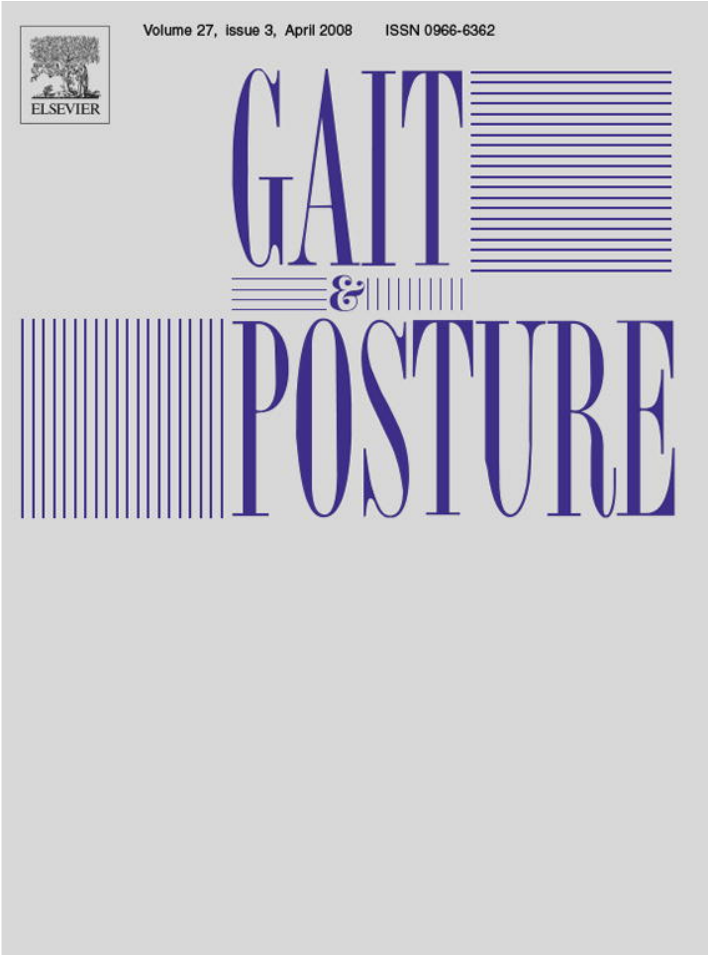
Volume 27, issue 3, April 2008 ISSN 0966-6362
ELSEVIER
GAIT & POSTURE

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Gait & Posture 27 (2008) 485–492
GAIT & POSTURE
www.elsevier.com/locate/gaitpost

Detecting differences between asymptomatic and osteoarthritic gait is influenced by changing the knee adduction moment model

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Received 4 October 2006; received in revised form 27 February 2007; accepted 11 June 2007

Abstract

Introduction: The adduction moment measured at the knee during gait is important to the study of osteoarthritis. The purpose of this study was to explore the effect of describing the knee adduction moment using three different biomechanical models, and furthermore, how the choice of model affects differences that are identified between asymptomatic and osteoarthritic gait.
Methods: Gait was measured for 44 asymptomatic subjects and 44 subjects with moderate osteoarthritis. The adduction moment was calculated and compared using three common biomechanical models: a 2D coordinate system, a 3D tibial coordinate system, and a 3D floating axis coordinate system. Several portions of the gait cycle waveform were compared between the two groups.
Results and discussion: It was found that the choice of biomechanical model changes the overall magnitude and shape of the adduction moment waveform (maximum value changed 8–14% and peak value changed 5–17%). Significant differences between the study groups were found for each model applied; but more importantly, the portions of the gait cycle exhibiting the differences depended on the model.
Conclusion: These findings support the importance of specifying the knee model and waveform feature used to compare asymptomatic and osteoarthritic groups. The overall magnitude of the adduction moment throughout stance, and the mid-stance adduction moment value were found to differentiate between the two groups regardless of the adduction moment model.

Keywords: Adduction moment; Knee osteoarthritis; Biomechanical model; Waveform features; Gait analysis

1. Introduction

The knee adduction moment has been associated with the progression and severity of osteoarthritis (OA). It has been shown that OA subjects have a significantly higher peak external knee adduction moment than asymptomatic control subjects [1–4]. There is also evidence that disease presence [5] and severity [6] is associated with the maximum knee adduction moment. Furthermore, successful surgical outcome (proximal tibial osteotomy) has been associated with a lower adduction moment [7,8]. There have been several proposed noninvasive interventions specifically designed to lower the adduction moment at the knee, such as toe-out gait [7,8] and knee braces [9–11].

While the adduction moment can be linked to the presence and severity of knee OA, there are two significant concerns with the literature characterizing the adduction moment at the knee. The first is the lack of a standard biomechanical model used to express this moment. The second is a discrepancy in the portion of the gait cycle that group differences have been reported. Table 1 is a sample of studies that have reported the adduction moment, with a summary of the biomechanical model and waveform feature analyzed in each study. From examining Table 1 it is evident that there is variety in both the biomechanical model and the waveform parameter used in the literature to describe the adduction moment.

