Clinical Biomechanics

Joint loading asymmetries in knee replacement patients observed both pre- and six months post-operation

Running title: Asymmetries in Knee Replacement Patients

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Abstract

Background Studies have highlighted asymmetries in knee joint moments during activities of daily living in individuals with osteoarthritis and joint replacements. However, there is a need to investigate the forces at the knee joints in order to establish the extent of loading asymmetry.

Methods Twenty healthy (mean, 62; range, 55-79 years of age) and 34 pre- to post-knee arthroplasty (mean, 64; range, 39-79 years of age) participants performed gait and sit-stand activities in a motion capture laboratory. Testing was conducted 4 weeks pre- and 6 months post- knee arthroplasty. Knee joint forces and moments were predicted using inverse dynamics and used to calculate peak loading and impulse data which were normalized to body weight (BW). Comparisons were made in loading between affected and contralateral limbs, and changes from pre- to post-knee arthroplasty.

Findings Pre-knee arthroplasty mean peak vertical knee forces were greater in the contralateral limb compared to the affected limb during both gait 3.5*BW vs. 3.2*BW and sit-stand 1.8*BW vs. 1.5*BW. During gait, peak knee adduction moment asymmetries significantly changed from pre- to post-knee arthroplasty (-0.3 to 0.8*% BWm.Ht), although differences in vertical knee forces remained. The sit-stand activity showed vertical ground reaction asymmetries slightly increased post- knee arthroplasty (from 0.06*BW pre- to 0.08*BW post). The healthy participants showed no noteworthy asymmetries.

Interpretation This study showed loading asymmetry of the ground reaction and TFJ forces between affected and contralateral limbs both pre- post-knee arthroplasty. Over reliance of the contralateral limb could lead to pathology.

Introduction

Knee osteoarthritis (OA) is a common age-related pathology causing pain and loss of function (Fitzgerald et al., 2004). The prevalence of knee joint OA has increased in recent years and now comprises one of the greatest sources of expenditure for modern society (NJR, 2007). When advance OA causes significant pain and functional decline for an individual, joint surgery is used to replace degenerated articular surfaces, with knee arthroplasty (KA) being the most common procedure for advanced OA (NJR, 2010). Evidence suggests that KA patients experience more difficulty performing daily tasks than the healthy age, matched population (Noble et al., 2005), and they often use compensatory strategies during gait and sit-to-stand (McClelland et al., 2007, Farquhar et al., 2009). The symmetry of joint movement (kinematics) and loading (kinetics) has been described to vary in the health population during activities such as gait, although relatively small differences are commonly observed (Sadeghi et al., 2000). When an individual has joint pain and pathology significant asymmetries can develop between the affected and contralateral limb, commonly to reduce loading in pathological joints (which can increase loading in the contralateral limb).

Asymmetries between limbs have been reported during several activities of daily living in patients with OA or with joint replacement. Studies have combined motion capture and basic inverse dynamic techniques to show asymmetries of joint moments during sit to stand (Farquhar et al., 2009, Christiansen and Stevens-Lapsley, 2010), stair ascent (Lamontagne et al., 2011), and gait (Alnahdi et al., 2011). Difference in effected and contralateral joint loading have been assessed in patient pre- and post-hip arthroplasty using motion capture and inverse dynamic modeling techniques (Shakoor et al., 2003). They found the contralateral knee was subjected to higher dynamic loading during gait pre-operatively, which was retained post-THA (range 10-23 months), with three of the five knee force and moment variables collected being significantly higher in the contralateral limb (knee adduction and extension moment, medial knee compartment contact force). This is despite improvements in pain and function scores. Metcalfe et al. [20] recently showed OA patients experienced increased joint moments in the effected knees compared to age matched healthy individuals. One year post-knee replacement (patients received either unilateral and total replacement), the affected limbs had returned to normal, with slightly higher moments in the contralateral limb (Metcalfe et al., 2012). These previous studies, however, have relied on inverse dynamics techniques that either include basic or no muscle forces to calculate joint reactions. Research has shown muscles and soft tissues have a significant contribution to forces and moments acting across a joint (Shelburne et al., 2006, Winby et al., 2009).

Recent evidence which has shown a significant association between elevated joint loading and OA progression (Bennell et al., 2011). In addition, the contralateral limb has been shown to predict long term function post-KA (Farquhar and Snyder-Mackler, 2010) and a large proportion of primary TKA patients will have their contralateral joints replaced within 10 years (Sayeed et al., 2011). There is a need to expand research surrounding joint loading pre- and post-KA and include predicted muscle forces that estimate the full extent of joint loading asymmetries. We therefore investigated whether (1) pre-KA patients would have greater asymmetry in joint loading between limbs (larger loading through the contralateral knees) compared to healthy individuals and (2) if this asymmetry would be retained post-operation.

