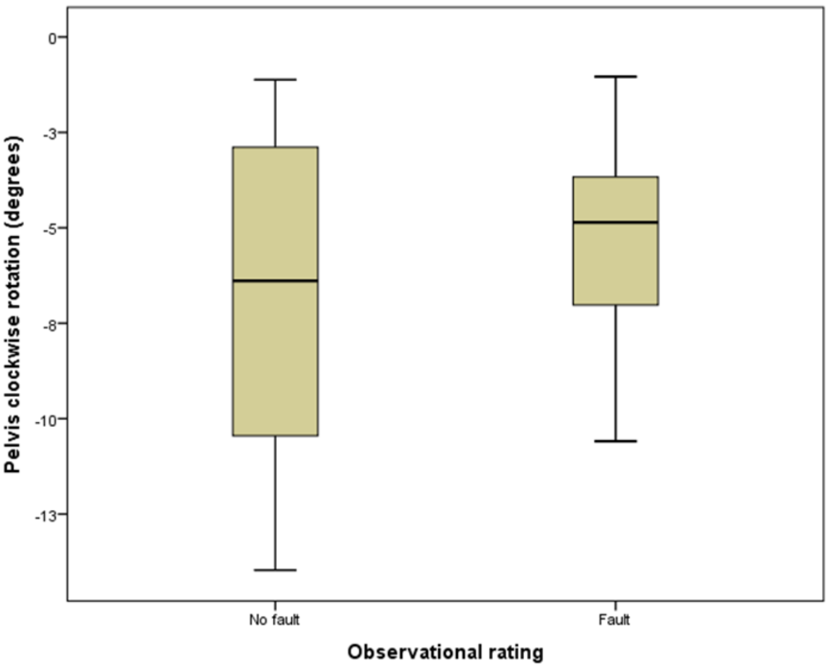


Box plots showing median, interquartile range, maximum, minimum and outliers for the peak excursion of pelvic anterior tilt for fault and no fault from the SKB test on the right side.

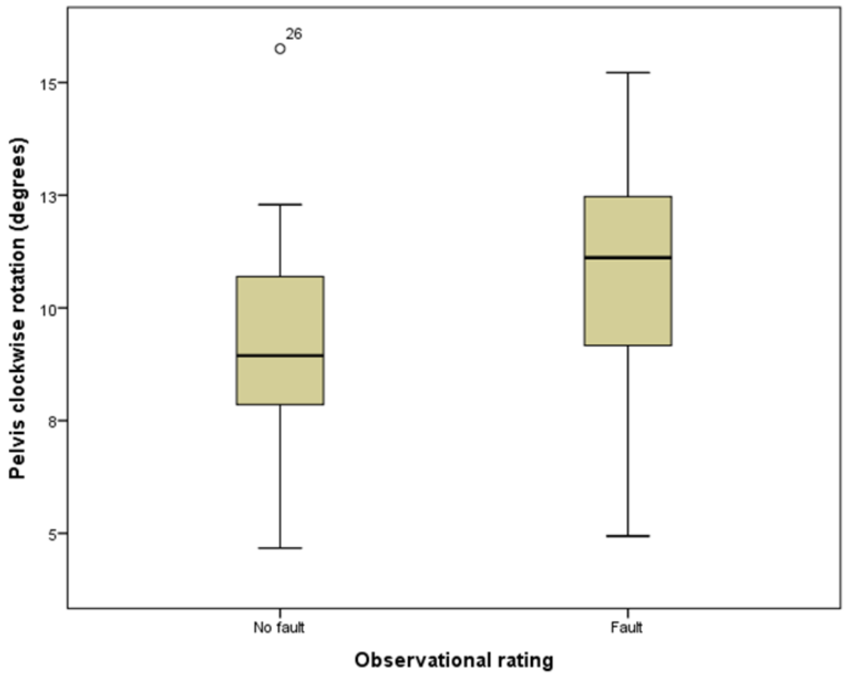
Appendix



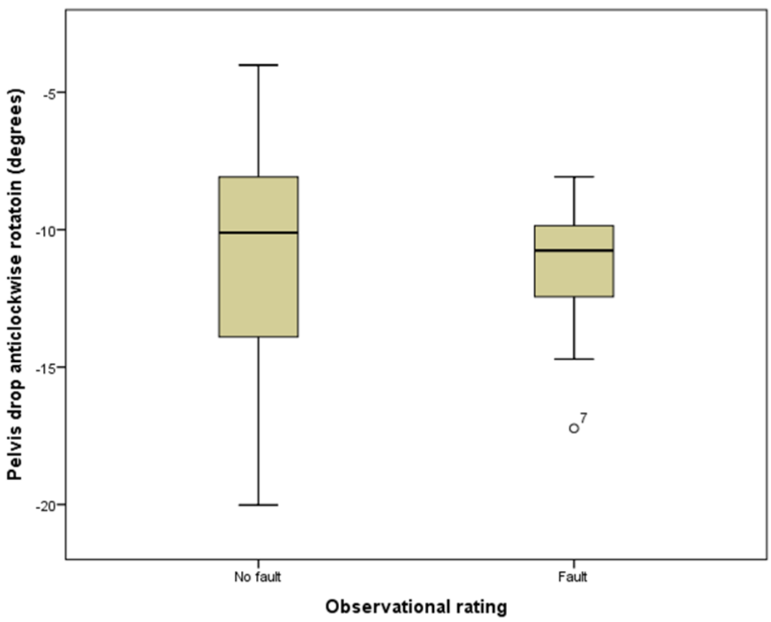
Box plots showing median, interquartile range, maximum, minimum and outliers for the peak excursion of pelvis lateral rotation for fault and no fault from the SKB Rot test on the right side.



Box plots showing median, interquartile range, maximum, minimum and outliers for the peak excursion of pelvis lateral rotation for fault and no fault from the SKB Rot test on the left side.

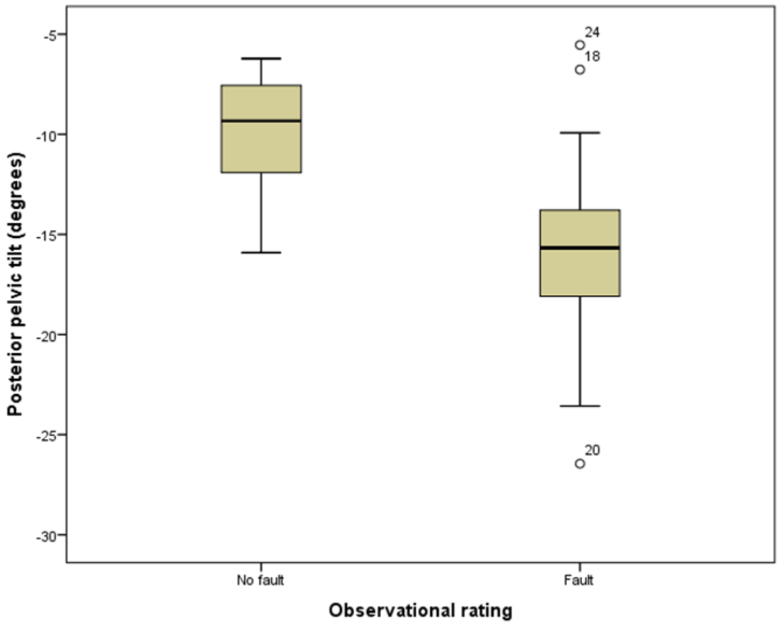


Box plots showing median, interquartile range, maximum, minimum and outliers for the peak excursion of pelvis lateral rotation for fault and no fault from the standing hip flexion test on the right side

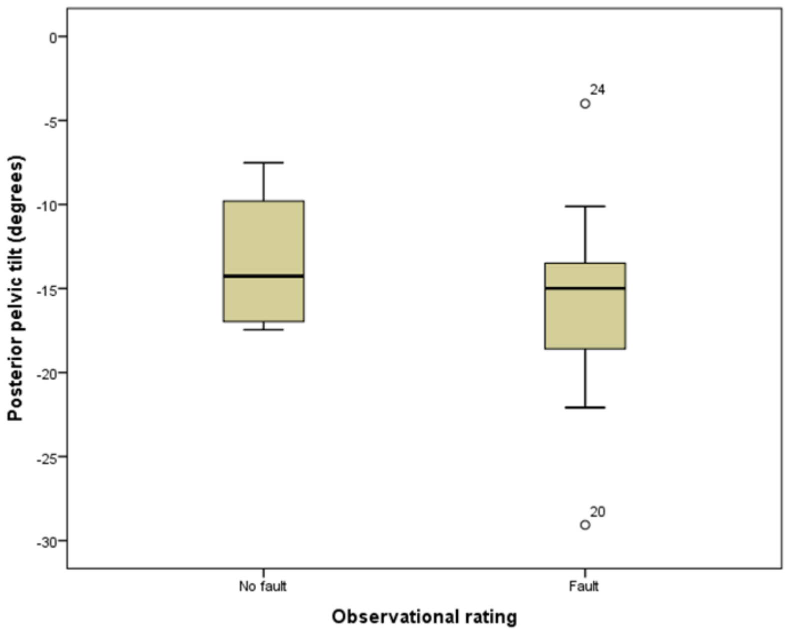


Box plots showing median, interquartile range, maximum, minimum and outliers for the peak excursion of pelvis lateral rotation for fault and no fault from the standing hip flexion test on the left side.

