The effect of internal and external foot rotation on the adduction moment and lateral–medial shear force at the knee during gait

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Summary It has been hypothesised that those with medial compartment knee osteoarthritis tend to externally rotate their foot during gait in order to unload the diseased compartment. This has been found to decrease the adduction moment at the knee during late stance, although the effects of foot rotation on shear forces at the knee have not yet been determined. Also, the effects of internal foot rotation on the knee during gait are not clear. This study performed a gait analysis on 11 healthy participants (M: 6; mean age 22.9 ± 1.8 years) in three conditions: (1) natural foot rotation position; (2) internal foot rotation and (3) external foot rotation. Three-dimensional gait analysis calculated the knee adduction moment and lateral–medial shear force magnitude during late stance, while external rotation of the foot decreased the magnitude of both these measures. This implies that walking with an externally and internally rotated foot may unload the diseased compartment for those with medial and lateral compartment knee OA, respectively. Also, the relationship of foot rotation angle to the adduction moment and lateral–medial shear force was strengthened when data were corrected for the subject’s normal walking condition. Knee OA subject data revealed that they were able to reduce the knee adduction moment more than normal subjects during late stance, indicating that other factors besides the rotation of the foot need to be investigated.

Introduction

Recently, there has been great interest in the mechanical factors that contribute to the development and progression of knee OA. Since OA involves the degeneration of cartilage, it is believed that the interaction between functional, anatomical and biological factors should be considered when attempting to determine OA's rate of progression. However, it is generally accepted that abnormal loading of the articular cartilage over time contributes to cartilage wear and eventually to knee OA. This suggests that the knee’s loading envi-
Effects of internal and external foot rotation on adduction moment during walking. Two measures of cartilage loading that have been implicated are the knee’s adduction moment and lateral—medial shear force created during walking.

In general terms, the knee’s adduction moment is due to the ground reaction force vector acting medially to the knee’s axis of rotation in the frontal plane, causing an external moment that would tend to rotate the tibia medially relative to the femur. Mechanically, a large adduction moment increases the load on the knee’s medial compartment and is a risk factor for medial knee OA if the resulting compressive force is abnormally high. This is supported by studies that show that the magnitude of the adduction moment determines the load distribution between the medial and lateral compartments of the knee joint and that its magnitude predicts the progression of OA. Additionally, people with medial compartment knee OA have a higher knee adduction moment than normal controls.

It is possible that, since an abnormally high adduction moment is a risk factor for medial OA, perhaps an abnormally low adduction moment is a risk factor for lateral OA. Historically, few studies have examined lateral knee OA as it was assumed to be a relatively rare condition. However, a more recent study has reported that lateral OA is more common in certain populations than originally thought. Two recent studies have demonstrated the relationship between lateral OA and a reduced adduction moment. In both a cross-sectional study of preoperative medial (n = 15) and lateral (n = 15) OA and in a longitudinal case study that tracked the gait patterns of previously healthy, asymptomatic older adults over a 5—11-year follow-up period, lateral OA subjects had significantly smaller adduction moments compared to normal controls.

Along with the adduction moment, shear loads at the knee might also need to be considered. Several studies have examined the effects of shear stress on animal and cadaver cartilage in vitro and have determined that shear forces are detrimental to cartilage health. The mechanism for the detrimental effect is not clear. Some researchers have implicated biochemical pathways, while others have implicated mechanical factors. It has also been suggested that the shear forces experienced by the knee during gait may be important in helping explain cartilage loss and the development of OA. Also, a study using principal components analysis and discriminant analysis of nine gait curves (three-dimensional forces, moments and angles) and eight discrete measures was successfully able to discriminate between an osteoarthritic and a normal population. The lateral—medial shear force was the variable explaining most of the variation in the first discriminatory feature and was also a factor in the second most discriminatory feature. In comparison, the adduction moment contributed less than the LM force to the percent variation explained for the first most discriminatory feature, and was not identified as a major contributing factor to the second most discriminatory feature. Therefore, shear forces appear to be an important factor in the progression of knee OA.

