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Increased knee joint loads during walking are present in subjects with knee osteoarthritis

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Summary

Objective: This study tests the hypothesis that the peak external knee adduction moment during gait is increased in a group of ambulatory subjects with knee osteoarthritis (OA) of varying radiographic severity who are being managed with medical therapy. Tibiofemoral knee OA more commonly affects the medial compartment. The external knee adduction moment can be used to assess the load distribution between the medial and lateral compartments of the knee joint. Additionally, this study tests if changes in the knee angles, such as a reduced midstance knee flexion angle, or reduced sagittal plane moments previously identified by others as load reducing mechanisms are present in this OA group.

Design: Thirty-one subjects with radiographic evidence of knee OA and medial compartment cartilage damage were gait tested after a 2-week drug washout period. Thirty-one normal subjects (asymptomatic control subjects) with a comparable age, weight and height distribution were also tested. Significant differences in the sagittal plane knee motion and peak external moments between the normal and knee OA groups were identified using *t* tests.

Results: Subjects with knee OA walked with a greater than normal peak external knee adduction moment (P=0.003). The midstance knee flexion angle was not significantly different between the two groups (P=0.625) nor were the peak flexion and extension moments (P>0.037).

Conclusions: Load reducing mechanisms, such as a decreased midstance knee flexion angle, identified by others in subjects with endstage knee OA or reduced external flexion or extension moments were not present in this group of subjects with knee OA who were being managed by conservative treatment. The finding of a significantly greater than normal external knee adduction moment in the knee OA group lends support to the hypothesis that an increased knee adduction moment during gait is associated with knee OA.

Key words: Knee OA, Gait, Joint loading, Osteoarthritis.

Introduction

Knee pain, much of it related to osteoarthritis (OA), has been described as reaching epidemic proportions[1]. Symptomatic OA of the knee affects 10% of adults over age 55 and, a quarter of those affected are severely disabled[2]. The incidence of knee OA increases with age[3] and it is believed to result from degenerative changes in cartilage which are to at least some extent mediated by harmful deleteriously increases in joint loading[4,5]. Increased forces may be a contributing factor to the development or progression of OA[6]. During walking, the forces across the knee are not transmitted equally between the medial and lateral compartments; rather, the load on the medial compartment is approximately 2.5 times greater than that on the lateral compartment[7]. This asymmetry in the distribution of the forces may help to explain the markedly higher prevalence of medial compartment involvement reported in subjects with tibiofemoral OA relative to the lateral compartment[8]. This is in keeping with the current paradigm that loading at the cartilage–bone interface is intimately involved with OA[9–14].

Most studies to date on the dynamic knee joint loads have concentrated primarily on the flexion/extension motion of the knee joint[15–18] or on the ground reaction forces[15,16,18]. For example, patients with advanced symptomatic knee OA who are preoperative for total knee replacement walk with decreased sagittal plane range of motion and a decreased loading rate of the ground reaction forces[15,16]. It has also been suggested that the demand on

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the quadriceps muscles and painful joint compressive stresses may be lessened due to a decreased knee flexion during midstance[16]. However, it remains unclear whether these measured changes in knee joint angles or ground reaction force loading rates actually result in lower knee joint loads.

Measurement of the knee joint moments provides a more direct indication of the actual knee joint loads. The external moments are the moments created about the joint center from the ground reaction forces and inertial forces. The external moments are equal and opposite to the net internal moment, which is primarily generated by muscle forces, soft tissue forces and contact forces. In the absence of decreased antagonist muscle activity, larger contact forces are associated with larger external moments.