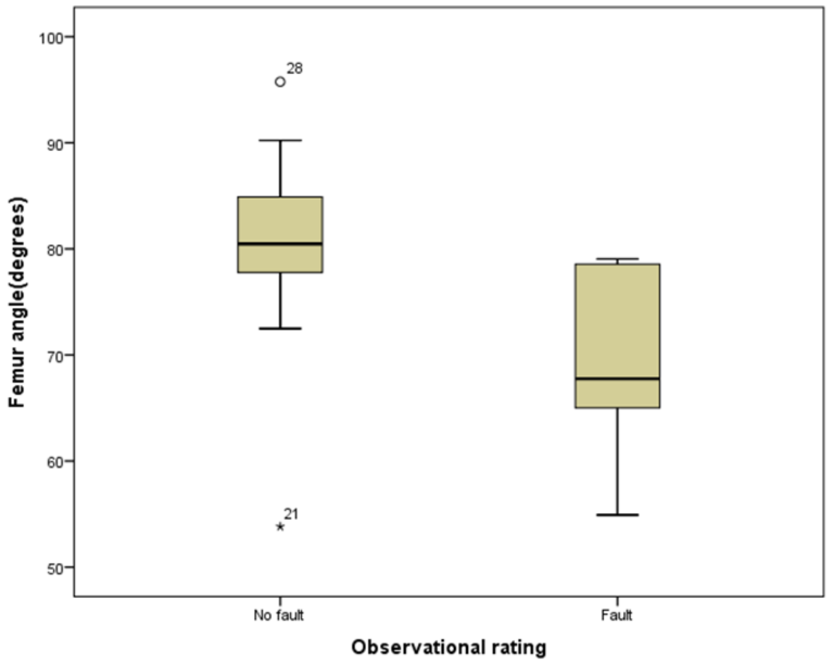
Appendix



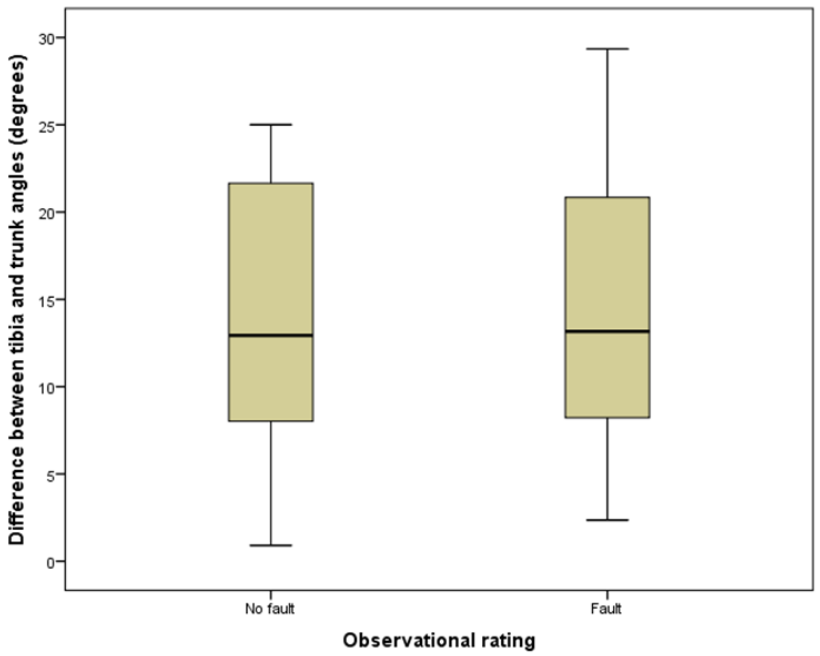
Box plots showing median, interquartile range, maximum, minimum and outliers for the peak excursion of posterior pelvic tilt for fault and no fault from the standing hip flexion test on the right side.



Box plots showing median, interquartile range, maximum, minimum and outliers for the peak excursion of posterior pelvic tilt for fault and no fault from the standing hip flexion test on the left side.

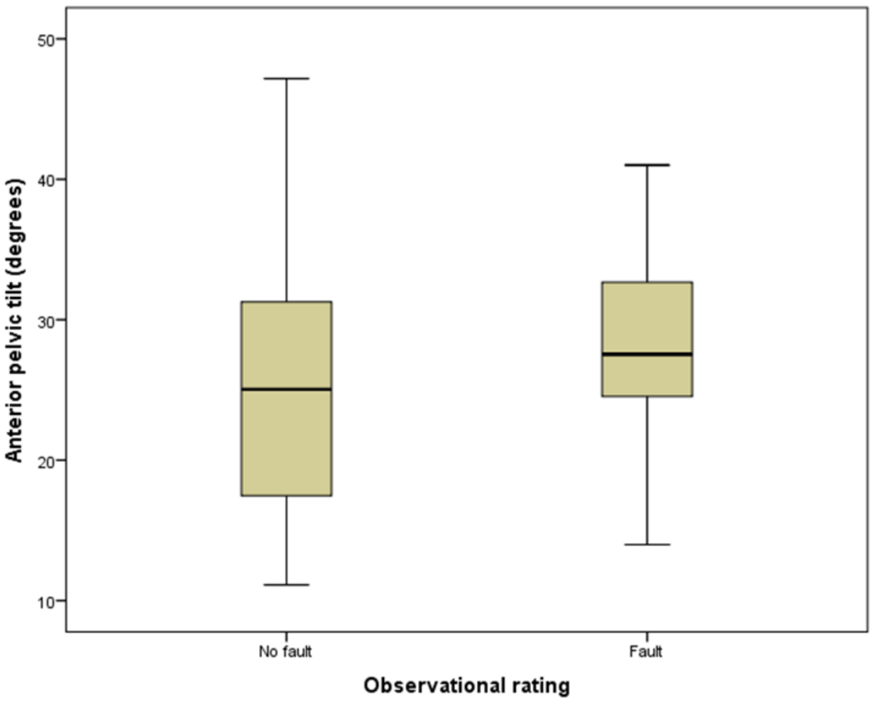


Box plots showing median, interquartile range, maximum, minimum and outliers for the peak excursion of femur flexion for fault and no fault from the deep squat test for the left side.



Box plots showing median, interquartile range, maximum, minimum and outliers for the difference between tibia and trunk angles at peak femur flexion for fault and no fault from the deep squat test for the left side.

Appendix



Box plots showing median, interquartile range, maximum, minimum and outliers for the peak excursion of femur flexion for fault and no fault from the deep squat test for the left side.

Appendix O **Case study exercise programme**

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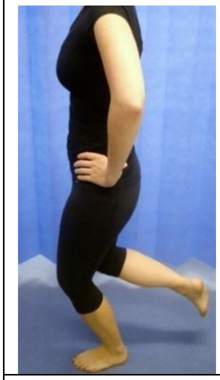
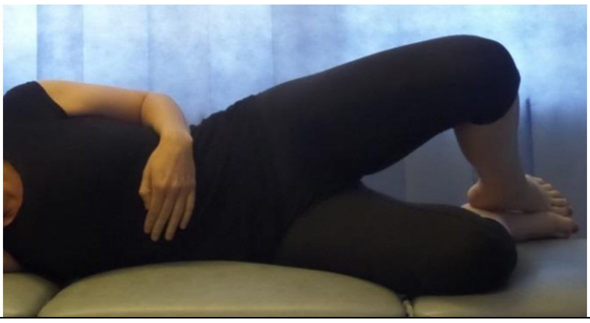
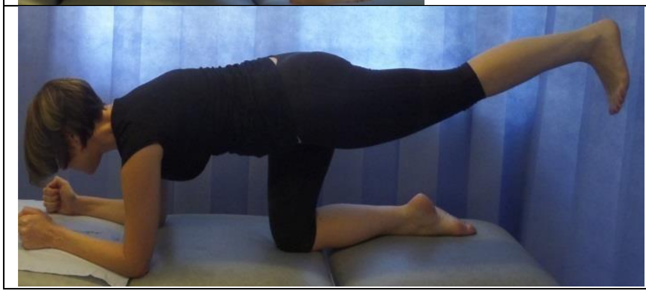
Exercise Programme -14/07/2015

	Maintain the neutral position as demonstrated during the session. Hold the position for 5 sec and complete the exercise for 1 min Left and Right.
	Maintain the neutral position as demonstrated during the session. Do not hold your breath. Hold the position for 10sec and complete the exercises for 1 min Left and Right.
	Maintain neutral and perform exercises slow and controlled Lift your knee without rotating your pelvis slowly up hold for 5sec and lower. Continue for 1 minute Left and Right.

