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**Objective Classification of Scapular Kinematics in Participants with Movement Faults of the Scapula on Clinical Assessment**

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**Abstract**

The aim of this study was to assess the potential of employing a classification tool to objectively classify participants with clinically assessed movement faults of the scapula. Six participants with a history of shoulder pain with movement faults of the scapula, and twelve healthy participants with no movement faults performed a flexion movement control test of the scapula, whilst scapular kinematic data were collected. Principle Component scores and discrete kinematic variables were used as input into a classifier. Five out of the six participants with a history of pain were successfully classified as having scapular movement faults with an accuracy of 72%. Variables related to upward rotation of the scapula had the most influence on the classification. The results of the study demonstrate the potential of adopting a multivariate approach in objective classification of participants with altered scapular kinematics in pathological groups.

**Keywords:** Scapula, kinematics, classification, Principle Component Analysis

**1. Introduction**

Dynamic assessment of scapular movement is an important factor associated with shoulder dysfunction ([Kibler and McMullen, 2003](#_ENREF_18), [Mottram, 2003](#_ENREF_26), [Caldwell et al., 2007](#_ENREF_1)). The clinical classification of abnormal scapular movement is used to evaluate scapular dyskinesis ([Kibler and McMullen, 2003](#_ENREF_18)), and has been recommended to form part of the basis of the evaluation of scapular dysfunction ([Kibler et al., 2009](#_ENREF_17)). Kibler and Sciascia ([2010](#_ENREF_19)) highlight that the clinical observation of scapular dyskinesis involves three aspects; abnormal scapular position at rest and/or during movement characterised by medial border prominence, inferior angle prominence and/or early scapular elevation (shrugging) on arm elevation, and rapid downward rotation during arm lowering. Clinical assessment, however, is based on the assumption that the clinician fully understands the movement patterns of the shoulder ([Caldwell et al., 2007](#_ENREF_1)), which can often be masked by soft tissues. Therefore, objective quantitative measurement of scapular kinematics is required to fully understand scapular dysfunction.

Investigations of scapular kinematics in patients with shoulder dysfunction have shown less upward rotation and posterior tilt of the scapula than healthy controls ([Ludewig and Cook, 2000](#_ENREF_22), [Lin et al., 2005](#_ENREF_20), [Luckasiewicz et al., 1999](#_ENREF_21), [Worsley et al., 2012](#_ENREF_35)), but results are not consistent, other studies have reported higher upward rotation and posterior tilt in patients with shoulder dysfunction([Graichen et al., 2001](#_ENREF_11), [McClure et al., 2006](#_ENREF_24)). The magnitude of the differences in these studies is small, often with large variability seen in scapular movements, making objective assessment of scapular dysfunction difficult ([Graichen et al., 2001](#_ENREF_11)). The movement of the scapula is a complex interaction of three rotations, in any one of which abnormal movement may occur. Therefore, examining each scapular rotation in isolation further increases the difficulty in forming an objective assessment of scapular dysfunction. In addition, a given kinematic waveform contains a vast amount of information when recording movement of the scapula. Studies often use only discrete values determined from the kinematic waveform, resulting in a loss of important information regarding the movement strategy. Principal component analysis (PCA) has been used in gait analysis to overcome a similar problem, and aided in the discrimination between healthy and pathological populations ([Deluzio and Astephen, 2007](#_ENREF_9)). PCA reduces interrelated variables into principal components (PC) but retains the variation in the original data and preserves important temporal information ([Jolliffe, 1986](#_ENREF_13)).

The ability to objectively classify patients with shoulder dysfunction, based on kinematic data collected during movement of the shoulder complex, would complement subjective interpretation and help identify patients with movement dysfunction of the scapula. Any given shoulder pathology is likely to be multifactorial in nature and sub-groups are likely to exist that demonstrate altered scapular kinematics, which may not be detected by groups means ([Graichen et al., 2001](#_ENREF_11)). Employing a multivariate approach to scapular kinematic analysis may contribute to characterisation of a given pathology and identification of potential sub-groups, to augment typical statistical analyses. Previous classification of scapular dysfunction based on a step-wise logistic regression demonstrated that scapular internal rotation during the lowering phase, serratus anterior muscle activity and a patient’s perception of function were the three greatest predictors of improved function in patients with shoulder impingement ([Hung et al., 2010](#_ENREF_12)). The prediction model, however, relies on the subjective score of the patient’s own perception of their function, therefore, it does not provide a fully objective classification of dynamic scapular movement dysfunction.