The external knee adduction moment is related to the distribution of forces between the medial and lateral compartments of the knee joint. It is defined as the torque that tends to adduct the knee during gait. Increased external knee adduction moments are indicative of increased loads on the medial compartment relative to the lateral compartment[7]. They have been associated with greater bone mineral content on the proximal medial aspect of the tibia relative to the lateral aspect in both normal subjects[19] and subjects with knee OA[20]. It has been reported that patients with varus gonarthrosis who were evaluated preoperatively prior to high tibial osteotomy had greater than normal external knee adduction moments[21]. Such increases in the knee adduction moment have been associated with poorer long-term post-surgical outcomes both clinically and radiographically[22]. The studies previously cited[15,16] implied, by studying ground reaction forces, that subjects with knee OA who were evaluated prior to total knee replacement walked with decreased knee joint loads. However, the study of patients preoperative for a high tibial osteotomy indicated that the medial compartment loads may have been increased as assessed by the external knee adduction moment[21]. We recently have shown in cross-sectional studies of subjects with knee OA that the external knee adduction moment was positively correlated with radiographic disease severity[23,24], but these studies did not examine any other knee joint angles or moments in comparison with a normal (control) population.

Therefore, most of the literature on gait in knee OA is based on patients destined for knee arthroplasty or high tibial osteotomy as part of their pre-operative evaluations[15–17,21,22]. It remains unclear whether the changes in knee joint loading observed in these pre-operative patients, who presumably had more symptomatically advanced knee OA, are related to the pathophysiology of disease progression or are merely secondary to the anatomic alterations of the diseased knee joint.

The more compelling question is whether subjects with symptomatically milder knee OA who have medial compartment cartilage damage walk with increased loads on that compartment relative to asymptomatic controls. If increased knee joint loading actually contributes to the development or progression of knee OA, understanding how gait differs from normal among these subjects may ultimately identify subjects more susceptible to progressive knee OA.

The first objective of this cross-sectional study is to test if subjects within a spectrum of medically managed knee OA walk with a greater than normal peak external knee adduction moment. The second objective is to test if alterations in the flexion/extension angles, such as a decreased midstance knee flexion angle, previously identified by others as load reducing mechanisms, or sagittal plane moments are present in this population and to examine whether these flexion/extension angles are significantly correlated with the peak external moments.

Method

KNEE OA SUBJECTS

Thirty-one subjects (18 females, 13 males) were retrospectively selected on the basis of definite medial joint space narrowing and no definite lateral joint space narrowing from a larger study population of 64 subjects who were tested in the gait laboratory and whose radiographs were still available at the time of writing this manuscript. These subjects had participated in a double-blind study at Rush-Presbyterian-St. Luke's Medical Center which investigated the effects of non-steroidal antiinflamatory drugs (NSAIDs) on knee joint loading during gait in patients with knee OA[25]. Subjects had been included in the double-blind study if they had knee pain, had a Kellgren and Lawrence (K–L) grade of 1, 2, 3 or 4[26], and were classified as functional class II or III by ARA criteria[27]. Exclusion criteria included anemia or any other hematological disorder, active liver disease, active peptic ulcer disease, gastrointestinal bleeding within the preceding 12 months, known or suspected allergy to antiinflammatory drugs, significant renal disease (creatinine level>2 mg/dl) or glucocorticoid therapy in any form within the preceding month. Subjects with a history of knee trauma, rheumatoid arthritis or knee surgery (excluding arthroscopy) were also excluded.

For the current study the gait data collected following a 2-week drug washout period were used. Subjects were asked not to take any pain relieving medications during the washout period. Prior to the washout period, subjects with knee OA reported using aspirin (five subjects), acetaminophen (one subject), NSAIDs (11 subjects), aspirin and NSAIDs (one subject), aspirin and acetaminophen (one subject), acetaminophen and NSAIDs (one subject) or NSAIDs and opiates (one subject). Nine subjects reported using no medication for their knee OA. A medication history was unavailable for one subject.

In order to focus the present study on subjects with medial OA, two additional radiographic criteria were imposed. Only subjects with definite signs of joint space narrowing in the medial compartment (grades 2 and 3) and no definite signs of joint space narrowing in the lateral compartment (grades 0 and 1) were included (see Radiographic Analysis). Thirty-four subjects met the medial joint space criterion, 60 subjects met the lateral joint space criterion and 31 subjects met both criteria. These 31 subjects constituted the study group for the present study. Joint space grading was used as a selection criterion since joint space grading has been found to be a reproducible measurement[28] and has been previously associated with knee OA[29]. It is expected that subjects with significant cartilage damage exclusively within the medial compartment will have a higher than normal adduction moment.