Patients and Methods

We recruited 20 healthy volunteers between the ages of 50 to 80 years (nine men, 11 women) from the local community who had no pain in the lower limbs, no previous pathologies in the last 2 years, and no known musculoskeletal or neurological diseases. We selected the patients using the following criteria: (1) primary knee arthroplasty, (2) no other comorbidities which significantly affect pain and function, (3) able to walk 50 meters. The mean age of the 34 patients was 64 years (range, 40-82 years); there were 14 men and 20 women. These patients were all diagnosed with OA after radiographs and clinical assessments were performed by the consultant; the patients were tested approximately 4 weeks prior to their KAs (14 unicompartmental KA and 20 total KA) and 6 months after their KA (Table 1). Institutional and National Health Service (NHS) ethics approval was attained prior to the study, and written informed consent was obtained from each participant.

The participant demographics showed that patients scheduled to undergo KAs were slightly older and had higher BMI compared to the healthy cohort, although none of these variables were significantly different between the groups (Table 1). All pre-KA patients had higher perceived pain and instability scores, as well as lower perceived function, measured by the Western Ontario and McMaster Universities Arthritis Index (WOMAC) (Bellamy et al., 1988) and the Oxford Knee Score (OKS) (Dawson et al., 1998).

Gait and sit to stand activities were assessed in patients 4 weeks pre-operation and at 6 months post-operation using a Vicon motion analysis system (Combination of 460 and T series, Vicon Motion Systems, Oxford, UK) and two Kistler force plates (Kistler Instrument AG, Kistler Group, Winterthur, Switzerland). Marker data were collected at 120 Hz, and analogue data from the force platforms were collected at 1080 Hz (Worsley, et al, , 2011). Marker and force plate data were low-pass filtered at 5 Hz during post-processing. Twenty-four retroreflective markers (9 mm) were placed directly on the skin of each participant using double-sided adhesive tape. Markers were placed in a modified Helen Hayes (Kadaba et al., 1990) marker set-up with anatomical landmarks established by a physiotherapist (PW). Additional markers were placed on the superior surface of the iliac crests to reconstruct the pelvis if other markers were occluded. Further markers were also added to the foot (the fifth metatarsal head, and cuboid and navicular bones) in order to model inversion and eversion articulations more accurately (Figure. 1A). Participants were asked to perform gait and sit-stand motions three times. Gait trials were performed along a 10-minute walkway and were normalized from heel strike to heel strike. The sit-stand motion was normalized from full-sitting to standing with the knees and trunk extended. The chair used for the sit-stand activity was of a standard 45-cm height, and the back of the chair was removed to ensure all pelvic markers were visible to the motion capture cameras. Participants were encouraged to perform the activities as they normally would in their home environments.

We then used the musculoskeletal modeling process published (Worsley et al., 2011). Briefly, inverse dynamics were calculated from the motion capture and force plate data using musculoskeletal modeling software (The AnyBody Modeling System™, AnyBody Technology, Aalborg, Denmark) (Damsgaard et al., 2006). From these models we obtained the following parameters: knee joint kinematics (angles) and kinetics (resultant joint moments and forces). Key parameters were; 1) vertical force plate reaction, 2) vertical TFJ force, 3) posterior-anterior TFJ force, 4) TFJ flexion moment 5) TFJ adduction moment. Patient-specific musculoskeletal models were derived from static standing postures (soft-tissue artifact is assumed to be minimal during quiet standing) and used to create the subject-specific models. Models were scaled from a single anthropometric data set (Klein Horsman et al., 2007) using criteria that take the BMI into account. A 13-segment, rigid body model, with 16° of freedom, was orientated in the segments included lower limb structures, the trunk, and the head. During the dynamic modeling process joint kinematics were established using a global optimization method, which utilized a set of Karush–Kuhn–Tucker optimality conditions. This approach calculates the position of each segment in relation to the measured markers, subject to the degrees of freedom within the model. Once optimized kinematics were derived, inverse dynamics were performed. In order to solve the known moments about each joint muscles were recruited using a MinMax solver where the load is distributed across muscle elements so that fatigue of a given muscle is postponed as long as possible (larger muscles provide most of the force) (Rasmussen et al., 2001). The model had over 300 Hilltype muscle elements, these were established based on anthropometric data and International Society of Biomechanics (ISB) standards (Klein Horsman et al., 2007, Wu et al., 2002). Final joint forces and moments were derived from the combination of applied (force plate), known (segment mass), and optimized muscle forces acting about each joint