Those with symptomatic medial OA often try to unload the diseased medial compartment by walking with an externally rotated foot. This foot rotation decreases the adduction moment during late stance when the whole foot is in contact with the ground and is thought to be an effective compensation strategy for those with medial compartment knee OA. Conversely, it may be speculated that walking with an internally rotated foot might be an effective strategy to unload the lateral compartment in lateral knee OA, although this has never been investigated. One study that examined the gait patterns of children aged 11—13 years attempted to test the knee kinetics with an intentional toe-in and toe-out gait and compare that to their normal gait patterns. They reported that the toe-in gait pattern increased the adduction moment, but there were no differences between the toe-out condition and the normal foot position condition; yet this study did not perform separate analyses of early- and late-stance values. Also, Lin et al. did not find a difference between the toe-out condition and normal foot position condition, which contradicts the current literature. This may be due to the fact that they did not perform separate analyses of both early- and late-stance curve parameters.

Although the effect of foot rotation on the knee’s adduction moment has been investigated, to our knowledge, the effect of foot rotation on the shear forces has never been previously examined. Therefore, this study will examine the effect of both internal and external foot rotation on the knee adduction moment (KAM) as well as on the lateral—medial force (LMF) created during level walking.

**Methods**

**Subjects**

The participants were 11 (M: 6) healthy university students with no previous history of lower
limb trauma or surgery. The university’s Research Ethics Board approved the study and the participants provided informed consent. The average age of participants was 22.9 years (1.8) with an average height of 176.7 cm (11.5) and an average weight of 72.4 kg (14.4).

Gait analysis

Data were collected with a modified version of a three-dimensional gait analysis system that has previously been described and validated. This system uses an optoelectronic motion tracking system (NDI, Waterloo, Ontario, Canada), an embedded force plate (AMTI, Newton, Mass, USA) and subject-specific anthropometrics to calculate 3D net forces and moments at the knee. The only difference between the system described in the literature and the one used in the current study is that it requires X-rays to locate internal bony landmarks, while in this study simple anthropometric values were used to estimate these locations.

Eight light-emitting diodes (LEDs) were required to collect the kinematics of the test leg. Subjects walked barefoot with markers placed on their skin at the greater trochanter, the later femoral epicondyle, the head of the fibula, the lateral malleolus, the heel and the head of the 5th metatarsal. Additional markers were also applied to forward projecting probes attached at the mid-thigh and the shank segment (upper tibia below the tubercle). Motion and force data were collected synchronously at 100 Hz.

A standard link segment model that considered the foot to be part of the shank was used to calculate the net forces and moments at the knee. The forces and moments were defined using the right hand rule in the tibia local coordinate system: the distal–proximal (DP) axis was parallel to the tibia’s long axis with an orthogonal axis running from the lateral to medial (LM) and another running from the posterior to anterior (PA). All forces were positive along the axis while moments were positive using a right hand rotation about the axis. Therefore, a positive moment in the frontal place would tend to move the tibia medially with respect to the femur (an adduction moment). The computed force and moments were the external net forces and net moments, not their internal counterparts.

Three separate walking conditions were defined: normal foot rotation (NFR), maximum comfortable internal foot rotation (INT) and maximum comfortable external foot rotation (EXT). Each subject performed five trials in each condition for a total of 15 trials. All 15 trials were presented in random order. To ensure consistent foot rotation angles across similar trials, each subject’s foot rotation was measured as he/she walked using his/her natural foot rotation position and then approximately 30° was added to and subtracted from this angle to establish the EXT and INT conditions. This angle is similar to values used in previous work on healthy subjects although if subjects were unable to walk normally at this angle, they were asked to walk with the maximum amount of comfortable foot rotation. As the foot rotates, the width of the foot as seen from the front changes. To ensure that the subjects could reproduce the degree of internal and external foot rotation they achieved during practice trials, parallel lines of tape were placed onto the floor such that when walking the subject’s foot would have to fill the gap between the tape lines. The subjects were instructed to walk at their naturally chosen cadence with their test foot inside the tape lines but filling the gap for the desired condition. Subjects were given several practice trials at the internal and external rotation conditions before data were collected. They were also required to take several steps to reach a constant velocity before stepping on the force plate.