The mean age, height and mass of the subjects with OA in the present study were 65±9 years, 168±9 centimeters and 76±12 kg. Pain levels were assessed using the pain subsection of the Rush modified Hospital for Special Surgery functional knee evaluation[30]. All subjects had the pain questions read to them immediately before the gait test. The modified HSS pain subsection has a score of 50 for 'no [pain] or ignores [pain]'; 45 for 'slight [pain] going up or

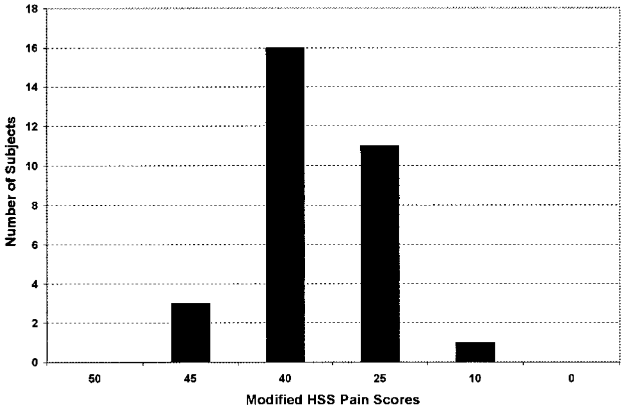

Fig. 1. Nineteen subjects reported no pain on the affected side while walking (pain scores of 40 and 45) and twelve subjects reported pain while walking (one pain score of 10 and 11 pain scores of 25).

down stairs or on long walks, no compromise on activities of daily living'; 40 for 'moderate pain when going up or down stairs or getting out of chair. No pain in level gait. Occasional pain medication'; 25 for 'pain in level gait with more on stairs, especially down, no rest pain, daily pain medication'; 10 for '[pain] at rest or night pain in addition to ambulatory pain. Pain medication taken regularly'; and 0 for 'continuous pain regardless of activity.' Two subjects reported bilateral pain (pain scores less than 40 on the right and left sides), 28 subjects reported unilateral pain (pain scores less than 40 on one side only) and one subject failed to report a contra lateral pain score for the contra lateral side. In the two subjects with bilateral pain, the affected side was defined as the side on which the subject reported the most pain. The affected side was the right side for 15 subjects and the left side for the remaining 16 subjects. Nineteen subjects therefore reported no pain on the affected side while walking (pain scores of 40 and 45) and 12 subjects reported pain while walking (one pain score of 10 and 11 pain scores of 25) (Fig. 1).

ASYMPTOMATIC CONTROL SUBJECTS (NORMAL SUBJECTS)

Thirty-one asymptomatic control subjects (18 females, 13 males) also underwent gait testing. No normal subject had a clinical diagnosis of knee OA or rheumatoid arthritis. No normal subject reported a history of knee trauma and no normal subject walked with pain. Asymptomatic normal subjects were selected to have a comparable age, height, weight and gender distribution as the subjects with OA. The mean age, height and mass of the normal subjects (62±9 years, 168±12 centimeters and 74±16 kg, respectively) were not significantly different from that of the subjects with knee OA (P=0.259, P=0.808 and P=0.584, respectively). The right side was analyzed for 15 of the normal subjects and the left side for the remaining 16 normal subjects.

INFORMED CONSENT

All subjects gave informed consent and the protocol was approved by the Institutional Review Board at Rush-Presbyterian-St Luke's Medical Center.

RADIOGRAPHIC ANALYSIS

Standard anterior–posterior weight bearing radiographs of the affected knee were obtained for all subjects with knee OA. All radiographs were read by a single trained rheumatologist and the K–L grade was determined for each subject using a standard atlas[26]. One subject had a K–L grade of 1, eight subjects a grade of 2, 17 subjects a grade of 3 and five subjects a grade of 4. Joint space narrowing in the medial and lateral compartment in each affected knee was qualitatively graded based on the atlas of Altman *et al*. [0 (no narrowing), 1 (mild narrowing), 2 (moderate narrowing) or 3 (severe narrowing)][27]. Twenty-four subjects with knee OA had a medial joint space narrowing score of 2 and seven subjects had a score of 3. Similarly, 24 subjects with knee OA had a lateral joint space narrowing score of zero and seven subjects had a score of 1. The average mechanical axis of the subjects with knee OA was 7°±4° (varus). The mechanical axis represents the angle formed between an axis from the center of the femoral head to the center of the knee and an axis from the center of the knee to the center of the ankle[31]. The mechanical axis was unavailable for one subject.