Appendix

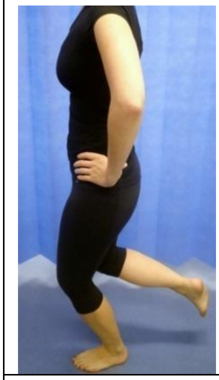
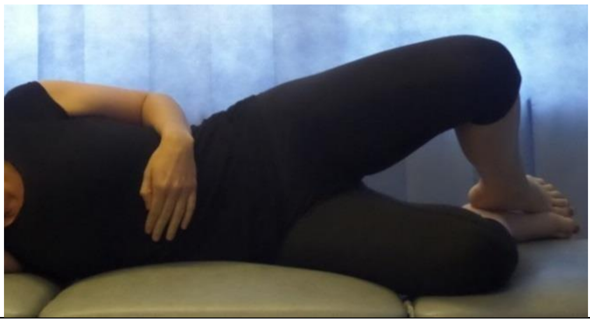
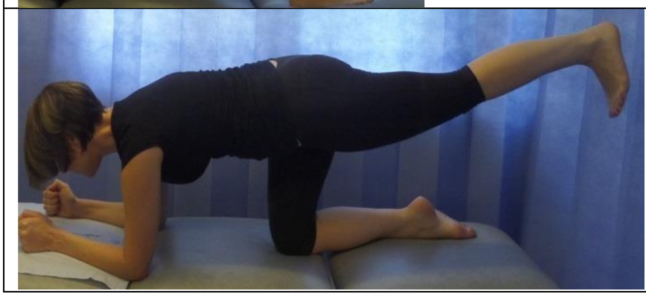
	Do not over extend your back. Remember only to move to neutral. Place arms on chest. Lift and lower your bum slowly for 1 minute Left and Right.
	Maintain your pelvis level while lifting your leg SLOWLY up hold 5sec and lower leg. Continue for 1 minute Left and Right.

UNIVERSITY OF Southampton

Exercise Programme -05/08/2015

	Maintain the neutral position as demonstrated during the session. Hold the position for 10 sec and complete the exercise for 1 min Left and Right.

Botha et al 2015 Faculty of Health Sciences, University of Southampton 1

	Maintain the neutral position as demonstrated during the session. Do not hold your breath. Hold the position for 20 sec and complete the exercises for 1 min Left and Right.
	Maintain neutral and perform exercises slow and controlled. Drop your ribs down as demonstrated in the session. Lift your knee without rotating your pelvis slowly up hold for 20 sec and lower. Continue for 1 minute Left and Right.
	Do not over extend your back. Remember only to move to neutral. Place arms on chest. Drop your ribs down as demonstrated in the session Lift and lower your bum slowly for 1 minute Left and Right.
	Maintain your pelvis level while lifting your leg SLOWLY up hold 20 sec and lower leg. Continue for 1 minute Left and Right.

 	Lying against a wall with your upper body supported, bending your bottom knee. Drop your ribs and lengthen your side as demonstrated during the session. Push your heel down to lengthen your leg. Lift your leg sideways up the wall slowly and lower 10 reps Left and Right.

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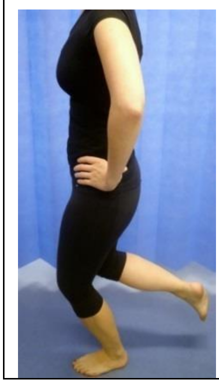
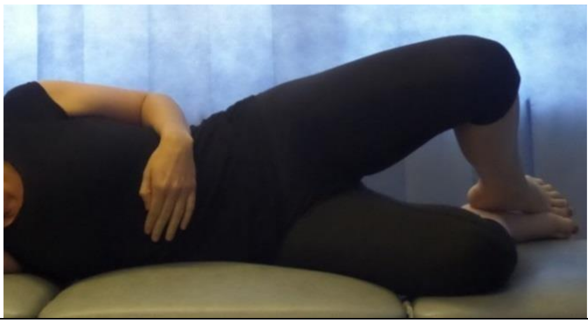
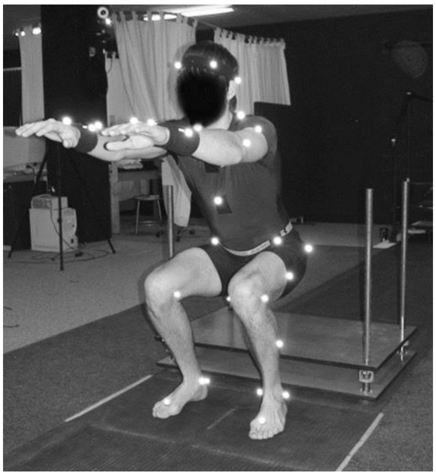
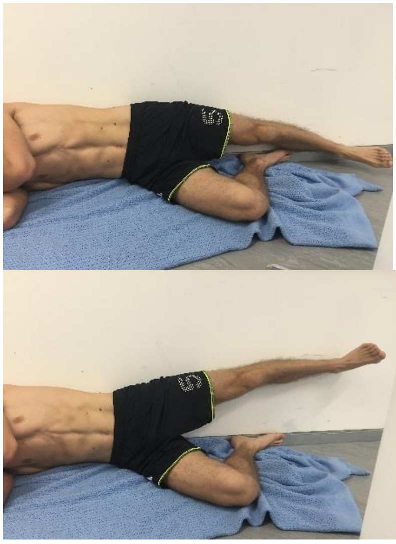
Exercise Programme -18/08/2015

	Maintain the neutral position as demonstrated during the session. Hold the position while raising the heel 10x 6 reps Left and Right.
	Maintain the neutral position as demonstrated during the session. Do not hold your breath. Hold the position for 20 sec and complete the exercises for 1 min Left and Right. Remember not to drop the hip.

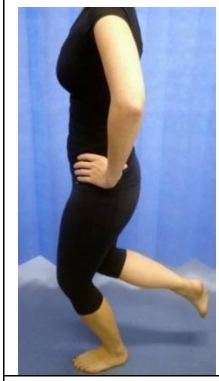
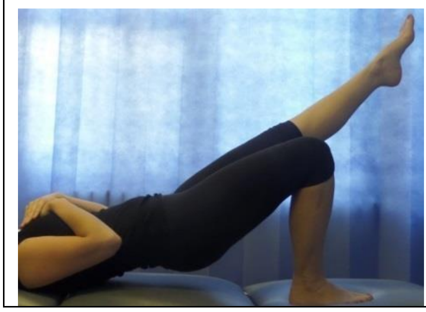
	Maintain neutral and perform exercises slow and controlled. Drop your ribs down as demonstrated in the session. Lift your knee without rotating your pelvis slowly up hold for 30 sec and lower. Continue for 1 minute Left and Right.
	Do not over extend your back. Remember only to move to neutral. Place arms on chest. Drop your ribs down as demonstrated in the session Lift and lower your bum slowly for 1 minute Left and Right.

	Place your heels on a little step to raise the heels. Squat down until your thighs are horizontal to the floor. Prevent leaning excessively forwards. Hold the position for 5 sec. Repeat 10x.

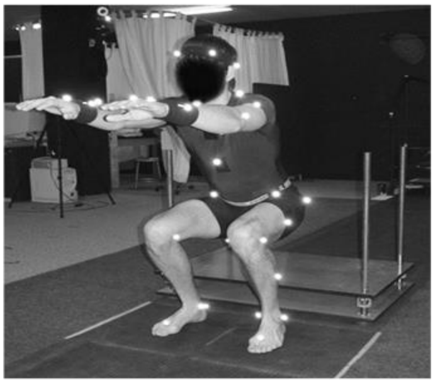
	Lying against a wall with your upper body supported, bending your bottom knee. Drop your ribs and lengthen your side as demonstrated during the session. Push your heel down to lengthen your leg. Rotate your leg upward. Lift your leg sideways up the wall slowly hold this position while you rotate your leg downward and upward for 10 reps Left and Right and slowly lower your leg. Progress to do this 5 x Left and Right
	Maintain your pelvis level while lifting your leg SLOWLY up hold 40 sec and lower leg. Continue for 1 minute Left and Right.

UNIVERSITY OF Southampton

Exercise Programme -15/09/2015

	Lunge onto a pillow. Maintain the neutral position as demonstrated during the session. Hold the position while raising the heel 10x 6 reps Left and Right.
	Maintain the neutral position as demonstrated during the session. Do not hold your breath. Hold the position: 30 sec hold for 4reps Progress to 1min hold 2 reps Progress to 2min hold 1 rep Remember not to drop the hip.
	Maintain neutral and perform exercises slow and controlled. Lift your knee without rotating your pelvis slowly up hold for 30 sec and lower. Continue for 1 minute Left and Right.
	Do not over extend your back. Remember only to move to neutral. Place arms on chest. Drop your ribs down as demonstrated in the session Lift and lower your bum slowly for 1 minute Left and Right.