Once the foot angles, as well as the LMF and KAM, were calculated for each trial, they were normalised by body weight and time normalised to 100% of the gait cycle. The five individual trials for each condition were averaged to produce a single representative trial for each subject at each foot rotation position. Early- and late-stance curve peaks were evident during the INT and NFR conditions for all subjects and these were used as outcome measures; however, these peaks were difficult to identify for 9 of the 11 KAM curves during late stance of the EXT condition. Therefore, the magnitude of the KAM at the same time as the late-stance ground reaction force peak was used for these nine EXT condition curves, as was done in previous work where this peak was not evident. Therefore, the resulting variables were early- and late-stance knee adduction moment (KAM_E and KAM_L) and lateral–medial shear force (LMF_E and LMF_L) values, as well as foot rotation angles for each subject in each of the three foot rotation conditions.

Standard time and distance gait parameters were also calculated for each trial to check if differences seen in the adduction moment or shear force could be attributed to changes in gait speed.

Statistical analysis

Key outcome measures were the early- and late-stance knee adduction moment and lateral–medial shear force (KAM_E, KAM_L, LMF_E, LMF_L). Main effects
and simple contrasts were tested across the three conditions using a repeated measures ANOVA with a Bonferroni correction based on the 12 knee gait kinetic comparisons that were made (three foot positions by four variables).

Similar repeated measures ANOVAs were used to test the main effect and simple contrasts between conditions for the average walking speed and foot rotation angle. For these tests, the critical $p$-value was adjusted using a Bonferroni correction based on the three comparisons (three foot positions) for each variable. These tests were performed to ensure that there were no differences in gait speeds across the three conditions, as this would affect the measured knee gait kinetics, and to ensure that the foot position angles between conditions were statistically different.

Regression analysis then determined the relationship between foot rotation and the adduction moment and shear force parameters. This was done in two ways. First, using the foot rotation and kinetic data as they were calculated. Second, for each subject, the foot rotation and kinetic measures during the NFR walk were subtracted from the values obtained during the INT and EXT walks. The change score for the kinetic measures (relative KAM and LMF) were regressed against the change score for the foot rotation (relative foot rotation angle). In the analysis of data relative to neutral, the neutral position data were set to zero and so they were not included.

Data collected previously on medial knee OA patients were used to determine if the relationship between foot rotation and the adduction moment found in our normal population was similar in this patient group. This was done using the regression equations calculated for relative foot position and the adduction moment in both early and late stance. The foot position change score was obtained by subtracting the reported foot position during the external rotation condition from the reported foot position in the normal rotation condition. The change score was then entered into the regression equation to estimate the magnitude of the adduction moment reduction. The predicted reduction was compared to the reported reduction.

Results

Repeated measures ANOVA on the KAM$_E$ and LMF$_E$ variables revealed a main effect for foot rotation and significance on all three individual contrasts; therefore all foot positions were significantly different. Thus, external rotation of the foot significantly decreased the magnitude of the KAM and LMF curves during late stance while internally rotating the foot increased their magnitude (Fig. 1 and Table 1). There was no significant main effect for the KAM$_E$ or LMF$_E$.

The uncorrected KAM$_E$ and LMF$_E$ revealed significant correlations with foot rotation while the early-stance values were not significantly correlated. Although these correlations were significant, the $R^2$-values for all four of these comparisons were relatively low, ranging from 0.093 to 0.498 (Fig. 2). Once the data were corrected by subtracting the NFR values, all correlations increased and were significant with the late-stance KAM and LMF displaying the strongest relationship with $R^2$-values of 0.973 and 0.864, respectively (Fig. 3). In addition, the regression results showed that foot rotation produced greater changes in late-stance KAM and LMF as compared to their early-stance counterparts.

Substituting the results of Guo et al. into the regression equations reported here showed that the relationship between the change in foot rotation and the change in the adduction moment was the same for our normal population and Guo et al.’s knee OA population during early stance (Table 2). However, during late stance, the knee OA population produced a greater decrease in the adduction moment than was predicted using the normal population equation (Table 2).

Finally, the ANOVA performed on the average velocities did not result in a significant main effect. Also, the ANOVA performed on the foot progression angle revealed a significant main effect and all simple contrasts were also significant (Table 1).