The knee was simplified to a hinge joint because of the known soft tissue artifact errors in motion capture techniques. This constraint on the model was placed because evidence surrounding estimations of secondary motions of the knee (e.g. internal external rotation) from motion capture data show significant errors (>4°), despite optimization techniques (Andersen et al., 2010). Resultant TFJ kinematics and kinetics, along with force plate data from the three trials for each of the activities, were averaged and collated for all participants. The kinetic forces produced from the musculoskeletal modeling and force plates were normalized to bodyweight (BW) and moments to percentage body weight and height. Recent evidence has highlighted the important of observing joint loading over the who activity cycle and not relying on discrete parameters (mean, peak etc.) (Bennell et al., 2011). We therefore analyzed both the peaks of the waveforms and the knee adduction impulse where the integral of the whole positive section of the curve was calculated (stance phase of gait, whole sit-stand cycle) .These data were then used to compare differences between affected and contralateral limbs (dominant and non-dominant limbs of the healthy group).

Two tailed and paired sample t-tests were used to examine differences between limb loading data. Two-way, repeated, measure ANOVAs were used to compare pre-KA to post-KA changes in loading differences among the limbs. Mann Whitney U tests were performed to compare healthy vs. pre-KA and healthy vs. post-KA between limb loading differences. All analysis was performed using Matlab (The MathWorks Inc, Massachusetts, USA).

Results

The healthy participants showed no significant differences between limbs in the force plate data or forces and moments acting at the knee joints during both activities. Pre-KA patients showed significant greater contralateral mean peak vertical TFJ force (Figure 2A, 3A) and TFJ adduction impulse (p=0.01, p=0.04) compared to the affected limb during gait (Table 2). This asymmetry of TFJ adduction impulse was significantly greater than the healthy control group (p=0.03). No other significant differences between affected and contralateral limb loading were observed pre-arthroplasty during gait. The sit-stand activity showed pre-KA patients had significantly increased peak vertical force plate reaction in the contralateral limb (p=0.01). At the TFJ there were also significantly greater peak forces (vertical and anterio-posterior) and moments (flexion, addiction and addiction impulse) in the contralateral limb pre-KA (Table 3). These asymmetries of loading were significantly greater than the health group for both vertical force plate reaction (p=0.007) and peak TFJ adduction moment (p=0.04).

Post-KA the only significant between limb asymmetry during gait was in the vertical knee reactions (Fig 2B), with greater loading in the contralateral limb (p=0.03). The mean peak vertical force on the contralateral TFJ was 0.4 *BW greater than the affected TFJ. When comparing changes from pre- to post-KA, both peak adduction moment and adduction impulse differences were significantly changed (p =0.01-0.03). However, during gait, ground reaction and TFJ forces were not shown to changes significantly (p>0.1) from pre- to post-KA. During sit-stand the contralateral limb vertical force plate and TFJ reactions remained significantly greater (p=0.01, p=0.04) than the affected side post-KA (Figure 3B). In addition, peak flexion moment and adduction impulse also remained significantly increased in the contralateral limb (p=0.03, p=0.04). The post-KA group also showed significantly greater asymmetries in the ground reaction forces than the healthy group (p=0.04). However, no statistically significant changes (p=0.54-0.84) were observed in the between limb loading differences from pre- to post-KA.

Discussion

Previous research has shown significant asymmetries in lower limb loading in individuals with OA and joint replacements (Metcalfe et al., 2012, Shakoor et al., 2003). However, these studies have predominantly relied on inverse dynamic simulations of activity data which calculated joint moments and neglect joint reactions which can be affected by muscle contributions. This study was performed to assess patient's pre- and post- knee arthroplasty using modeling techniques which calculated resultant joint forces and moments subject to both extrinsic factors (foot reactions) and muscle contributions. The purpose of the study was to identify any differences between affected and contralateral limb loading, and to assess if symmetry of loading patterns were changed pre- to post-knee arthroplasty. .

We found asymmetries in loading between affected and contralateral limbs pre-knee arthroplasty during both gait and sit-stand activities. During gait the most significant differences were observed in vertical knee force and adduction moment impulses. Results showed a significant increase in contralateral knee loading compared to the affected side for vertical knee reaction, but a significantly lesser knee adduction moment. This result is similar to other studies have assessed between limb loading in patients suffering from osteoarthritis (Hunt et al., 2006, Metcalfe et al., 2012, Chan et al., 2005). The magnitudes of these peak adduction moments appear similar between studies (Table 4). However, the normalization of these data has varied in the literature making direct comparisons difficult (Chan et al., 2005, Hunt et al., 2006). Previous studies (Farquhar et al., 2009, Mizner and Snyder-Mackler,

2005) have also highlighted asymmetry in movement patterns during the sit-to-stand task in OA patients and the early months following unilateral knee arthroplasty. This asymmetry has been associated with shifts in posture to reduce weight bearing through the operated lower limb (Mizner and Snyder-Mackler, 2005).This shift in weight balance could help to explain the large differences in vertical force plates and knee joint loading between affected and contralateral knees in our study. Previous reports of these ground reaction asymmetries have ranged from 0.03-0.1*BW, with the results from the present study falling within these values.