	Maintain a neutral position not dropping the pelvis. Hold for 10sec and repeat 6 reps Left and Right.

 	Lying against a wall with your upper body supported, bending your bottom knee. Drop your ribs and lengthen your side as demonstrated during the session. Push your heel down to lengthen your leg. Rotate your leg upward. Lift your leg sideways up the wall slowly hold this position while you rotate your leg downward and upward for 10 reps Left and Right and slowly lower your leg. Progress to do this 5 x Left and Right
	Lie on your side, lift your pelvis. Maintaining a neutral posture. Hold 10 sec for 6reps Left and Right.
	Place your heels on a little step to raise the heels. Squat down until your thighs are horizontal to the floor. Prevent leaning excessively forwards. Hold the position for 5 sec. Repeat 10x.

Appendix P Exercise programmes for hip control to protect lower limb joints during exercise: effects on muscle activation and biomechanics in male adolescent academy footballers.

Appendix A: Manual for the proposed exercise intervention to manage Hip and Pelvic Movement Control

Table of Contents

1. Background

The Arthritis Research UK Centre of Excellence for Sport, Exercise and Osteoarthritis identified hip osteoarthritis (OA) as a research priority, given its prevalence in the general population, which becomes exaggerated in physically active populations (Turner, Barlow and Heathcote-Elliott, 2000; Drawer and Fuller, 2001; Shepard, Banks and Ryan, 2003). The condition of femoroacetabular Impingement (FAI) is being used as a model to study development of OA in a programme of studies across all four of the Centre's work packages: WP1 Epidemiology, WP2 Biomarkers, WP3 Movement Dysfunction and Interventions; WP4 Translation and Patient and Public Involvement. The relevance of FAI was specifically highlighted, as subtle morphological changes of the proximal femur associated with FAI, are a major risk factor for the development of OA (Agricola et al., 2013) and total joint replacement (Thomas et al., 2014) Furthermore, there is increasing evidence that these morphological changes develop in young people, especially the active population (Agricola et al., 2012; Tibor and Leunig, 2012; Tak et al., 2015). The Centre aims to gain insight into the development of OA especially from injury, exercise and obesity leading to effective prevention and treatments for the general public and people of all ages participating in sports. The Centre provides a collaborative multidisciplinary environment with expert researchers across seven universities, as well as international collaborators, enabling knowledge exchange to improve the quality and enhance the outcomes of the research.

A preliminary project during the investigator (Nadine Botha) MRes and Internship was conducted to collect pilot data, based within the Southampton arm of the Centre to inform the development of the exercise intervention. The project was a case-control study of the clinical and functional tests in three participant groups (matched for age, height, weight and BMI) recruited by convenience sampling of male football participants aged 9-18 years:

- Academy Footballers diagnosed with symptomatic FAI
- Academy Footballers diagnosed with asymptomatic FAI
- Academy Footballers asymptomatic with no available diagnosis of any hip pathology

The preliminary work aimed to:

1.1 Develop a set of clinical and functional movement tests for assessing movement patterns and control of hip movement in young males. Clinical screening tests included measurement of hip internal rotation, palpating anterior hip structures, tests for hip impingement and anterior instability. While, functional movement tests were observed for faults to assess movement patterns.

1.2 Validate the movement control tests in a collaborative biomechanical study (Dr Martin Warner), involving kinematic and kinetic measurements for the functional tests using 3-D motion analysis (Vicon) and measurement of muscle activity using surface electromyography (EMG). This work is still ongoing and will be conducted alongside the intervention study by a PhD student (Dave Wilson).

1.3 Investigate whether there are abnormalities in movement patterns in young academy footballers.

The present results to date in nine players with symptomatic FAI report high levels of hip and groin disability (Botha et al., 2014) , similar to previous studies (Clohisy et al., 2009). Hip internal rotation range is reduced when compared to published values from non-sporting young males (Manning and Hudson, 2009a). The preliminary findings of the novel work on movement control are that both the symptomatic and asymptomatic footballer groups show poor movement control in flexion and medial rotation. Abnormal movement patterns were observed clinically during a small knee bend test in nine male academy footballers aged 12–18 years with hip/groin pain, diagnosed with FAI (Botha et al., 2014). Participants were unable to control hip flexion in one or more aspects, mostly seen as the trunk leaning forwards and the hip moving into increased flexion (Botha et al., 2014). Participants also demonstrated poorly controlled hip medial rotation (Botha et al., 2014). The validation work (Warner et al) continues and preliminary analysis indicated validity but techniques are being explored to find an optimal way of analysing the complex 3-D motion analysis data for meaningful presentation of results. A PhD project (Dave Wilson) will now focus on extending this work on validity of movement screening tools.

2. Movement Control

The proposed intervention fits with the concept that the cycle of events from joint injury leading to OA and further injury may be broken by improving quality of movement to reduce abnormal loading on joints. Poor movement patterns contributing to the impairment of the ability to control hip and pelvic movement associated with FAI may indicate mechanisms of dysfunction and can inform development of effective interventions. Preliminary findings in the present research on FAI in adolescent footballers show restricted internal hip rotation and poor movement control of hip flexion and medial rotation (Botha, 2013; Botha et al., 2014), with higher number of faults observed in increased hip flexion, trunk leaning forwards, hips swaying back, femoral line moving medially, hip hitching and hip or pelvis rotation following the trunk (Botha, 2013; Botha et al., 2014).

The efficiency of movement control can be evaluated with movement control tests, in which a person is asked to cognitively control movement at a specific joint (e.g. the hip), whilst challenging the ability to maintain this control with movement at an adjacent joint (Comerford and Mottram, 2001; Cook, Burton and Hoogenboom, 2006; Cook et al., 2010; Comerford and Mottram, 2012; Roberts, 2013). People with pain often fail these tests, demonstrating poor movement patterns (Luomajoki et al., 2008; Worsley et al., 2013a). Impaired movement control can imply disturbance or abnormality in the movement system (Sahrmann, 2002; O'Sullivan, 2005; Cook, Burton and Hoogenboom, 2006). The loss of movement precision is proposed to contribute to repeated stresses to tissues, causing alterations in control strategies. There is evidence that movement impairments at the hip and pelvis may trigger injuries such as anterior cruciate ligament tears (Hewett et al., 2005), iliotibial band syndrome (Noehren, Davis and Hamill, 2007), and patellofemoral joint pain (PFJP)(Powers, 2003). Therefore, improvement in movement control at the hip and/or pelvis may also contribute to the prevention of joint injuries more distally in the kinetic chain.

A systematic review reveals the majority of publications on conservative management of FAI are review and/or discussion articles, with 48% promoting physical therapy-led care and RCTs are lacking (Wall et al., 2013). Professional football clubs that use movement control exercises are seeing reduction in FAI symptoms and other lower limb injuries.

Therefore, targeted movement control exercises for identified hip and pelvic movement faults are needed to improve the correct use of muscles to avoid abnormal loading of lower limb joints, improving conservative evidence based treatment. Preventive and early targeted conservative treatment of FAI, particularly during skeletal development in adolescents, may prevent joint injury and possibly later hip OA; ensuring safe exercise to keep active.

3. The Exercise Intervention Programme

The results to date of the current preliminary pilot work have informed the development of a targeted exercise intervention package to manage movement control patterns and hip ROM restrictions (Botha, 2013; Botha et al., 2014). The outline of the intervention programme may need necessary changes after assessing movement patterns in recreational community footballers during baseline measurement. Footballers in the community may present with different movement patterns as the academy players studied during the preliminary work, therefore the intervention will need to be adjusted accordingly. Furthermore, input from the PPI player and coach ambassadors will be essential during the introduction stages of the intervention within clubs.