Discussion

The results demonstrate the previously described relationship between foot rotation and the adduction moment during the late-stance phase of gait and they also extend the relationship to include the internal rotation of the foot. They demonstrate that, as the foot is rotated externally, the adduction moment decreases and, when the foot is rotated internally, the adduction moment increases during late stance. The adduction moment is a good predictor of the ratio of medial-to-lateral bone mineral content, suggesting that a high adduction moment increases the load on the medial compartment while a low adduction moment increases the load on the lateral compartment of the knee. Accordingly, it has been reported that those with medial knee OA walk with their foot more externally rotated to decrease the
Figure 1 Average adduction moment and lateral–medial shear force gait curves \((n = 11)\) for all three foot rotation conditions. Note: (*) significant main effect for foot rotation at \(p < 0.01\).

Table 1 All outcome variables presented for all three foot rotation conditions

<table>
<thead>
<tr>
<th>Foot position</th>
<th>Velocity ((\text{m/s}))</th>
<th>Foot rotation angle* ((\text{deg}))</th>
<th>Adduction moment ((\text{Nm/kg}))</th>
<th>Lateral–medial force ((\text{N/kg}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Early stance</td>
<td>Late stance</td>
<td>Early stance</td>
<td>Late stance</td>
</tr>
<tr>
<td>Normal</td>
<td>1.10 (0.12)</td>
<td>18.52 (8.15)</td>
<td>0.31 (0.16)</td>
<td>0.25 (0.16)</td>
</tr>
<tr>
<td>Internal</td>
<td>1.08 (0.16)</td>
<td>−9.10 (7.91)</td>
<td>0.28 (0.16)</td>
<td>0.41 (0.14)</td>
</tr>
<tr>
<td>External</td>
<td>1.12 (0.15)</td>
<td>40.24 (8.74)</td>
<td>0.35 (0.18)</td>
<td>0.02 (0.16)</td>
</tr>
</tbody>
</table>

Different letters represent significant contrasts at \(p < 0.01\) with appropriate Bonferroni corrections. * Significant main effect at \(p < 0.01\) with appropriate Bonferroni corrections.

These results support such a mechanism and suggest that perhaps those with lateral compartment disease may want to internally rotate their foot to decrease the load on the lateral compartment. The results from recent longitudinal\(^4\) and cross-sectional\(^8\) studies suggest that a high adduction moment is associated with medial OA while a low adduction moment is associated with lateral OA. Therefore, using the appropriate foot rotation during gait to normalise this moment and shift the load on to the non-diseased compartment may slow disease progression.

This study quantified the magnitude of change in the adduction moment associated with a change in foot progression angle. It should be noted that this relationship is stronger when both the foot rotation and adduction moment measurement are relative to the subject’s ‘normal’ gait. Therefore, the magnitude of change in the adduction moment is

Table 2 Results of the attempt to predict corrected adduction moment peaks from data collected on knee OA subjects with regression equations calculated on a normal population

<table>
<thead>
<tr>
<th>Corrected foot rotation angle ((\text{deg}))</th>
<th>Corrected adduction moment ((\text{Nm/kg}))</th>
<th>Predicted adduction moment ((\text{Nm/kg}))</th>
<th>Difference (times standard error of regression)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Early stance</td>
<td>16.6</td>
<td>0.02</td>
<td>0.031</td>
</tr>
<tr>
<td>Late stance</td>
<td>16.6</td>
<td>−0.53</td>
<td>−0.19</td>
</tr>
</tbody>
</table>

Corrected values are calculated by subtracting the external rotation condition from the normal rotation condition. Predicted adduction moment values are calculated using regression equations presented in Fig. 1.
Figure 2 Relationship between foot rotation angle and the two gait outcome measures (adduction moment and lateral—medial shear force) during early- and late-stance using uncorrected data. Note: (*) significant correlation at $p < 0.01$. Negative foot rotation angle = internal rotation; positive foot rotation angle = external rotation.