A hybrid approach of classifying patients, which involves the reduction of kinematic data using PCA followed by classification of patients using a statistical classifier technique based on the Dempster-Shafer Theory of Evidence has been developed for use in gait analysis ([Jones et al., 2006](#_ENREF_14)).Its generic application has been demonstrated through its use for classifying knee and hip biomechanics in joint replacement patients([Jones et al., 2008](#_ENREF_15), [Whatling et al., 2008](#_ENREF_34)). This type of approach, yet to be adopted in scapular kinematics, may provide a method of overcoming the difficulties of objectively assessing scapular dysfunction. The aim of the present study was to examine the potential of using a classification tool to objectively classify participants who have clinically assessed movement faults of the scapula.

**2. Method**

**2.1. Participants**

Two groups of participants, healthy control and history of pain, were recruited from staff and students of the University of Southampton and the neighbouring community. Twelve healthy control participants, aged 22-49 years (Table 1) who had bilateral pain free shoulder range of motion to 135° of active humeral elevation were studied. Participants were excluded if they had a history of shoulder pain, presence of shoulder, neck and arm pain, previous shoulder injury, neurological disease, systemic inflammatory disease, history of surgery to the cervical, thoracic spine or shoulder complex or a fracture of the neck. The healthy control participants were required to not exhibit any clinical presentation of movement faults on the Shoulder Flexion Scapular Movement Control (SFSMC) test described below. The history of pain group consisted of six participants, aged 23-68 (Table 1), who had a self-reported history of, but not current, shoulder pain and/or pathology. Shoulder pain had to have limited the participant’s activity for more than one week, or required treatment, regardless of medical diagnosis. A physiotherapist assessed the participants prior to testing to ensure they were bilaterally pain free during active shoulder movements. History of pain participants were also required to exhibit clinical presentation of movement faults on the SFSMC test. The study was approved by the School of Health Professions and Rehabilitation Sciences Ethics Committee, and all participants provided written informed consent.

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| Table 1: Participant demographics. Mean ± standard deviation (range). | | | | |
|  | Age (years) | Height (cm) | Weight (kg) | Gender |
|  |  |  |  |  |
| Healthy control (n=12) | 31.1 ± 9.4  (22 – 49) | 172.3 ± 6.4  (165 – 183) | 67.1 ± 11.1  (45 – 82) | 4 Males  8 Females |
|  |  |  |  |  |
| History of pain  (n=6) | 43.8 ± 16.0  (23 – 68) | 171.7 ± 10.9  (155 – 185) | 71.2 ± 15.1  (53 – 90) | 4 Males  2 Females |
|  |  |  |  |  |