GAIT ANALYSIS

Reflective markers were affixed to the skin over the most superior portion of the iliac crest, the greater trochanter, the lateral joint line of the knee, the lateral malleolus and the base of the fifth metatarsal. Subjects were asked to walk at self-selected speeds of 'slow', 'normal' and 'fast.' Gait parameters were obtained using a method previously described that involves a multicomponent force plate (Bertec, Columbus, OH) and an optoelectronic camera system (Computerized Functional Testing Corporation, Chicago, IL)[32]. As the subject walked on the force plate, the camera system recorded the motion of each marker while the force plate recorded ground reaction forces. This analysis system has an average linear accuracy of 7 mm and an average angular accuracy of 1° relative to its calibration volume.

The locations of the hip, knee and ankle joint centers were calculated using the marker positions and the anatomic measurements of each subject. Inverse dynamics were used to calculate three-dimensional external moments and the inertial forces were included[32]. In this approach the positions, accelerations and ground reaction forces are known and the resulting external moments and intersegmental forces are determined from Newton's second law of motion. Newton's second law of motion establishes that the sum of the forces on a body equals mass times acceleration and that the sum of the moments equals the moment of inertia times the angular acceleration. The leg was modeled as three rigid segments and the inertial properties of each rigid segment were modeled as slender rods and then lumped at the center of mass of the segment. When calculating the external moments, the model assumes no axial rotation about the long axis of each segment. The calculations start at the foot as the only unknowns are the external intersegmental forces and moments at the ankle. Calculations then proceed to the knee and hip. The full details of these calculations are given in reference 32. All external moments were normalized to the subjects' body weight times height (%Bw×Ht).

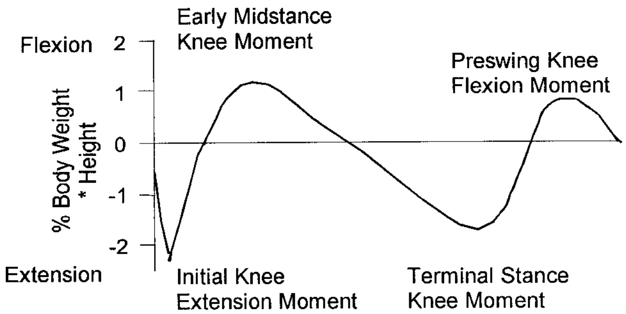

Fig. 2. A representation of the sagittal plane external moment throughout the stance phase of gait is shown above.

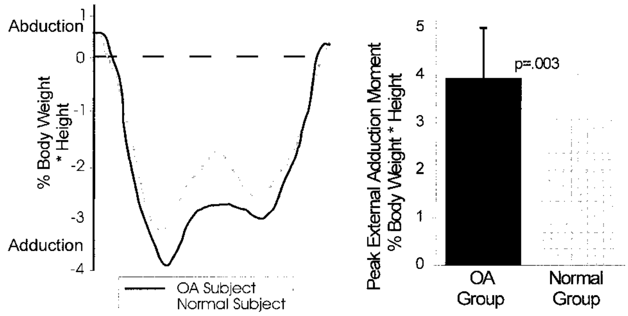

Fig. 3. On the left is a representation of the external adduction moment throughout the stance phase of gait for a subject with knee OA and a normal subject. The subjects with knee OA walked with a significantly greater than normal peak external knee adduction moment (P=0.003).