The present study found the asymmetries in loading that were observed pre-KA were general observed post-KA for gait and more significantly sit-stand. During gait the most significant change in was seen in TFJ adduction moments (peak and impulse), where pre-KA increases in the affected limb were reversed post-KA. This is a finding shared by Metcalfe et al., where small but significant changes in knee adduction impulse were observed during gait (Metcalfe et al., 2012). The present study has shown that although some changes have been observed in gait, the sit-stand activity was predominantly unchanged with increased loading on the contralateral limb. To our knowledge there is very little research looking into the nature of ground reaction and joint loading asymmetries from pre- to post-KA during sit-stand. What the evidence does show is an apparent association between the time of assessment post-KA and the level of asymmetry, with those assessed later having less asymmetry (Farquhar et al., 2008). Indeed, those assessed up to 3 months post-KA have shown as much as 0.1*BW ground reaction force increase in the contralateral limb (Mizner and Snyder-Mackler, 2005). In contrast, those assessed 12 months post-KA had as little as 0.03*BW, with our study falling within this range 0.07*BW. There is the potential that if we had followed our patients up over a longer period the asymmetries we observed may have reduced. However, comparisons between studies are limited due to the different patient populations being assessed and the different analytical approaches of the studies.

Shakoor et al has hypothesized that neuromuscular adaptations that place greater loads on the contralateral limb in joint replacement patients may have consequences for the development of multiarticular OA particularly if these movement patterns do not resolve (Shakoor et al., 2002). Indeed, recent evidence by Bennell et al. [5] showed that knee adduction moment impulse was independently associated with greater loss in the medial, tibial, cartilage volume over a 12-month period (Bennell et al., 2011). Further studies are needed to determine whether there is an association between changes in joint loading and the development of contralateral joint pathology, though this would be challenging because of multiple factors that can cause OA (genetics, hormones, anatomy, obesity, age) (Hart et al., 1999). Increasing the need for research is the evidence that the contralateral limb predicts function 3 years post-unilateral KA, and the average non-operated limb weakens over time, possibly representing not only changes resulting from aging but progression of OA (Farquhar and Snyder-Mackler, 2010). Further, 35% to 43% of patients who have undergone unilateral TKAs have replacements on the contralateral side within 10 years (McMahon and Block, 2003, Sayeed et al., 2011), with evident implications on patient health and cost to society.

The authors acknowledge limitations to the present study. Firstly this study was conducted on small samples of healthy and knee arthroplasty patients. The implication are that the results cannot be generalized across populations and larger longitudinal studies are required to assess the loading of joints during activities of daily living in different sub-populations. There were also some differences in the demographics of the participants with the KA patients having a larger BMI than the healthy subjects. Secondly, the length of follow up for knee arthroplasty patients was only 6 months and continued recovery of function is known to occur in excess of one year post-operation (Vogt and Saarbach, 2009). However, studies have shown early adaptations in joint movement patterns are retained one year post-operation (Levinger et al., 2012). Thirdly, our findings must be interpreted in the context of accuracy of methods to estimate the loading asymmetries. Estimated joint moments and forces from the musculoskeletal models relies on a set of assumptions, including anthropometric scaling, joint simplification and muscle recruitment solvers which do not allow for co-contractions. The most stringent test of the modeling outputs is conducted during the “Grand Challenge Competition to Predict In Vivo Knee Loads” (Fregly et al., 2011). This annual competition provides researchers with in vivo motion capture, ground reaction, electromyography, muscle strength, imaging, and instrumented tibial prosthesis contact force data for gait and other movement trials. The software used within this study (The AnyBody Modeling System™, AnyBody Technology, Aalborg, Denmark) predicted medial and lateral knee contact forces for two specified gait trials. The predictions did follow the in vivo medial contact force trends (although some over prediction), but the predictions did not follow the in vivo, lateral, contact force measurements. Thus, the accuracy of the total contact force predictions was unclear. Based on the fact that both limbs in the model used the same set of assumptions and are subject to the same limitations, there is an argument that these asymmetries truly exist. The magnitudes of these asymmetries, however, may not be reflected in our estimations.

Conclusions

Patient’s scheduled for knee arthroplasty had significantly increased ground reaction and resultant knee forces and moments in their contralateral limb during both gait and sit-stand. Six months post-knee arthroplasty symmetry of TFJ adduction moment significantly changed during gait, although knee forces continued to be increased on the contralateral side.