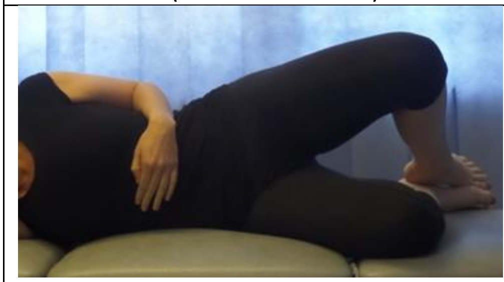
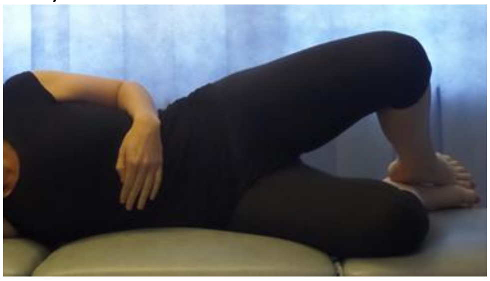
3.1 Development of the exercise programme

The current literature has been used to inform the targeted exercise programme to address the movement faults observed in academy footballers discussed in the sections above (e.g. FIFA 11+ (Soligard et al., 2008; Bizzini and Dvorak, 2015), Functional Movement Screening (FMS) (Cook, Burton and Hoogenboom, 2006; Cook et al., 2010), Movement optimising training (MOT) (Mottram and Comerford, 2008; Mottram et al., 2015), Kinetic Control (Comerford and Mottram, 2012; Mottram et al., 2015), Non-operative treatment/conservative management (Filipa et al., 2010; Emara et al., 2011; Selkowitz, Beneck and Powers, 2013; Wall et al., 2013; Loudon and Reiman, 2014).

kinetic chain.

The pre-activity exercise programme developed to manage hip and pelvic movement control has been based on the current FIFA 11+ programme which has been adapted to include exercises to address the movement faults observed in academy (Botha, 2013; Botha et al., 2014) footballers . The FIFA 11+ is well established and developed under the leadership of the FIFA Medical and Research Centre (F-MARC), to reduce the incidence of football injuries. The FIFA 11+ have reported significant lower injury incidence (Soligard et al., 2008; Soligard et al., 2010; Steffen et al., 2013; Owoeye et al., 2014), while some studies did not find significant reductions in incidence (Steffen et al., 2008; Hammes et al., 2014). The FIFA 11+ prevention programme seem to significantly reduced the overall rate of injury and lower extremity injury (Soligard et al., 2008; Steffen et al., 2013; Owoeye et al., 2014), however the rate of injury reduction based on injury reduction by body location (e.g. hip, knee and ankle) do not reach the level of significance (Soligard et al., 2008; Owoeye et al., 2014). As mentioned previously there is evidence that movement impairments at the hip and pelvis may trigger injuries distally in the kinetic chain (Powers, 2003; Hewett et al., 2005; Noehren, Davis and Hamill, 2007). Therefore, targeting the exercises to address the movement faults observed to improve poor movement patterns of the hip and pelvis may not only reduce the overall rate of injury but also contribute to the prevention of joint injuries by body location and more distally in the The impact of poor hip movement control on the kinetic chain (the lower back proximally, and knee, ankle and foot distally) have been considered in selecting the multi-joint movement control exercises. Exercises has been selected and included to address the main observation of poor movement control of hip flexion and medial rotation. Figure 1 show the exercises which have been included in the motor control training, strength and balance section of the FIFA 11+ which will form part of the proposed pre-activity exercise programme. The exercises were selected to activate the middle portion of the gluteus medius which is an abductor and the gluteus maximus which is an extensor and external rotator (Neumann, 2010), to address the hip flexion and medial rotation movement faults. The exercises target the gluteal muscles while minimizing the activation of the tensor fascia lata (Selkowitz et al., 2013).

The exercise programme will form part of the footballers' warm-up which will take no longer than 15 minutes, performed for 12 weeks prior to any training or games. The investigator (NB) will arrange a training session with the coaches and team captains from the clubs who will be conducting the intervention in which the intervention programme will be introduced. The programme will also be taught to the players by the NB to ensure the participants are confident in performing the exercises correctly. A smartphone application Physitrack is being explored which coaches can access on the pitch while performing the exercise programme. The application will have video clips of the exercises to ensure they are performed correctly with data on adherence and progress of the programme. The investigator will visit each club weekly to participate in a training session to facilitate correct technique, progression of the programme components and monitor adherence. Furthermore, coaches will be able to phone or e-mail the investigator if they have any questions or problems. Players will begin with level one exercises. For a standardised exercise approach and simplicity all the players will progress to the next level of all the exercises after four weeks. The full pre-activity exercises programme is detailed in Appendix 1 with the movement faults addressed by each exercise.

Exercise	**Faults Addressing**
 Sideways Bench Static knees flexed • 3 sets (20 sec each side) – 2min	Trunk side flexion Medial rotation hip Hip hitching Axial rotation hip
 Clam exercise(Selkowitz etal 2013) • 1 set lift hold 2sec and lower (60 sec each side)- 2min  Clam exercise(Selkowitz etal 2013) • 3 sets hold 20 sec each side – 2min  Clam Advanced • 3 sets hold 20 sec each side – 2min	Medial rotation hip Pelvic hitching Pelvic rotation
	Hip flexion Trunk flexion

Single leg bridge (Selkowitz etal 2013) • 3 sets hold 20 sec each side – 2 min  Hip Extension knee bend(Selkowitz etal 2013) • 3 sets hold 20 sec each side – 2 min  Hip Extension knee straight(Selkowitz etal 2013) • 3 sets hold 20 sec each side – 2min	
 Hip Flexor stretch with hip, knee and ankle mobility	Hip flexion, knee and ankle mobilisation
 Hip internal rotation stretch	Hip internal rotation restriction

Figure 1: Exercises included to the FIFA 11+ motor control training, strength and balance section which will be used as the pre-activity exercise programme.

3.2 Network of Advisors

An international Movement Screening and Interventions Group of researchers and clinicians has formed through networking activities by the Arthritis Research UK Centre for Sport, Exercise and Osteoarthritis, to gain consensus from the wide variety of approaches now available (See Appendix 2). Advice from collaborating expert advisors with experience in exercise interventions have been utilised, including: Prof Kim Bennell (University of Melbourne; hip OA exercise interventions, clinical trials), Prof Nadine Foster (University of Keele; conservative management of FAI, clinical trials) and Matt Radcliffe (Manchester United Football Club First team Physiotherapist, UK).

3.3 Mechanism of exercise intervention

Knowledge of the mechanisms of why movement control exercises work is limited, particularly around the hip and pelvis. However, what we do know is that most muscles are composed predominantly of two different types of motor units, which is useful for rehabilitation (Lieber, 2009). Slow motor units are fatigue resistant with a slow speed of contraction and a low contraction force. Also, they have low threshold for activation and are recruited in non-fatiguing postural control tasks and functional movements. Fast motor units are fast fatiguing when recruited and have higher threshold for activation making them predominantly recruited as load increases, with fatiguing functional activities or when fast movements are performed (Monster et al., 1978)

Recruitment is modulated by the higher central nervous system (CNS) and is powerfully influenced by the afferent proprioceptive system (along with some behavioural and psychological contextual factors). Hypertrophy is a peripheral adaptation in muscle in response to demand along with CNS adaptations and is a result of overload training (Widmaier et al., 2007). Low threshold motor control does not alter peripheral muscle structure to a great extend but improves the CNS recruitment of muscles to fine tune muscle coordination and improve the efficiency of movement (e.g. like upgrading the software of a computer to perform its task more efficiently and to get the most out of the hardware already present, which always requires cognitive operator training and familiarisation)(Hodges and Moseley, 2003).

Low threshold motor control training is primarily directed towards restoring normal or optimal recruitment strategies. Improvements in function are indirect consequences of recovering the slow motor unit recruitment threshold and restoring optimal patterns of recruitment. This requires practising a highly cognitive, very specific non-functional movement skill. Also, this involves the highest levels of CNS function, known as cognitive programming (Lephart et al., 1997), therefore, the proposed intervention is a movement control re-training programme and neural adaptation is expected to occur.

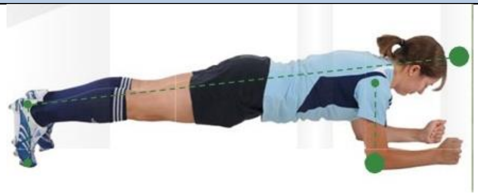
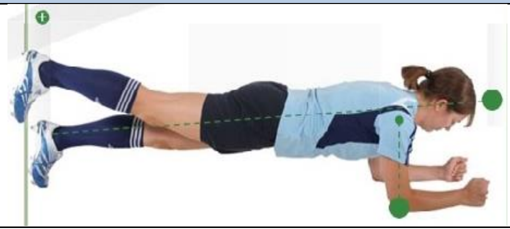
The pre-activity exercises programme will be performed for 12 weeks. It is still unclear what the long-term effects are after completion of the 12 week exercise programme and whether the programme needs to be continued while people are staying active. We are anticipating that as long as people are active and exercising that they will need to continue this motor control training programme as a form of 'warm up' before exercise to maintain ideal patterns of recruitment; therefore protecting joints and continue helping to prevent injuries. After completion of the 12 week programme we will encourage coaches to continue using the pre-activity exercise programme as part of their warm-up programme. This proof of concept study is needed first before the long-term effects are studied. Also it is not yet clear the precise mechanism but this study will be conducted alongside another study which will look at the biomechanical and neurophysiological mechanisms of dysfunction (Dave Wilson, PhD student).