**2.2. Motion analysis**

A Vicon 460 (Vicon Motion Systems, Oxford, UK) motion capture system with 6 cameras operating at 120Hz was used to obtain scapulothoracic kinematics. An acromion marker cluster (AMC) was used to obtain scapular kinematics relative to the thorax. The AMC method has been shown to be valid during arm elevation to 120° ([Karduna et al., 2001](#_ENREF_16), [Meskers et al., 2007](#_ENREF_25), [van Andel et al., 2009](#_ENREF_32)) and lowering to within 3.9°, 5.1° and 5.0° for internal, upward and posterior rotation respectively ([Warner et al., 2012](#_ENREF_33)). The AMC consisted of a plastic ‘boomerang’ shaped base with three 6.5mm retro-reflective markers attached. The centre of the AMC was positioned on the posterior aspect of the acromion, the location of which is known to produce the least amount of error compared to other locations on the acromion ([Shaheen et al., 2011](#_ENREF_30)). One aspect of the ‘boomerang’ followed the spine of the scapula and the other pointing anterior in the scapular plane (Figure 1). Arm elevation angles were recorded from a cluster of markers attached to the upper arm. Static calibration trials were used to determine the location of bony landmarks within the local coordinate systems of the markers using the CAST technique ([Capozzo et al., 1995](#_ENREF_2)). The CAST technique uses a ‘wand’ with markers attached to determine the location of anatomical landmarks with respect to a cluster of markers. The tip of the wand is placed against bony landmark of the scapular in turn (acromion angle, root of the medial spine and inferior angle) and a three second capture of the wand and AMC is made. The location of the tip of the wand represents the location of the anatomical landmark in the global coordinate system, and is determined from the markers on the wand. The location of the anatomical landmark is then determined with respect to the local coordinate system of the AMC, and recreated during the dynamic movement trials. This was repeated for the humeral anatomical landmarks (lateral and medial epicondyles) with respect to marker cluster attached to the upper arm. The position of the arm when performing the calibration of anatomical landmarks affects the accuracy of AMC measurements ([Prinold et al., 2011](#_ENREF_27)). Scapular kinematics at lower arm elevation angles, following the lowering phase, was of most interest in the present study as changes in scapular kinematics were more likely to occur at these lower arm positions when performing the SFSMC test. The bony landmarks of the scapula were, therefore, calibrated with the arm at 0° elevation. Anatomical local coordinate systems, in accordance with ISB recommendations, were then constructed for the thorax, scapula and humerus ([Wu et al., 2005](#_ENREF_36)). An Euler angle rotation sequence, also in accordance with ISB recommendations, of internal rotation (Y), upward rotation (X) and posterior tilt (Z) was adopted to determine scapular orientation relative to the thorax ([Wu et al., 2005](#_ENREF_36)). Kinematic data was recorded with the scapula at rest (before being placed into the optimal orientation described below), when placed into the optimal orientation and during the SFSMC test. Kinematic data during the SFSMC test were truncated at the points where arm elevation commenced and ceased following arm lowering. The kinematic waveforms were then interpolated over 101 data points and then averaged across the three repeated trials.

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Figure 1: Acromion marker cluster (AMC) used to record movements of the scapula.

**2.3 Movement control of the scapula**

The Shoulder Flexion Scapular Movement Control (SFSMC) test ([Mottram, 2003](#_ENREF_26), [Comerford and Mottram, 2012](#_ENREF_5)) is aimed at identifying movement faults of the scapula, which may be indicative of scapular dyskinesis, through the concept of dissociation ([Comerford and Mottram, 2001](#_ENREF_4), [Sahrmann, 2002](#_ENREF_28)). The concept involves maintaining control of the segment of interest, the scapula, whilst challenging the ability to maintain this control during movement of the adjacent segment, the arm. The test involves passive placement of the scapula by an experienced physiotherapist into an individual specific optimal orientation. The optimal orientation involved positioning the acromion above the superior angle (to ensure the scapula was out of downward rotation) and the medial spine of the scapula against the thorax (to ensure the scapula was out of internal rotation). Participants aimed to maintain this orientation whilst performing arm flexion to 90° and subsequent lowering to 0° in the sagittal plane. The physiotherapist observed the participant for movement faults which included; superior and inferior movement of the acromion and medial movement or posterior protrusion of the inferior angle of the scapula. A test fail was noted if any of these movement faults were present. The participants were given three practice trials before completing a further three SFSMC tests, which were assessed by the physiotherapist. A further three tests were performed by the participant where kinematic data was recorded. Concurrent physiotherapist assessment of the SFSMC test and recording of kinematic data was not possible as the positioning of the physiotherapist during the test caused marker occlusion.

**2.4. Principal Component Analysis**

Principle component analysis (PCA) was completed on the averaged kinematic waveforms recorded during the SFSMC test. Each rotation from the scapula was assessed individually using the averaged kinematic waveform from each participant. Firstly the waveform was normalised for each data point along the waveform by subtracting the mean and then dividing by the standard deviation ([Chau, 2001](#_ENREF_3)). A correlation matrix (**C**) was then calculated between the *n* x 101 matrix of standardised variables (**Z**), where *n* is the number of participants, and its transpose (**ZT**); , where p is the number of input variables ([Chau, 2001](#_ENREF_3)). Eigen decomposition was then performed on the resulting correlation matrix (**C**) to find the eigen values and eigen vectors; C=*E*Λ*E*T where the columns of matrix *E* contain the eigenvectors and Λ is the diagonal matrix of eigenvalues of **C**, which provide the amount of variance within each principal component ([Chau, 2001](#_ENREF_3), [Daultry, 1976](#_ENREF_7), [Tabachnick and Fidell, 1989](#_ENREF_31)). The diagonal matrix of eigenvalues was ranked from most to least variance. To determine which principal components to retain, the cumulative energy plot was used (i.e. the cumulative sum of the ranked variance). Principal components were retained until the cumulative sum of the variance had reached 95% ([Jolliffe, 1986](#_ENREF_13)). Once the principal components had been determined, the next step was to identify the sections of the kinematic waveform that corresponded to each PC. This was performed by assessing the matrix of the component loadings, **L**, defined as the weighted relationship between the principal component and the original variable; **L** = EΛ1/2 ([Daultry, 1976](#_ENREF_7), [Chau, 2001](#_ENREF_3), [Tabachnick and Fidell, 1989](#_ENREF_31)). The section of the kinematic waveform that corresponded with the principal component was when the factor loading exceeded a threshold of 0.71 ([Comrey, 1973](#_ENREF_6), [Jones et al., 2008](#_ENREF_15)). The final principal component score (Ω) was the product of the standardised variables (**Z**) and the eigenvectors (**E**); Ω = **ZE**. An independent sample t-test was used to test for significant differences between the history of pain group with movement faults, and the healthy control group.