However, the sit-stand activity showed no improvement from pre- to post- knee arthroplasty, with continued increased loading on the contralateral limb. The implications of these sustained asymmetries in joint loading require further investigation, with regards to the deposition of the contralateral limb developing pathology.

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Legends

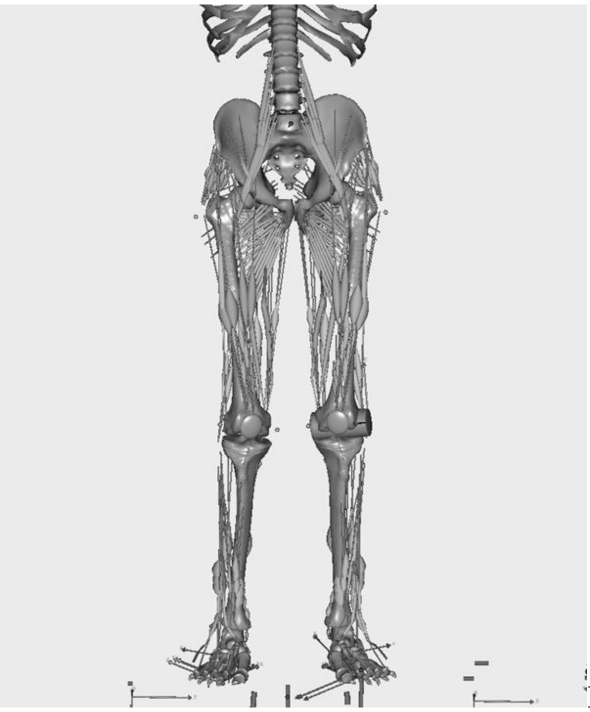
Fig. 1 A The motion capture and modeling techniques included (A) a marker set-up during a gait trial and (**B**) a 16°-of-freedom AnyBody musculoskeletal model with over 300 muscles.

Fig. 2A-B Illustrated here are the mean vertical knee forces during the gait cycle in mean values for (A) pre-KA patients and (B) post-KA patients. The affected side is represented by a solid line, and the contralateral side is represented by a dashed line.

Fig. 3A-B Illustrated here is the vertical knee force during sit-to-stand activities in mean values for (A) pre-KA patients and (B) post-KA patients. The affected side is represented by a solid line, and the contralateral side is represented by a dashed line.