There is guidance or evidence available about a dose effect but this proof of concept study is needed first before dose effects are studied. A previous study (FIFA 11+) in Canada looked at dose effect of adherence on performance in youth female soccer players who participated on average 2.2 intervention sessions a week showed improvement in balance measured by the Star Excursion Balance Test (SEBT) compared to the low adherence group who performed 1.5 sessions per week (Steffen et al., 2013). Similar improvements were found in the SEBT during an 8 week neuromuscular training programme (Filipa et al., 2010) or 12 sessions of wobble board and postural stability training (Fitzgerald et al., 2010).

Appendix A1: The exercise intervention programme

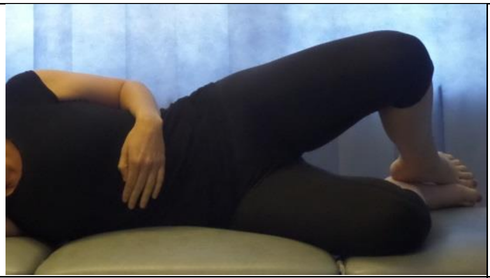
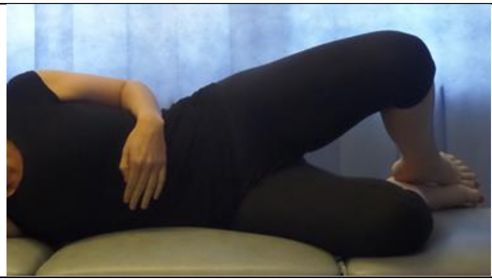
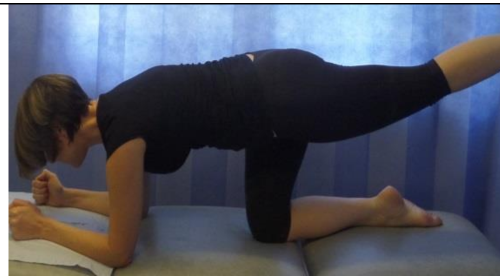
The pre-activity exercise programme is based on the FIFA 11+ motor control training, strength, balance section and is designed to complement the FIFA 11+ without increasing the time of the warm-up session. The exercise programme will form part of the footballers' warm-up which will take no longer than 15 minutes, performed for 12 weeks prior to any training or games.

Players will begin with level one exercise and for simplicity all the players will progress to the next level of all the exercises after four weeks. The emphasis of the exercise programme is for all the exercises to be performed correctly with good quality of movement. Therefore the coach or the team captain will supervise the programme and correct the players if necessary.

	Motor Control training, Strength, Balance			
Row	**Level 1**	**Level 2**	**Level 3**	**Movement Faults addressing**
1				Trunk flexion Hip flexion
	The Bench Static (FIFA 11+) • 3 sets 20 sec hold – 1min	**The Bench Alternate Legs (FIFA 11+)** • Lift leg with 2 sec holds (40-60 sec each side) – 2min	**The Bench one leg lift and hold (FIFA 11+)** • 3 sets hold 20 sec each side – 2min	

2				Trunk side flexion Medial rotation hip Hip hitching Axial rotation hip
	Sideways Bench Static knees flexed • 3 sets (20 sec each side) – 2min	**Sideways Bench Raise and Lower (FIFA 11+)** • 3 sets raise hold 20 sec and lower hip (each side) – 2min	**Sideways Bench with Leg Lift (FIFA 11+)** • 3 sets lift uppermost leg and lower (20 sec each side) – 2min	
3				Trunk Flexion Hip Flexion Hamstring strength
	Hamstrings Beginner (FIFA 11+) • 1 set (3-5 reps) – 30 sec	**Hamstrings Intermediate (FIFA 11+)** • 1 set (7-10 reps)- 1min	**Hamstrings Advanced (FIFA 11+)** • 1 set (minimum 12-15 reps)- 2min	

4				Proprioceptive Medial rotation hip Trunk side flexion Hip Flexion
	Single Leg Stance Hold Ball (FIFA 11+) • 2 sets (30 sec on each leg)-2min	**Single Leg Stance Throw Ball (FIFA 11+)** • 2 sets Throw ball while hold balance (30 sec each leg) – 2min	**Single Leg Stance Test Partner (FIFA 11+)** • 2 sets partner push the other off balance (30 sec on each leg)- 2min	
5				Medial rotation hip Hip flexion Trunk side bend Trunk flexion
	Squats with side step (Selkowitz etal 2013) • 2 sets side step each side (30 sec)-2min	**Squats Lunge hold with heel raise** • 2 sets (10 raises each leg)-2min	**Squats Walking Lunges** • 2 sets (10 lunges each leg)-2min	

6				Medial rotation hip Pelvic hitching Pelvic rotation
	Clam exercise(Selkowitz etal 2013) • 1 set lift hold 2sec and lower (60 sec each side)- 2min	**Clam exercise(Selkowitz etal 2013)** • 3 sets hold 20 sec each side – 2min	**Clam Advanced** • 3 sets hold 20 sec each side – 2min	
7				Hip flexion Trunk flexion
	Single leg bridge (Selkowitz etal 2013) • 3 sets hold 20 sec each side – 2 min	**Hip Extension knee bend(Selkowitz etal 2013)** • 3 sets hold 20 sec each side – 2 min	**Hip Extension knee straight(Selkowitz etal 2013)** • 3 sets hold 20 sec each side – 2min	
	STRETCHES – hold 20 sec 3 reps each side – 4min			
8				

	2 min	 2min
	Hip Flexor stretch with hip, knee and ankle mobility	Hip internal rotation stretch

Appendix A2: international Movement Screening and Interventions Group of researchers and clinician

Members	Expertise	Role
Mark Comerford (Brisbane, AUS) Sarah Mottram (Chichester, UK) Mo Gimpel (Southampton Football Club, UK)	Physiotherapists with expertise in screening for uncontrolled movement. Expertise in dealing with hip injuries within a Premier Football club through improving movement control, injury prevention.	Original collaborators on preliminary project to develop the movement control screening tests.
Dr Keith Stokes (University of Bath) Prof Kim Bennell (University of Melbourne) Prof Nadine Foster (University of Keele) Prof Carolyn Emery (University of Calgary, Canada)	Movement control screening and interventions, injury surveilance. Hip OA exercise interventions, clinical trials. Conservative management of FAI, clinical trials. Sport injury epidemiology, prevention, adherence and translation intervention, clinical trials.	Advisors on original protocol to NIHR CDR Fellowship application.
Prof Kim Bennell (University of Melbourne) Prof Nadine Foster (University of Keele) Matt Radcliffe (Manchester United Football Club, UK).	Hip OA exercise interventions, clinical trials. Conservative management of FAI, clinical trials. Prevent injuries within a Premier Football club through improving movement control, expertise pre-activity exercise programmes.	Advisor on current proposed intervention study.
Dr Jackie Whittaker (Canada) Prof Darin Padua (University of North Carolina)	Sport Injury Prevention Research, expertise systematic review. Injury prediction and prevention, preventative interventions.	Collaborators advising on a systematic review on Movement Screening.
Prof Anna Frohm (Karolinska Institute, Sweden) Dr Cara Lewis (University of Boston)	Movement control screening and interventions, clinical trials. FAI, movement control, exercise interventions and biomechanics.	International Movement screening and Interventions group members

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Appendix Q **Hip and Groin Case Study Paper**

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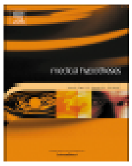

Accuracy of movement quality screening to document effects of neuromuscular control retraining exercises in a young ex-footballer with hip and groin symptoms: A proof of concept case study

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ABSTRACT

Hip and groin pain is common in footballers and altering movement patterns can reduce symptoms. Observational tests of movement control are thought to identify abnormal movement patterns, but their accuracy needs yet to be confirmed by comparison with an objective measure. To assess the accuracy, using 3D motion analysis, of observational movement control tests and their ability to detect changes, and document changes in symptoms following a neuromuscular control exercise programme in an ex-footballer with hip and groin pain. A 25-year-old male with chronic bilateral hip and groin pain had their movement control ability rated and kinematic data collected using 3D motion analysis while performing Small Knee Bend (SKB) and SKB with Rotation (SKB Rot) tests pre-and post-neuromuscular control exercise training. Movement control was rated as at fault if they were unable to control specific trunk and pelvic movements during the tests. The Copenhagen Hip and Groin Outcome Score (HAGOS) was used to assess symptoms. Following the intervention, observational rating during the SKB test improved from fault to no fault for anterior pelvic tilt, which decreased by 17° and 16° during right and left leg SKB tests respectively. The HAGOS symptoms subsection improved from 36% to 61%. Observational movement screening ratings were supported by 3-D motion analysis. These findings indicate that the screening tool was accurate for detecting improvements in trunk and pelvic movement control following an exercise programme in an ex-footballer who had presented with hip and groin pain.