Dependent on the magnitude of change in foot position from normal and not the absolute foot position. There were no differences in early-stance adduction moment values across the three foot rotation conditions. This agrees with previous research suggesting that the early peak adduction moment is best predicted by static joint alignment and not foot position.\(^{17}\)

Also, since gait speed alters the magnitude of the adduction moment,\(^{24}\) it is important to note

Figure 3 Relationship between foot rotation angle and the two gait outcome measures (adduction moment and lateral—medial shear force) during early- and late-stance using corrected data. Note: (*) significant correlation at $p < 0.01$. Negative foot rotation angle = internal rotation; positive foot rotation angle = external rotation.
that there were no differences in gait velocities between the three foot rotation conditions and therefore speed can be discounted as a factor in the observed changes in knee kinetics.

Although the literature has mostly concentrated on the adduction moment when examining gait variables that may affect the initiation and progression of knee OA, recent work has suggested that perhaps the shear forces experienced during gait should be considered as well.\textsuperscript{4,5} The current results show a similar relationship between foot angle and the late-stance lateral—medial shear force as that for the adduction moment. Correlation analysis demonstrated a strong relationship between the change scores for foot position and the magnitude of lateral—medial shear force. Since shear forces have been shown to be detrimental to cartilage health in vitro,\textsuperscript{9—12} the relationship among the adduction moment, foot rotation and shear force needs to be examined further. As we have limited options to produce appropriate muscle activity to counteract external adduction moments in the frontal plane, a large or small adduction moment may create a varus or valgus rotation at the knee, respectively. Such a rotation would alter the angle of the tibial plateau relative to the vertical load vector creating knee malalignment and, as a result, some portion of the vertical load would be transmitted as an increased shear stress. This may explain the results of Sharma et al.\textsuperscript{25} as they found that subjects with increased quadriceps strength at baseline were at an increased risk for OA progression only when their knees were malaligned. Therefore, the increased quadriceps strength combined with an abnormal alignment would mean that the cartilage is exposed to increased shear stress. This shear stress would be laterally directed for a large (varus) moment and medially directed for a small (valgus) moment. Therefore, foot rotation during gait may reduce the shear stress by altering the external moment and maintaining the angle of the tibial plateau so that the cartilage experiences compression rather than shear.

The relationships calculated on this normal population were also tested on data from the literature collected on a knee OA population.\textsuperscript{18} The results show that during the early-stance phase of the gait cycle the relationship between the adduction moment and foot rotation angle is the same for the normal and OA populations. This is not surprising as foot rotation is not one of the mechanical factors that effects the early-stance adduction moment peak.\textsuperscript{17} However, during the late-stance phase, the knee OA group was able to decrease the adduction moment much more than was predicted by the equations developed on control population. This suggests that, although foot rotation plays a role in decreasing the late-stance knee adduction moment peak, in the patient population there are additional factors that need to be investigated. One possible explanation for this difference could be that the subjects in Guo et al.’s study\textsuperscript{18} were walking faster than the subjects in the current work. Perhaps the relationship between gait speed and foot rotation needs to be further examined. Also, the patterns of muscular activity during gait are different between those with knee OA and healthy subjects\textsuperscript{26} and, while muscle activity was not measured in either this current work or that of Guo et al.,\textsuperscript{18} muscle activity may provide further insight into the effects of foot rotation on the loading environment of the knee.

With the reported relationship between foot rotation and the medial—lateral shear force, it is apparent that more work examining the role of shear forces in the breaking down of cartilage both in vivo and in vitro is needed to understand its effect on cartilage health. This may help to identify specific interventions that can minimise shear forces, thereby allowing cartilage to remain healthy longer. Patients with medial compartment knee OA attempt to increase the activity of the lateral lower limb musculature to counteract the high external medial joint loads such as the adduction moment.\textsuperscript{26} Therefore, future studies examining the neuromuscular changes associated with foot rotation during gait are warranted. It may be that foot rotation alters muscular activation, thereby changing the knee’s loading environment and protecting the cartilage.

**Practical implications**

- External rotation of the foot during gait shifts the load off the medial knee compartment, while internal rotation of the foot during gait shifts the load off the lateral knee compartment.
- Interventions aimed at normalising the adduction moment and medial—lateral shear forces across the knee during gait may help reduce pain and delay the onset and progression of knee OA.
- Knee OA patients are able to reduce the adduction moment at the knee much more than normal subjects during late stance, indicating that other factors besides the foot rotation need to be considered in this population.
References