STATISTICAL ANALYSIS

Since the magnitude of the external moments are highly speed dependent[33], a representative trial was analyzed at about the same walking speed for each subject. The mean walking speeds of the analyzed trials for the subjects with knee OA and normal subjects were 0.98±0.07 m/s and 0.98±0.10 m/s, respectively (P=0.876). The primary analysis consisted of testing for a significant difference in the peak external knee adduction moment between the knee OA and normal groups using Student's t-tests. The secondary analysis consisted of testing for significant differences in the other gait parameters likely to be related to overall joint loading and function (minimum knee flexion, midstance knee flexion, knee flexion at terminal stance, knee range of motion, and the peak external flexion and extension moments). An example of the external flexion and extension moments examined is shown in Fig. 2. Pearson correlation coefficients were used to test for significant correlations between the knee angles and external moments. A significance level of α=0.025 was used throughout to account for multiple comparisons. Under these conditions, a sample size of 31 subjects and 31 controls provides 80% power for detecting a mean difference as small as 80% of the standard deviation. A sample size of 31 subjects provides 80% power for detecting a correlation coefficient as small as R=0.50.

Results

Among the subjects with knee OA and radiographic evidence of medial compartment cartilage damage, the peak external knee adduction moment was significantly greater than normal (P=0.003, Fig. 3). The peak external knee adduction moment was not significantly correlated with the sagittal plane knee angles (minimum knee angle, midstance knee angle and terminal extension knee angle) (P=0.072, P=0.772, P=0.894, respectively) or knee range of motion (P=0.098). Thus, alterations in the knee angles identified by others were not related to alterations in the external knee adduction moment.

None of the four peak external sagittal plane knee moments (initial knee extension moment, early midstance knee moment, terminal stance knee moment, preswing knee flexion moment) was significantly different between the OA and normal groups (P=0.217, P=0.153, P=0.036, P=0.297, respectively) (Table I). However, subjects with knee OA exhibited a tendency to walk with a decreased terminal stance moment (external extension moment) (P=0.036).

Some subjects with knee OA and some normal subjects did not walk with an external flexion moment during midstance but instead walked with an external extension moment. This type of gait pattern has previously been referred to as a 'quadriceps avoidance' gait[20]. Eight of the 31 OA subjects (26%) and three of the 31 normal subjects (10%) walked with a 'quadriceps avoidance gait'. However, the proportion of subjects who walked with a quadriceps avoidance gait was not significantly different between the knee OA and normal groups (P=0.099).

Table I
Differences in sagittal plane motion and external moments between the knee OA and normal groups

Variable	Knee OA group	Normal group	P-value
Sagittal plane motion (°)			
*Minimum knee angle	1±5	−2±4	0.008
Midstance knee angle	15±7	15±7	0.625
Terminal extension knee angle	7±6	4±6	0.405
Maximum knee flexion angle	59±7	62±6	0.166
*Range of motion	58±7	64±5	0.001
Sagittal plane external moments (%Bw×Ht)			
Initial knee extension moment	−2.3±0.6	−2.5±0.8	0.217
Early mistance knee moment	1.1±1.5	1.6±1.5	0.153
Terminal stance knee moment	−1.8±1.3	−2.4±0.8	0.036
Preswing knee flexion moment	0.9±0.5	0.8±0.3	0.297

*Indicates significant differences (P<0.025).

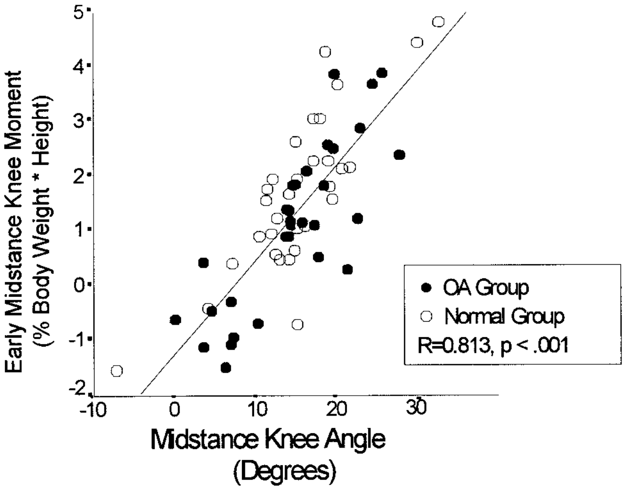

Fig. 4. The peak early midstance knee moment was significantly correlated with the peak midstance knee angle (R=0.813, P<0.001), indicating that the subjects who walked with a 'quadriceps avoidance gait' walked with a stiff knee.