Introduction

Hip and groin injuries are common in football [1]. One possible diagnosis for hip and groin pain is femoroacetabular impingement (FAI), which involves limited joint clearance between the femoral neck junction and the acetabular rim [2,3]. High levels of cam impingement, a type of FAI, were reported in elite soccer players, with 68% demonstrating radiographic evidence [4]. However, high levels of FAI may not correlate with symptoms as Kapron et al. [5] reported 95% of collegiate American Footballers had one or more radiographic signs of FAI but were largely asymptomatic.

While FAI is thought to be a structural problem, Austin et al. [6] proposed that symptoms may be caused by an interaction of bony morphology with certain movement patterns. Therefore, changing movement patterns could reduce symptoms. Changing pelvis and trunk movement patterns through the use of exercises has been shown to reduce hip and groin symptoms in a case series [7]. However, the changes in trunk or pelvis movement were not reported [7]. Additionally, FAI symptoms were reduced during a step down activity by changing movement patterns in a case study, but there was no follow up [6]. There is a lack of evidence that neuromuscular exercise programmes can change movement patterns and symptoms in the hip but some evidence supports such a link for the shoulder joint [8].

To identify abnormal movement patterns that could lead to symptoms such as hip and groin pain, movement control ("movement screening") is being used increasingly used [9,10]. For example, increased hip and trunk flexion during the small knee bend (SKB) test which assesses hip movement control were observed in male academy footballers with MRI confirmed morphological changes associated with FAI [11]. The SKB test is commonly used in the literature [12–15], and participants with poor SKB test scores exhibited weaker and slower muscle activation of the hip abductors, indicative of hip muscle dysfunction [15]. Trunk rotation is required in sports that involve actions such as kicking, sprinting and changes of direction, which are common in football. Holding the SKB and then rotating the trunk in the SKB rotation test assesses relative stiffness (restrictions) of thoracolumbar

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rotation, while maintaining pelvic control [16]. However, to increase our understanding of the link between movement and symptoms, accurate measurement of movement is required. Using specific observational movement tests to assess movement patterns needs to be compared to an objective measurement, such as 3D motion analysis [17,18].

Relevant patient reported outcome measures are important to accurately measure changes in symptoms. The Copenhagen Hip and Groin Outcome Score (HAGOS) was developed for use with hip and or groin pain [19]. One of the six subscales of the HAGOS is the symptoms scale, in which symptoms are rated from 0 (representing extreme problems) and 100 (no hip and/or groin problems). Several authors have used the HAGOS with FAI [20,21] and recommend its use [22].

The aim of the present single case report was to document observational ratings of hip and pelvic movement control during small knee bend (SKB) and SKB rotation (SKB Rot) tests and examine whether the ratings were confirmed by kinematic changes using 3D motion analysis both before and after an exercise programme in an ex-footballer with hip and groin pain. Changes in symptoms were also examined using the HAGOS.

Materials and methods

Ethics approval was granted from the University of Southampton, Faculty of Health Sciences Ethics Committee prior to data collection (Ethics no. 12680). The participant, a 25-year-old male (body mass 74.3 kg, height 182 cm, body mass index 22.3) had a nine-year history of bilateral hip and groin pain. He played football from the ages of 6–19 and was at the highest level of non-professional football in Italy before he had stop due to symptoms. Based on a diagnosis of FAI the participant underwent arthroscopic surgery on the left hip in July 2013 and had a labral repair and acetabular trimming. No physiotherapy or any other treatment was carried out prior to surgery. Following surgery, the participant had 22 sessions of physiotherapy rehabilitation that included stretches and strengthening around the hip joint but was unable to return to football.

Motion analysis

A Vicon Motion Capture System with 12 cameras (6 x T40 and 6 x T160) recording at 100 Hz was used to capture 48 retroreflective marker locations (Fig. 1). Markers were attached to the incisura jugularis (IJ), processus xiphpodeus (PX), C7 and T8 vertebra and bilaterally to the anterior superior iliac spine (ASIS), posterior superior iliac spine (PSIS) and iliac crests. Markers were placed on the anterior, lateral and posterior of the thigh and shank, lateral and femoral condyles and lateral and medial malleoli of the tibia. Markers were also placed on the heel (posterior calcaneus), dorsal aspect of 5th metatarsal head and the dorsal aspect of 1st metatarsal head to define the foot. The participant performed a star movement to functionally determine hip joint centres, and knee flexion/extension to functionally determine knee axis [23,24].

For both the SKB and SKB Rot tests the aim was to perform prescribed movements, with the ability to do so graded against benchmark criteria. The tests were designed to assess control of body segments while other segments moved based on the principle of movement control.

During the tests the aim was to keep the non-weight bearing thigh vertical and the knee flexed to 90°. To standardise the depth of the squat the weight bearing knee was flexed to move approximately 2 cm past the toes (corresponding to approximately 50° of knee flexion) [25]. Depth of squat was chosen to try and challenge the participant's movement control and similar to the methodology used in a previous studies [15,26–36]. The participant was given instructions on how to perform the test (Table 1). Up to four practice trials were permitted. Feedback was given to try and correct movement as the tasks are designed to test ability to control movements and not assess natural

Fig. 1. Anterior view of reflective marker placement for motion capture and EMG placement.

performance. The rater (NB) stood in front or to the side of the participant to rate the test manoeuvre as either demonstrating sufficient control (no fault) or no control (fault) against the benchmark criteria (Table 1). Three trials were rated, and movements recorded using 3D motion analysis which was set up and recorded by DW.

The SKB Rot test was performed in a similar manner compared to the SKB with the addition of rotating the trunk around the longitudinal axis by approximately 30° whilst keeping the pelvis facing forwards. The participant rotated towards the side of the weight bearing leg initially and then to the opposite side and scored against benchmark criteria (Table 2).

The faults identified from the movement tests were used to design a personalised exercise programme, which the participant was taught how to move correctly. The participant was asked to carry out their exercises at home twice a day, similar to the methodology used in a motor control retraining study [8] and complete a diary to record adherence.

The participant visited the laboratory every two weeks and was observed performing their exercises to assess progress and alter the

Table 1
Small Knee Bend (SKB) test instructions and scoring from Botha [37], with permission.

Verbal Instruction	Outcome	Right	Left
• Stand on one leg with your foot pointing forward. • Place the unsupported foot behind you by bending your knee 90°.	Does the trunk lean forwards (flex)?	Y = 1; N = 0	Y = 1; N = 0
• While keeping your body upright, keeping your pelvis and heel in position, bend your knee so that your knee is in line with your 2nd toe and moves past it until you can no longer see the tape line.	Does the pelvis tilt forwards (anterior)?	Y = 1; N = 0	Y = 1; N = 0
• Do you understand the instructions?	Total Score		

programme as applicable. Based on the poor movement control of the hips, pelvis and trunk identified from the movement test the intervention included exercises such as the lunge, clam, bridge, squat, hip extension and abduction. Correct technique was emphasised, such as during the clam, the participant was instructed to keep the trunk and pelvis still and in neutral alignment, while moving the upper leg. Difficulty of the intervention was progressed as judged to be clinically appropriate (by NB).

Data management – pre-processing

Motion analysis data were post-processed via Vicon Nexus software (Version 2.3) and exported to Matlab (The Math-Works, Natick, USA) for kinematic analysis using custom Matlab code. A rigid body approach was adopted to define the trunk, pelvis, femur, tibia and foot segments. The Optimal Common Shape Technique (OCST) was used to reduce the effect of soft tissue artefact using a local optimisation method during the star movement [38]. A functional joint centre for the hip was determined using the Symmetrical Centre of Rotation Estimation (SCoRE) technique [39], and a functional knee flexion axis was determined from non-weight bearing knee flexion cycles from 0 to 90° using the Symmetrical Axis of Rotation (SARA) technique [40]. Local coordinate systems were used to define the 3D location and orientation of each segment where the positive X-axis was pointing to the right, the positive Y-axis forward and the positive Z-axis up (Table 3).

Euler angle decomposition was then performed to obtain joint kinematics in an X (flexion/extension), Y (abduction/adduction) and Z (internal/external rotation) order between proximal to distal segments, pelvis to femur, femur to tibia in local coordinate system. Thorax and pelvis kinematics were relative to global coordinate system.

An automated method was developed to identify the start and end of movement for the tests. Start of the movement was defined as when the angular velocity of the weight bearing knee flexion exceeded 10% of maximum angular velocity and non-weight bearing knee flexion > 60°. The end of the movement was defined as when angular velocity of weight bearing knee flexion < 10% of minimum knee angular velocity during the knee extension phase. The automated identification of start and end points was visually checked to ensure the true start and end points were identified and adjusted, if required. Kinematic data were normalised with respect to time through interpolation of the data to 1001 points from the start to end of the movement.