**2.5. Classification**

The data used as input into the classifier were a series of discrete kinematic variables derived from the averaged kinematic waveforms for each participant. These variables consisted of the orientation of the scapula when at rest, when in the optimal position, at various arm positions during the SFSMC test and the first principal component score for each scapular rotation (Table 2). An independent samples t-test was used to test for significant difference between the history of pain group and the healthy control group. Two classifications were performed, an initial baseline classification where all eighteen variables were used as input, and a main classification consisting of a reduced data set of input variables based on the results of the baseline classification. The classifier adopted in the study was the Cardiff Dempster-Shafer classification method, as described by Jones et al([2006](#_ENREF_14)). The classifier allows the combination of different input variables to arrive at a degree of belief for a given hypothesis (*m*), derived from the available evidence ([Dempster, 1968](#_ENREF_10), [Shafer, 1976](#_ENREF_29)). The hypothesis (*m*) in the current study is that participants with a history of shoulder pain have movement faults of the scapula. Each input variable for a given participant (*v*) was standardised and converted into confidence factors (0-1) using a sigmoid function; where *k* is the Pearson’s correlation coefficient for the variable (*v*) and denotes the gradient of the sigmoid function, and θ denotes the group mean value of the variable (*v*) ([Jones et al., 2006](#_ENREF_14)). The variable was then assigned a belief value to obtain a body of evidence (BOE), subject to the bounds of uncertainty (0.7 and 1) ([Jones et al., 2006](#_ENREF_14)). The BOE belief values correspond to the belief in support of the hypothesis *m*{(*x*)}, not in support of the hypothesis *m*({¬*x*}), and uncertainty m({*x*,¬*x*}). The participant’s individual BOE for each variable were then combined using Dempster’s rule of combination to provide a final BOE for each participant. Finally, the combined BOE was visualised on a simplex plot([Jones et al., 2006](#_ENREF_14)).A participant is classified as either not having movement faults if their combined BOE is positioned on the left hand side of the plot, or having movement faults if their combined BOE is positioned on the right hand side of the plot. The lower right vertex of the simplex plot is associated with support of the hypothesis, *m*({*x*}), the lower left vertex is associated with non-support of the hypothesis, *m*({¬*x*}), and the top vertex of the triangle is associated to the level of uncertainty of the classification. The closer the participant to a vertex of the triangle, the greater the belief associated with that vertex ([Jones et al., 2006](#_ENREF_14)). To rank the variables in order of those that had greatest influence in the DST classification, an objective function (OB) was used. For each variable (*v*) this is defined as the Euclidean distance of the group position to the correct vertex simplex plot ([Jones et al., 2008](#_ENREF_15)). A leave-one-out cross validation approach (LOOCV) was then adopted to obtain an overall accuracy score for the strength of the classification.