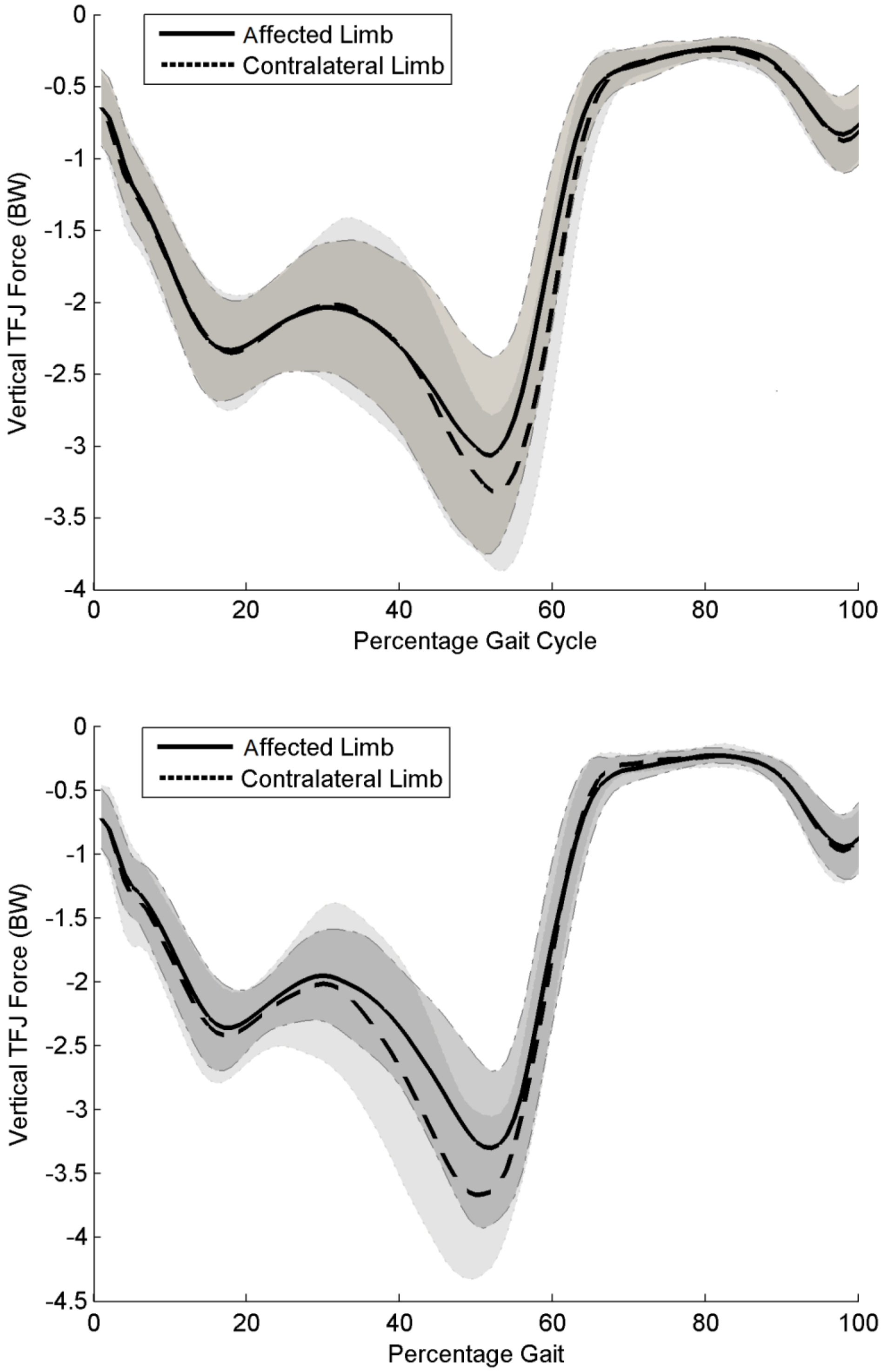
Figure 1

A



B

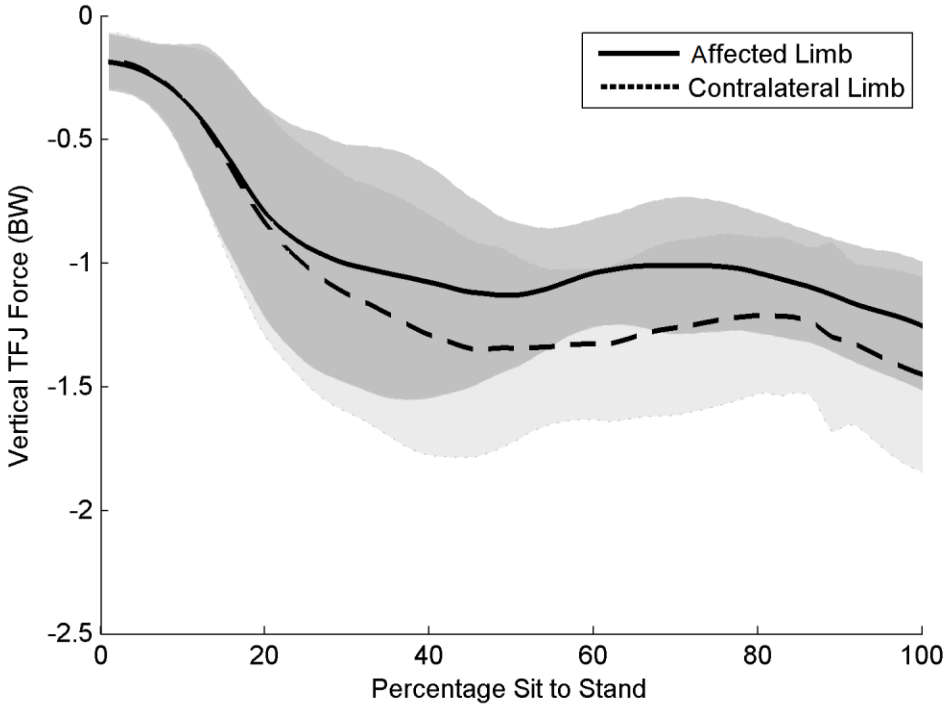
Figure 2


Affected Limb
Contralateral Limb
Vertical TFJ Force (BW)
Percentage Gait Cycle
Affected Limb
Contralateral Limb
Vertical TFJ Force (BW)
Percentage Gait