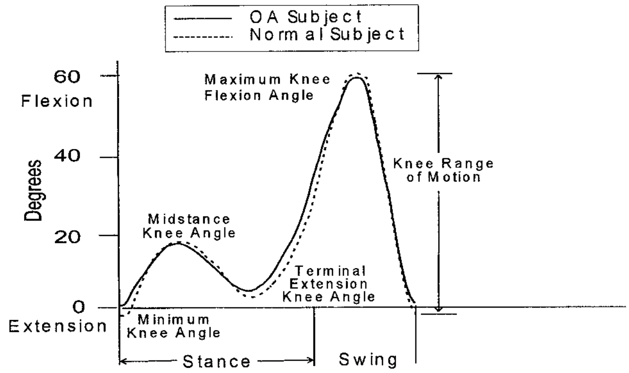

Fig. 5. A representation of sagittal plane motion for a subject with knee OA and a normal subject is shown above. Subjects with knee OA walked with a significantly less than normal minimum knee angle (P=0.008).

Consistent with the peak external flexion moment during midstance not being significantly different from normal, the midstance knee flexion angle was also not significantly different from normal (P=0.625). The peak midstance knee moment was significantly correlated with the peak midstance knee angle (R=0.813, P<0.001 for all subjects) (Fig. 4). Therefore the subjects walking with a 'quadriceps avoidance gait' were primarily subjects who walked with a stiff knee gait (i.e. decreased knee flexion during midstance).

Consistent with the peak terminal stance knee moment not being significantly different from normal, the terminal extension knee angle was also not significantly different from normal (P=0.096) (Table I). The peak terminal stance knee moment was significantly correlated with the terminal extension knee angle for all subjects (R=0.768, P<0.001).

The minimum knee angle of the knee OA group was significantly greater than normal (P=0.008). The knee range of motion (maximum flexion minus maximum extension) was significantly less than normal (P=0.001) (Table I, Fig. 5). The difference in knee range of motion was largely due to the difference in the minimum knee angle (P=0.008) and not the maximum knee angle (P=0.166). Moreover, even though the subjects with knee OA and normal subjects were walking at the same speed, the subjects with knee OA walked with a significantly decreased normalized stride length (stride length divided by height) (P=0.012) and a significantly increased cadence (P=0.008).

Discussion

The significantly higher than normal peak external knee adduction moment in the subjects with knee OA suggests that these subjects are walking with increased knee joint loads on the medial compartment. Previously, Prodromos *et al*. reported the finding of a higher than normal adduction moment in a population of knee OA patients who were pre-operative for high tibial osteotomy[21]. In that study, a high pre-operative knee adduction moment was associated with a poor post-surgical outcome. Whereas the Prodromos *et al*. study[21] examined the external knee adduction moment in pre-surgical patients with symptomatically advanced OA, the present study examines a broader range of subjects with radiographic evidence of OA who were being managed by 'conservative' medical therapy and hence presumably had less severe symptoms of OA. The finding of an increased knee adduction moment in the present study population of subjects with knee OA who are being managed by 'conservative' medical therapy further suggests that an increased adduction moment is intrinsically associated with the pathogenesis of knee OA.

The greater adduction moment in the subjects with knee OA contradicts the findings of Weidenhielm *et al*.[34] and a recently published study by Kaufman *et al*.[35] in which no significant difference in peak adduction moment was found between patients with moderate medial knee OA and normal subjects. The lack of a detected difference in these studies may have partially been due to the fact that the normal subjects walked significantly faster than the OA subjects[34,35]. Based on a review of gait studies on subjects with knee OA published to date, Messier concluded that it was difficult to discern the effect of OA on gait because of population differences between the OA groups and the normal control groups with respect to age, footwear, body mass and walking speed[36]. In the present study, the knee OA subjects and asymptomatic controls were comparable with respect to age, weight, height and walking speed. In addition, the selection criteria in the present study of at least moderate medial joint space narrowing and no greater than minimal lateral joint space narrowing may have resulted in a more homogeneous group of subjects with knee OA with medial compartment cartilage damage as compared to these other studies. This could increase the likelihood of detecting a greater external knee adduction moment. Differences in the extent and location of the radiographic degeneration as well as the severity of the pain and functional limitations may further account for these different findings between studies.