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| Table 2: Classification accuracy for each variable and overall classification accuracy for baseline and main classifications. Variables *v*1, *v*2, *v*3, *v*5, *v*6 and *v*8 were used as input for the main classification. | | | |
|  | Variable (*v*) | Variable classification accuracy | |
|  | |
| Baseline classification | Main classification |
|  |  |  |  |
|  |  |  |  |
| *v*1 | Upward rotation at end of test | 75% | 78% |
| *v*2 | Upward rotation PC1 score | 71% | 72% |
| *v*3 | Resting upward rotation | 67% | 67% |
| *v*4 | Posterior tilt at start of test | 63% |  |
| *v*5 | Internal rotation at end of test | 58% | 61% |
| *v*6 | Internal rotation at start of test | 58% | 61% |
| *v*7 | Optimal internal rotation | 58% |  |
| *v*8 | Upward rotation at 90° arm elevation | 58% | 61% |
| *v*9 | Upward rotation at start of test | 54% |  |
| *v*10 | Internal rotation PC1 score | 54% |  |
| *v*11 | Internal rotation at 90° arm elevation | 50% |  |
| *v*12 | Optimal upward rotation | 46% |  |
| *v*13 | Posterior tilt at 90° arm elevation | 33% |  |
| *v*14 | Optimal posterior tilt | 33% |  |
| *v*15 | Resting internal rotation | 33% |  |
| *v*16 | Posterior tilt PC1 score | 33% |  |
| *v*17 | Posterior tilt at end of test | 13% |  |
| *v*18 | Resting posterior tilt | 13% |  |
| Classification accuracy | | 50% | 72% |

**3. Results**

Clinical assessment of the participants confirmed that all history of pain participants failed the SFSMC movement control test as they were deemed unable to control the scapula and showed signs of scapular movement faults. All healthy control participants passed the SFSMC test as they were able to control the scapula and showed no signs of movement faults.

**3.1. Principal component analysis**

Examination of the cumulative energy plot to determine which PCs to retain, revealed that the first (PC1) and second (PC2) PCs for each scapular rotation accounted for 95% of the variance amongst the participants for each scapular rotation. Therefore, PC1 and PC2 were retained for further analysis. The factor loadings were examined to identify the portion of the waveform that corresponded to each PC and revealed that PC1 was above the 0.71 threshold across the entire kinematic waveform. This was found in all scapular rotations. PC2, however, did not reach the 0.71 threshold at any point during the waveform in all scapular rotations and was discarded from further analysis. Independent samples t-test showed a significant (p = 0.02) group difference between healthy control participants and history of pain participants for upward rotation’s PC1 score (Table 3), and was included for use in the objective classification.

|  |  |  |  |
| --- | --- | --- | --- |
| Table 3: Mean and standard deviation of input variable data used for classification. | | | |
| Variable | | History of pain | Healthy control |
| *v1* | Upward rotation at end of test\* | -7.9° ± 6.4 | -1.9° ± 9.0 |
| *v2* | Upward rotation PC1 score\* | -7.6 ±7.7 | 1.9 ± 12.0 |
| *v3* | Resting upward rotation | -8.6° ± 8.6 | -5.1° ± 3.8 |
| *v5* | Internal rotation at end of test | 32.6° ± 4.9 | 32.3° ± 6.5 |
| *v6* | Internal rotation at start of test | 30.8° ± 4.5 | 29.1° ± 6.6 |
| *v8* | Upward rotation at 90° arm elevation\* | 7.8° ± 5.3 | 13.7° ± 7.5 |

\*Significant difference between control group and history of pain group (p<0.05).

**3.2. Dempster-Shafer Theory (DST) classification**

The initial baseline classification (Baseline classification) using eighteen input variables was completed to determine which variables had the most influence on the classification of participants (Table 2). The overall classification accuracy of the baseline classification was 50%, with the variables related to upward rotation of the scapula having the greatest influence on the classification (Table 2). The number of input variables was then reduced to six in order to achieve a participant to input variable ratio of 3:1.The highest ranked variables, and those that had shown a statistically significant difference between groups, were used (Table 3).This led to eight variables, therefore, further steps were adopted to remove variables and improve the participant to variable ratio. The variable related to posterior tilt of the scapula at the start of the test was removed due to the known measurement error and poor reliability associated with this scapular rotation ([van Andel et al., 2009](#_ENREF_32), [Warner et al., 2012](#_ENREF_33)). The variable related to internal rotation at the optimal position was also removed as this variable represents a similar position to internal rotation at the start of the test. This resulted in six variables that were used as inputs to the classifier for the main classification.