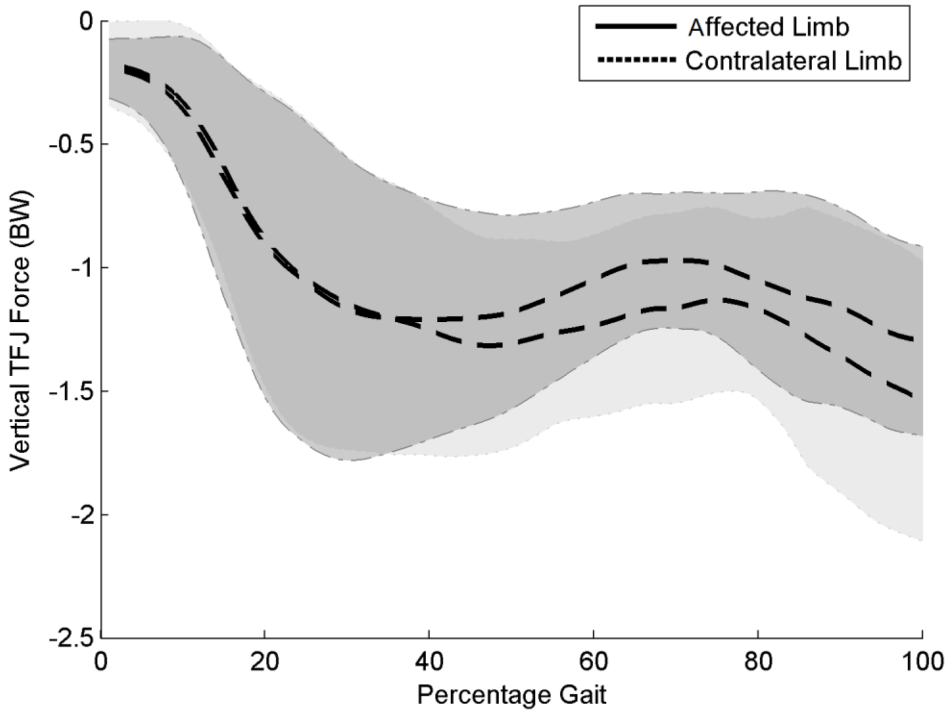
A

B

Figure 3


Affected Limb
Contralateral Limb
Vertical TFJ Force (BW)
Percentage Sit to Stand
0
-0.5
-1
-1.5
-2
-2.5
0
20
40
60
80
100

A


Affected Limb
Contralateral Limb
Vertical TFJ Force (BW)
Percentage Gait
0
-0.5
-1
-1.5
-2
-2.5
0
20
40
60
80
100

B

Table 1. Demographics of 20 healthy and 34 pre- and post-knee arthroplasty (KA) participants.

Variable	Healthy	Pre-KA	Post-KA	Healthy vs. Pre-KA	Pre-KA vs. post-KA
Age (years)	62 ± 6	64 ± 10	65 ± 9	p=0.43	p=0.71
Weight (kg)	78 ± 13	85 ± 18	86 ± 17	p=0.18	p=0.57
Height (cm)	166 ± 11	167 ± 10	167 ± 10	p=0.97	p=0.97
BMI	28 ± 4	31 ± 6	31 ± 5	p=0.23	p=0.93
WOMAC	1 ± 3	46 ± 15	17 ± 13	p<0.001	p<0.001
OKS	47 ± 2	24 ± 9	38 ± 8	p<0.001	p<0.001

Mean value presented ± SD; OKS = Oxford Knee Score.; WOMAC = Western Ontario and McMaster Universities Arthritis Index

Table 2. Moments and forces at the knee and force plates during gait in 20 healthy and 34 pre- to post-knee arthroplasty participants. Statistical significance between limbs† and groups‡ are detailed (p<0.05).

	Healthy		Pre-operation		Post-operation				
Parameter	Dom.	Non-dom.	Contra.	Affected	Contra.	Affected	Healthy vs. Pre-KA	Healthy vs. Post-KA	Pre-KA vs. Post-KA
Peak FP vertical reaction (BW)	1.1 ± 0.1	1.1 ± 0.1	1.1 ± 0.1	1.1 ± 0.1	1.1 ± 0.1	1.1 ± 0.1	p=0.81	p=0.75	p=0.2
Peak Vertical TFJ reaction (BW)	3.4 ± 0.5	3.2 ± 0.6	3.5 ± 0.6	3.2 ± 0.6†	3.9 ± 0.6	3.5 ± 0.6†	p=0.37	p=0.25	p=0.33
Peak P-A TFJ reaction (BW)	0.6 ± 0.2	0.6 ± 0.3	0.7 ± 0.3	0.6 ± 0.3	0.7 ± 0.2	0.6 ± 0.3	p=0.39	p=0.42	p=0.1
Peak TFJ flexion mom (Nm/BW.Ht%)	2.6 ± 0.5	2.5 ± 0.4	2.2 ± 0.7	2.1 ± 0.7	2.1 ± 0.8	2.1 ± 0.7	p=0.61	p=0.57	p=0.34
Peak TFJ adduct mom (Nm/BW.Ht%)	1.8 ± 0.5	1.9 ± 0.4	2.6 ± 1.3	2.9 ± 1.4	2.9 ± 1.0	2.1 ± 1.0	p=0.56	p=0.27	p=0.04‡
TFJ adduct impulse (Nm.s/BW.Ht%)	1.4 ± 0.4	1.3 ± 0.4	0.6 ± 0.4	1.1 ± 0.6†	1.4 ± 0.5	1.2 ± 0.4	p=0.03‡	p=0.33	p=0.02‡