Outcome parameters were derived from the kinematics and consisted of peak excursion of trunk flexion and pelvic anterior tilt from the start of knee flexion (Table 4). The outcome parameter for the 'does the pelvis follow the trunk?' criterion/question of the SKB Rot test was the coupling angle derived from an angle-angle plot between the axial rotation of the trunk and pelvis (Seay et al. [41]). Four unique coordination patterns were identified from this coupling angle: in-phase coordination between pelvis and trunk (both segments moving simultaneously in the same direction); antiphase coordination between pelvis and trunk (both segments moving simultaneously in opposite direction); trunk-only motion; and pelvis-only motion.

The mean and standard deviation of the outcome parameters were calculated over three trials. Observational rating data were recorded onto a Microsoft Excel spreadsheet to compare pre- and post-intervention.

The participant completed the symptom section of the HAGOS pre- and post-intervention and a Microsoft Excel spreadsheet was used to calculate the percentage score [19].

Results

Following a seven-week exercise intervention, comprising 22 sessions, HAGOS symptoms subsection scores improved from 36% to 61%. The participant reported that reduced hip and groin symptoms had led to increased physical activity, including restarting indoor football and climbing. Also, they were cycling more due to less pain when abducting their hip to get on and off their bicycle.

On observational movement quality assessment, the participant exhibited faults of both 'anterior pelvic tilt' and 'trunk flexion' pre-intervention, but no fault post-intervention during the SKB test. Kinematic data supported the improvement with substantial decrease in trunk flexion (Table 3); 12° on the right and 10° on the left (Table 3). Anterior pelvic tilt decreased by 17° on the right and 16° on the left (Table 5).

The participant lost balance on trial 1 of pre-intervention on the left side and trial 3 post intervention on the right side during the SKB Rot test, therefore these trials were removed from analysis. The participant was observed to have 'pelvis follow trunk' and 'trunk flexion' faults pre-intervention, which were not present post-intervention. Analysis of trunk flexion kinematics revealed reductions of 6° on the right and 11° on the left (Table 6). The percentage when the trunk and pelvis were in phase decreased by 20% on the right and 27% on the left from pre-to post intervention (Table 6).

Table 2
Small Knee Bend with Rotation (SKB Rot) test instructions and scoring, from [37], with permission.

Verbal Instruction	Outcome	Right	Left
• Stand on one leg with your foot pointing forward. • Place the unsupported foot behind you by bending your knee 90°.	Does the hip and pelvis follow the trunk?	Y = 1; N = 0	Y = 1; N = 0
• While keeping your body upright, keeping your pelvis and heel in position, bend your knee so that your knee aligns along your 2nd toe.	Does the trunk lean forwards (flex)?	Y = 1; N = 0	Y = 1; N = 0
• While holding this position turn your upper body to the left and right looking over your shoulder 30° • Do you understand the instructions?	Total Score		

Table 3
Definitions of local coordinate orientation for thorax, pelvis, femur and tibia segments.

Segment	X	Y	Z
Thorax	Perpendicular to Z and Y axes pointing to the right	Line between C7 and IJ that is perpendicular to the Z axis pointing forwards	Line between midpoint of IJ and C7 and midpoint of PX to T8 pointing upwards
Pelvis	Line through right to left ASIS markers and perpendicular the Y axis pointing right	Line from midpoint between left and right ASIS and midpoint between left and right PSIS markers pointing forwards	Perpendicular to X and Y axes pointing upwards
Femur	Line between medial and lateral femoral condyle markers projected on functional knee axis and perpendicular to the Z axis pointing to the right	Perpendicular to Z and X axes pointing forwards	Line between hip joint centre and knee joint centre (midpoint of line between medial and lateral femoral condyles projected onto functional knee axis in the femur frame).
Tibia	Line between medial and lateral femoral condyle markers and perpendicular to the Z axis pointing to the right	Perpendicular to Z and X axes pointing forwards	Line between knee joint centre (midpoint of line between medial and lateral femoral condyles projected onto functional knee axis in the tibia frame) and ankle joint centre (midpoint of line between medial and lateral malleoli)

Table 4
Details of how kinematic values were calculated for the movement faults from the SKB and SKB Rot tests.

Test	Fault	Outcome parameter
SKB	Does the trunk lean forwards (flex)?	Peak trunk flexion excursion from the start of knee flexion
	Does the pelvis tilt forwards (anterior)?	Peak pelvis anterior tilt excursion from the start of knee flexion
SKB Rot	Does the hip and pelvis follow the trunk?	Percentage of time pelvis and trunk segment's axial rotation were in-phase from the start to end of trunk rotation
	Does the trunk lean forwards (flex)?	Peak trunk flexion excursion from start of knee flexion

Table 5
Mean peak excursion kinematics related to movement faults for the SKB task, pre and post intervention.

Movement Faults	Pre intervention			Post intervention	
	Side	Fault present	Mean (SD)	Fault present	Mean (SD)
Trunk flexion (°)	Right	Yes	13.3 (1.3)	No	1.5 (1.9)
	Left	Yes	10.9 (5.2)	No	0.8 (0.0)
Anterior pelvic tilt (°)	Right	Yes	21.6 (2.2)	No	4.4 (0.5)
	Left	Yes	20.4 (3.5)	No	4.8 (0.1)

Table 6
Kinematics related to movement faults for the SKB Rot task, pre- and post-intervention.

Movement Fault	Pre-intervention			Post-intervention	
	Side	Fault present	Mean (SD)	Fault present	Mean (SD)
Pelvis follow trunk (% trunk and pelvis in phase)	Right	Yes	27.0 (11.3)	No	7.4 (1.9)
	Left	Yes	47.1 (4.5)	No	20.5 (3.2)
Trunk flexion (°)	Right	Yes	11.3 (3.3)	No	5.7 (4.0)
	Left	Yes	14.1 (2.6)	No	2.9 (0.4)

Discussion

The aim of the study was to examine whether changes in observational ratings of movement from SKB and SKB Rot tasks were supported by kinematics measured using 3D motion analysis following an exercise programme in an ex-footballer with hip and groin pain. The changes in observed movement patterns of the trunk and pelvis in the present study were supported by the objective changes in relevant kinematics measured using 3D motion analysis. These results suggest that observational rating can be an accurate method for detecting changes in the movement faults in the participant studied. The results of the present case study further suggest that movement patterns can be altered with an associated reduction in hip and groin symptoms.

The large improvement in the HAGOS symptoms sub-score from 36% to 61% can be considered a clinically relevant improvement as it is substantially above the smallest detectable change (SDC) value at an individual level previously determined to be about 18% (95% CI 14.1–23.2) [19].

Whilst causation cannot be established in the current study the reduction of symptoms in the present study could be associated with the decrease in trunk flexion during both the SKB and SKB Rot tests following the intervention. Increased trunk flexion is thought to be linked to poor hip muscle control leading to movement into end range hip flexion, which is associated with symptoms in FAI [37,42]. In support of the theory of poor hip muscle control and trunk movement, Crossley and co-workers [15] reported significant delay in onset of electromyography in anterior gluteus medius ($p = 0.07$) and posterior gluteus medius ($p = 0.045$) for those who were rated as poor compared to good performers of a single leg squat. Trunk flexion was not specifically rated but was included in the criteria for rating good or bad performance of the single leg squat. Although muscle activity was not evaluated in the present study, the results of Crossley et al. [15] suggest decreased trunk flexion could indicate improved hip muscle control, which was the focus of the intervention in the present study. Furthermore, reduction in pelvic anterior tilt, improved control of trunk rotation and trunk flexion suggest an increased ability to control the hip muscles in the present study.

Limitations of the present study include it being a single case study with limited follow up. The lack of blinding of the observational rater to knowing that the participant carried out an exercise programme aimed at improving their movement pattern could have caused bias. However, the changes in the kinematic data indicate that the observational ratings were accurate, so bias did not appear to influence them.

Conclusions

The results of the present study suggest that the observational rating of movement from the SKB and SKB Rot tasks may be accurate, as using 3D motion analysis there was a difference in the kinematics assessed to be at fault vs. those not at fault. Sensitivity to change in the observational movement screen was also established suggesting the observational tests may be an accurate tool to detect changes in movement patterns with treatment. Proof of concept of the effect of neuromuscular training was evidenced by the improved movement patterns of the trunk and pelvis achieved in a short space of time, which also led to a reduction in chronic hip and groin symptoms. A larger study is

Appendix

warranted to determine concurrent validity of the observational rating of the HLLMS which was indicated by this proof of concept study. Also, a study with a longer follow up that assesses hip muscle activation is warranted to improve our understanding of how movement patterns could be changed to reduce hip and groin symptoms.

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Conflict of interest

The authors report no conflicts of interest

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.mehy.2018.08.027.

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