The results of the main classification, with the chosen six input variables, demonstrated an increased LOOCV classification accuracy of 72% and classified five out of six history of pain participants into the movement fault dominant region (Figure 2). Eight out of twelve of the healthy control participants were classified into the non-movement fault dominant region (Figure 2). For the main classification upward scapular rotation at the end of the SFSMC test had the greatest influence over the classification of participants (Table 2). The history of pain group had a significantly lower upward scapular rotation position compared to the healthy control group at 90° arm flexion and at the end of the test (Table 3).

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Figure2: Simplex plot classification for history of pain (crosses) and healthy control (circles) participants. Participants were classified towards the movement faults (MF), no movement faults (NMF), or towards uncertainty (NMF,MF) regions.

**4. Discussion**

The clinical assessment of shoulder dyskinesis has been proposed to classify patients with shoulder dysfunction and help inform treatment ([Kibler and McMullen, 2003](#_ENREF_18), [Caldwell et al., 2007](#_ENREF_1)). The quantitative classification technique employed in the present study classified five out of six history of pain participants as having movement faults of the scapula, with one participant classified close to the decision boundary as having no moment faults. This demonstrates that it was sometimes possible to objectively classify participants solely based on kinematic data with an accuracy of 72%. This multivariate approach, utilising measurements of scapular orientation at various points during a given task and different scapular rotations, removes the subjective interpretation of scapular dysfunction which is limited by the skill of the clinician performing the assessment ([Caldwell et al., 2007](#_ENREF_1)).Although, it is not suggested that this type of classification should replace clinical assessment, but could be used to compliment the assessment of a given pathology. Of the six parameters that were used as input into the main classification, upward scapular rotation at the end of the test (i.e. after lowering of the arm) had the greatest influence on the classification, and confirms clinical observation that often suggests that abnormal scapular orientation during arm lowering is a distinguishable factor in people with shoulder pain([Kibler and Sciascia, 2010](#_ENREF_19)).The second most influential parameter on the classification was the score of the first principal component for upward rotation. Reduction of the kinematic waveform through the use of principal component analysis (PCA) provided a means of reducing the data into a more manageable form, whilst retaining temporal information. The first principal component for upward rotation (PC1) accounted for over 90% of the variance amongst participants and was related to the entire kinematic waveform. The variability amongst participants would likely be as a result of the relative orientation of the scapula during the test, as there was a tendency for the history of pain participants to exhibit a lower upward scapula rotation during the test. Generalising these results to a larger population, however, is limited due to the small sample size. The studied population may not represent the normal distribution of a general population, and may violate the assumption of a Gaussian distribution used when creating a larger data set of PCs from the original data. Further work on a larger population of participants is needed. Although PCA did not identify specific regions of the waveform of increased variability in movement patterns of the scapula, it did provide a useful score related to the overall orientation of the scapular during the test that could be used further analysis.

The objective classification of movement faults generally agreed with the clinical observation, however, four of the healthy control participants and one history of pain participant were incorrectly classified. This may be due to the inherent large variability observed in scapular kinematics([de Groot, 1997](#_ENREF_8)).Another possible reason for the misclassification is that alterations in scapular kinematics can occur in sub-groups of populations ([Ludewig and Reynolds, 2009](#_ENREF_23)) and considering the multifactorial nature in the aetiology of shoulder dysfunction it is not known whether participants that exhibit altered kinematics are at risk of developing symptoms. The advantage of employing this type of analysis, however, is the ability to identify these potential sub-groups and examine the factors that have led to the altered kinematics. These sub-groups may not be detected by traditional group mean analysis ([Graichen et al., 2001](#_ENREF_11)). The misclassification may also be a result of a misidentification of movement faults by the physiotherapist. The reliability of the SFSMC test has yet to be assessed and the clinician in the present study was not blind to the presence of a history of shoulder pain in the participants. The clinical assessment of movement faults may, therefore, may be biased, and it is possible that the healthy misclassified participants may exhibit movement faults. In addition, the clinical assessment of the presence of movement faults was completed independently of the kinematic data collection and there is a possibility that the participant adopted different movement strategies when being assessed by the physiotherapist compared to when kinematic data were collected. To ensure this was not the case, the participants performed the SFSMC test several times and only those who consistently failed, or passed, the test were included.