The decreased knee range of motion and decreased stride length in the present study were consistent with the findings of Messier *et al*.[18]. The lack of a decreased midstance knee angle in the knee OA group is not consistent with the findings of Stauffer *et al*.[16]. It is possible that the discrepancy between the decreased knee flexion angle found by Stauffer *et al*.[16] and the lack of significant differences in the midstance knee flexion angle found in the present study could be due to differences between the two OA populations with respect to quadriceps strength, pain, patellofemoral degenerative changes, effusion or passive knee flexion contractures.

Stauffer *et al*.[16] suggested that walking with a decreased midstance knee flexion angle would decrease the quadriceps force and thus the compressive forces across the knee joint. In the present study, the midstance knee angle and the peak midstance knee moment were significantly correlated. Thus, those subjects who walked with lower midstance knee flexion angles also walked with lower external knee flexion moments. However, the subjects with OA in the present study did not walk with this adaptation since both the midstance knee angle and the peak midstance knee moment were not significantly different from normal. Furthermore, a decreased midstance knee flexion angle is only related to a decreased compressive force if there is not a concomitant increase in co-contraction from the knee flexors. This is especially true for subjects who walked with an extremely stiff knee throughout stance and therefore have a 'quadriceps avoidance' gait. These subjects had an external extension moment rather than an external flexion moment for their peak midstance knee moment. The magnitude of this extension moment can be high and could potentially result in even greater joint compressive forces than those OA subjects with a more normal midstance knee angle. Kaufman *et al*.[35] reported a decreased peak internal knee extensor moment (external flexion moment) in a group of subjects with knee OA. The present study did not find decreased peak sagittal plane knee moments in our group of subjects with knee OA. As previously stated, these differences may be due to population differences in age, footwear, body mass, strength, extent and location of radiographic degeneration or walking speed as well as other variations in the selection criteria between these two studies.

As in the Prodromos *et al*. study[21] and several of the other OA studies[15–18,22,24,34,35], the comparison normal group was an asymptomatic population with no clinical diagnosis of OA. Limitations of the present study include the possibility that some of the asymptomatic normal subjects could have had undiagnosed knee OA, as knee radiographs were not obtained for the normal subjects. Nonetheless, it would be expected that the inclusion of normal subjects with undiagnosed radiographic knee OA would tend to minimize the difference in the knee adduction moment observed between the two groups. In addition, the subjects with knee OA were tested after a two-week washout period from analgesics or NSAIDS, thus their pain levels may have been greater than that which they usually experience. Increases in pain levels have been associated with decreased external knee adduction moments[25,27]. Therefore, it is likely that if these subjects with knee OA had been tested prior to the washout protocol, their adduction moments would have been even greater. For these two reasons, it is likely that this study represents a conservative estimate of the increase in the adduction moment in the subjects with knee OA.

In conclusion, the results of this study support the hypothesis that the peak external knee adduction moment is higher than normal in subjects with radiographic signs of knee OA with medial compartment cartilage damage who are being managed by 'conservative' medical therapy. This implies that higher medial compartment knee joint loads are present in this population. Due to the cross-sectional design of this study, it is possible that this finding could be secondary to a disease process of OA. Hence, only long-term longitudinal studies have the power to truly elucidate the role of dynamic loading in the progression of knee OA. If the adduction moment is found to be a significant risk factor for knee OA, it could be used as a diagnostic tool in order to establish, before the onset of irreversible degenerative changes, which people are at a high risk for developing knee OA. Ultimately, a greater understanding of the relationship between loading and the onset or progression of knee OA could lead to new treatments for knee OA. A variety of non-surgical interventions offer the potential for lowering the external knee adduction moment and pain in subjects with knee OA. Both stiff hinged braces that maintain the knee in valgus alignment and lateral heel wedges have been reported to provide pain relief[38–41] and a reduction in the adduction moment[42–45].

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