Mean presented ± SD; TFJ = Tibiofemoral joint; FP = Force plate; KA = Knee arthroplasty; P-A = Posterior-Anterior; N = Newton ; BW = Bodyweight; Nm = Newton meter ; Ht = Height

Table 3. Moments and forces at the knee and force plates during sit-stand in 20 healthy and 34 pre- to post-knee arthroplasty participants. Statistical significance between limbs† and groups‡ are detailed (p < 0.05).

	Healthy		Preoperation		Postoperation				
Parameter	Dom.	Non-dom.	Contra.	Affected	Contra.	Affected	Healthy vs. Pre-KA	Healthy vs. Post-KA	Pre-KA vs. Post-KA
Peak FP vertical reaction (BW)	0.55 ± 0.1	0.54 ± 0.1	0.61 ± 0.1	0.55 ± 0.1†	0.61 ± 0.1	0.53 ± 0.1†	p<0.01‡	p<0.05‡	p=0.8
Peak Vertical TFJ reaction (BW)	1.7 ± 0.4	1.8 ± 0.6	1.8 ± 0.4	1.5 ± 0.4†	1.8 ± 0.4	1.6 ± 0.5†	p=0.32	p=0.29	p=0.84
Peak P-A TFJ reaction (BW)	1.5 ± 0.5	1.6 ± 0.6	1.6 ± 0.6	1.3 ± 0.5†	1.4 ± 0.6	1.2 ± 0.5	p=0.32	p=0.45	p=0.7
Peak TFJ flexion mom (Nm/BW.Ht%)	3.2 ± 1.1	3.5 ± 1.2	3.2 ± 1.1	2.5 ± 1.2†	2.4 ± 1.1	2.1 ± 1.1†	p=0.21	p=0.27	p=0.54
Peak TFJ adduct mom (Nm/BW.Ht%)	3.5 ± 1.7	3.1 ± 1.6	3.5 ± 1.5	2.7 ± 1.6†	3.6 ± 1.4	3.1 ± 1.1	p<0.05‡	p=0.27	p=0.55
TFJ adduct impulse (Nm.s/BW.Ht%)	2.3 ± 1.2	2.3 ± 1.4	2.1 ± 1.5	1.6 ± 1.6†	2.3 ± 1.4	1.8 ± 1.5†	p=0.29	p=0.33	p=0.67

*Mean presented ± SD; TFJ = Tibiofemoral joint; FP = Force plate; KA = Knee arthroplasty; P-A = Posterior-Anterior; N = Newton ; BW = Bodyweight; Nm = Newton meter ; Ht = Height

Table 4. Summary of literature investigating loading differences at the knee, in osteoarthritic and knee arthroplasty patients.

Study	Sample	Time post-KA (months)	Activity	Peak knee adduction difference	Peak knee adduction impulse difference	Peak knee vertical reaction difference	Peak vertical ground reaction difference
Metcalfe et al., 2012	14 (KA)	12	Gait	NA	0.1 Nm.s/BW.Ht	NA	NA
Shakoor et al., 2003	22 (THA)	10-23	Gait	0.1% BWm.Ht	NA	0.3*BW	NA
Alnahdi et al., 2010	24 (THA)	12	Gait	0.06 Nm/kg.Ht	0.03 Nm/kg.m.s	NA	NA
Chan et al., 2005	14 (OA)	NA	Gait	0.26 Nm/kg	NA	NA	NA
Hunt et al., 2006	100 (OA)	NA	Gait	0.5% BWm.Ht	NA	NA	0.03*BW
Farquhar et al., 2008	12 (TKA)	3	Sit-stand	NA	NA	NA	0.08*BW
Farquhar et al., 2008	12 (TKA)	12	Sit-stand	NA	NA	NA	0.03*BW
Mizner and Snyder-Mackler, 2005	14 (TKA)	3	Sit-stand	NA	NA	NA	0.1*BW
Worsley et al	34 (KA)	6	Gait Sit-stand	0.8% BWm.Ht 0.5% BWm.Ht	0.2% Nm.s/BW.Ht 0.5% Nm.s/BW.Ht	0.4*BW 0.24*BW	0.03*BW 0.07*BW

*NA – data not applicable or not available.