There are limitations with the present study that require acknowledgment, primarily concerned with the participant group examined. Only six participants were recruited into the history of pain group and twelve into the healthy control group. With six variables used as input to the classifier the resulting participant to variable ratio was 3:1. This ratio is smaller than what would normally be considered satisfactory for multivariate analysis. In addition to the low numbers of participants, the participants’ cause of the history of shoulder pain was not constrained to a particular pathology. It is conceivable that performing a similar methodology on a participant group that are currently suffering from shoulder impingement, for example, would result in a different outcome for the classification, with altered ranking of the input variables. The direct clinical application of the results of this study, therefore, is limited. The results do demonstrate, however, that the concept of objective classification based on a multivariate approach using kinematic data may provide a more objective interpretation for researchers examining altered scapular kinematics.

**5. Conclusion**

The novel approach of using a multivariate classification tool provided a reasonably successful approach to of objectively classifying participants with clinically assessed movement faults of the scapula based solely on kinematic data. This is despite the large variability observed within scapular kinematics and the relatively small participant numbers studied. This approach could be used for future objective classification of participants to characterise different pathological groups, used to identify potential sub-groups of participants and how these should be assessed clinically towards stratified patient assessment for targeted rehabilitation, or used to assess the effectiveness of treatment to correct movement faults of the scapula.

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References

C. Caldwell, S. Sahrmann & L. V. Dillen 2007. "Use of a movement system impairment diagnosis of physical therapy in the management of a patient with shoulder pain". *J Orthop Sports Phys Ther,* 37**,** 551-563.

A. Capozzo, F. Catani, U. Della Croce & A. Leardini 1995. "Position and orientation in space of bones during movement: anatomical frame definition and determination". *Clin. Biomech.,* 10**,** 171-178.

T. Chau 2001. "A review of analytical techniques for gait data. Part 1: fuzzy, statistical and fractal methods". *Gait Posture,* 13**,** 49-66.

M. J. Comerford & S. L. Mottram 2001. "Movement and stability dysfunction - comtemporary developments". *Man. Ther.,* 6**,** 15-26.

M. J. Comerford & S. L. Mottram 2012. *Kinetic control: the management of uncontrolled movement*, Elsevier.

A. Comrey 1973. *A first course in factor analysis,* New York, Academic Press.

S. Daultry 1976. *Principal Component Analysis,* Norwich, Geo Abstracts Ltd.

J. H. de Groot 1997. "The variability of shoulder motions recorded by means of palpation". *Clin. Biomech.,* 12**,** 461-472.

K. J. Deluzio & J. L. Astephen 2007. "Biomechanical features of gait waveform data associated with knee osteoarthritis: An application of principal component analysis". *Gait and Posture,* 25**,** 86-93.

A. P. Dempster 1968. "A generalization of Bayseian inference (with discussion)". *J Roy Statist Soc Ser B,* 30**,** 205-247.

H. Graichen, T. Stammberger, H. Boné, E. Wiedemann, K. H. Englmeier, M. Reiser & F. Eckstein 2001. "Three-dimensional analysis of shoulder girdle and supraspinatus motion patterns in patients with impingement syndrome". *J. Orth. Res.,* 19**,** 1192-1198.

C. J. Hung, M. H. Jan, Y. F. Lin, T. Q. Wang & J. J. Lin 2010. "Scapular kinematics and impairment features for classifying patients with subacromial impingement syndrome". *Man. Ther.,* 15**,** 547-551.

L. T. Jolliffe 1986. *Principle Component Analysis,* New York, Springer.

L. Jones, M. J. Beynon, C. A. Holt & S. Roy 2006. "An application of the Dempster-Shafer theory of evidence to the classification of knee function and detection of improvement due to total knee replacement surgery". *J. Biomech.,* 39**,** 2512-2520.

L. Jones, C. A. Holt & M. J. Beynon 2008. "Reduction, classification and ranking of motion analysis data: an application to osteoarthritic and normal knee function data". *Comput. Methods Biomech. Biomed. Eng.,* 11**,** 31-40.

A. R. Karduna, P. W. McClure, L. A. Michener & B. Sennett 2001. "Dynamic measurements of three-dimensional scapular kinematics: a validation study". *J. Biomech. Eng.,* 123**,** 184-191.

W. B. Kibler, P. M. Ludewig, P. McClure, T. L. Uhl & A. Sciasia 2009. "Scapular summit: introduction". *J Orthop Sports Phys Ther,* 39**,** A1-A13.

W. B. Kibler & J. McMullen 2003. "Scapular dyskinesis and its relation to shoulder pain". *J. Am. Acad. Orthop. Surg.,* 11**,** 142-151.

W. B. Kibler & A. Sciascia 2010. "Current concepts: scapular dyskinesis". *Br. J. Sports Med.,* 44**,** 300-305.

J. J. Lin, W. P. Hanten, S. L. Olson, T. S. Roddey, D. A. Soto-quijano, H. K. Lim & A. M. Sherwood 2005. "Functional activity characteristics of individuals with shoulder dysfunctions". *J. Electromyogr. Kinesiol.,* 15**,** 576-586.

A. C. Luckasiewicz, P. W. McClure, L. A. Michener, N. Pratt & B. Sennett 1999. "Comparison of 3-dimensional scapular position and orientation between subjects with and without shoulder impingement". *J Orthop Sports Phys Ther,* 29**,** 574-586.

P. M. Ludewig & T. M. Cook 2000. "Alterations in shoulder kinematics and associated muscle activity in people with symptoms of shoulder impingement". *Phys. Ther.,* 80**,** 276-91.

P. M. Ludewig & J. F. Reynolds 2009. "The association of scapular kinematics and glenohumeral joint pathologies". *J Orthop Sports Phys Ther,* 39**,** 90-104.

P. W. McClure, L. A. Michener & A. R. Karduna 2006. "Shoulder function and 3-dimensional scapular kinematics in people with and without shoulder impingement syndrome". *Phys. Ther.,* 86**,** 1075-1090.

C. G. M. Meskers, M. A. J. van de Sande & J. H. de Groot 2007. "Comparison between tripod and skin-fixed recording of scapular motion". *J. Biomech.,* 40**,** 941-948.

S. L. Mottram 2003. Dynamic stability of the scapula. *In:* BEETON, K. S. (ed.) *Manual therapy masterclasses - the peripheral joints.* Edinburgh: Churchill Livingstone.

J. A. I. Prinold, A. F. Shaheen & A. M. J. Bull 2011. "Skin-fixed scapula trackers: A comparison of two dynamic methods across a range of calibration positions". *J. Biomech.,* 44**,** 2004-2007.

S. A. Sahrmann 2002. *Diagnosis and treatment of movement impairment syndromes*, Mosby.

G. Shafer 1976. *A mathematical theory of evidence,* Princetown, University Press.

A. F. Shaheen, C. M. Alexander & A. M. J. Bull 2011. "Effects of attachment position and shoulder orientation during calibration on the accuracy of the acromial tracker". *J. Biomech.,* 44**,** 1410-1413.

B. G. Tabachnick & L. S. Fidell 1989. *Using Multivariate Statistics,* Cambridge; Philadelphia, Harper & Row.

C. J. van Andel, K. van Hutten, M. Eversdijk, D. J. Veeger & J. Harlaar 2009. "Recording scapular motion using an acromion marker cluster". *Gait Posture,* 29**,** 123-128.

M. B. Warner, P. H. Chappell & M. J. Stokes 2012. "Measuring scapular kinematics during arm lowering using the acromion marker cluster". *Hum Mov Sci,* 31**,** 386-396.

G. Whatling, H. V. Dabke, C. A. Holt, L. Jones, J. Madete, P. M. Alderman & P. Roberts 2008. "Objective functional assessment of total hip arthoplasty following two common surgical approaches: the posterior and direct lateral approaches". *Proc Inst Mech Eng H,* 226**,** 897-905.

P. Worsley, M. B. Warner, S. L. Mottram, S. D. Gadola, H. E. J. Veeger, H. J. Hermans, D. Morrissey, P. Little, C. Cooper, A. Carr & M. J. Stokes 2012. "Motor control retraining exercises for shoulder impingement: effects on function, muscle activation, and biomechanics in young adults". *J. Shoulder. Elb. Surg.,* In press.

G. Wu, F. C. T. van der Helm, H. E. J. Veeger, M. Makhsous, P. V. Roy, C. Anglin, J. Nagels, A. R. Karduna, K. McQuade, X. Wang, F. W. Werner & B. Buchholz 2005. "ISB recommendation on definitions of joint coordinate systems of the various joints for the reporting of human joint motion - Part II: shoulder, elbow, wrist and hand". *J. Biomech.,* 38**,** 981-992.