The axis about which the adduction moment is calculated has not been standardized in the literature. Three common biomechanical models (joint coordinate systems) have been

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doi:10.1016/j.gaitpost.2007.06.004

Table 1
Studies that have reported the knee adduction moment

Study	Groups evaluated	Model used	Waveform feature
Sharma et al. [5]	OA	2D axis	Maximum
Hurwitz et al. [2]	OA & Asym	2D axis	First & second peak
Mundermann et al. [6]	OA & Asym	2D axis	Maximum
Kaufman et al. [15]	OA & Asym	3D tibial axis	Maximum
Gok et al. [3]	OA & Asym	3D tibial axis	Maximum
Baliunas et al. [1]	OA & Asym	2D axis	Maximum
Andrews et al. [12]	Asym (toe-out)	2D axis	Maximum, late & early stance
Self et al. [9]	Asym (brace)	3D tibial axis	15%, 20%, 25%, 30% stance
Landry et al. [14]	OA & Asym	3D floating axis	Principal component analysis
Weidenhielm et al. [4]	OA & Asym	2D axis	Maximum & mid-stance
Prodromos et al. [7]	OA & Asym (surgical outcome)	2D axis	Maximum
Wang et al. [8]	OA & Asym (surgical outcome)	2D axis	Maximum
Hunt et al. [17]	OA	3D tibial axis	Maximum & mid-stance
McLean et al. [13]	ACL injuries	3D floating axis	Maximum

Column 1: the study; column 2: the subject group being evaluated; column 3: which model was used to calculate the adduction moment; column 4: which adduction moment waveform feature was analysed.
Note: OA = osteoarthritic group (no specific severity); Asym = asymptomatic group.

used to calculate the external adduction moment at the knee (Fig. 1). The first model is a 2D coordinate system model [1,2,5–8,12] in which the adduction moment axis does not follow the internal/external rotation of the lower limb. The second model is a 3D floating axis coordinate system model [13,14] in which the adduction moment axis only follows the internal/external rotation of the femur. The last model is a 3D tibial based coordinate system model [3,15–17] in which the adduction moment axis only follows the internal/external rotation of the tibia. Manal et al. [18] provided evidence that changing the transverse orientation of this 3D tibial based coordinate system model changes the overall magnitude and shape of the adduction moment in a healthy population.

Although in many studies an association between osteoarthritis and peak knee adduction moment has been demonstrated, there has been an inconsistency in which part of the gait cycle differences have been identified (Table 1). A representative adduction moment waveform is presented in Fig. 2, along with amplitude features that have been commonly examined. These features include the first peak

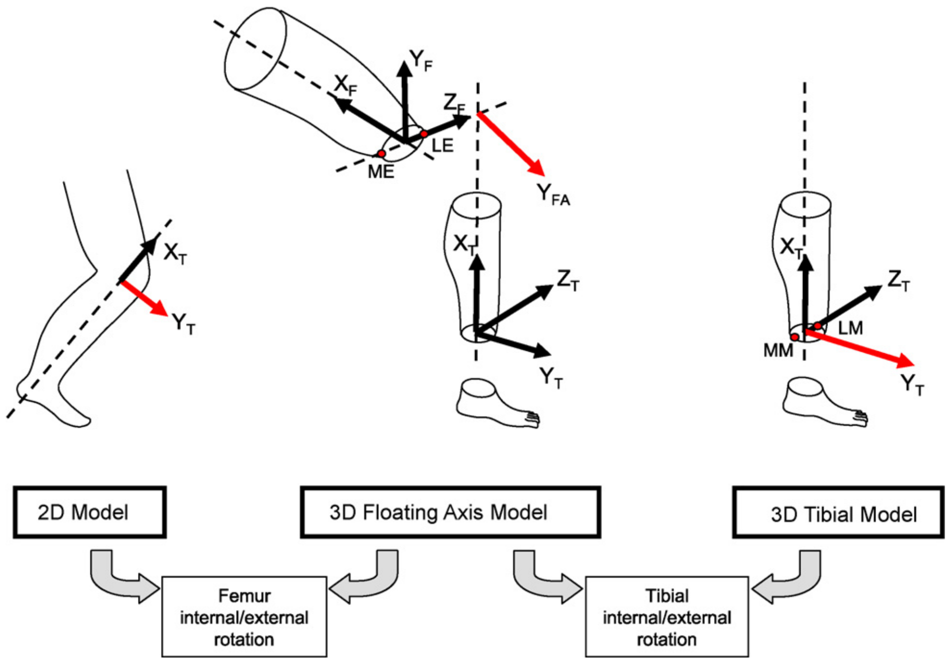

Fig. 1. Differences between the three adduction moment models. 2D: coordinate system is based in the tibia with the adduction axis (Y_T) aligned with the direction the subject is walking. X_T is the long axis of the tibia and is perpendicular to Y_T. Floating axis [25]: coordinate system is defined in both the tibia and femur. Z_F is an axis that passes through the medial epicondyle (ME) and lateral epicondyle (LE) and X_T is the long axis of the tibia. Y_{FA} is the adduction axis (common perpendicular of Z_F and X_T). Tibial axis: coordinate system defined in the tibia. Z_T is the axis that passes through the medial malleolus (MM) and the lateral malleolus (LM) and X_T is long axis of the tibia. Y_T is the adduction axis (common perpendicular of Z_T and X_T).

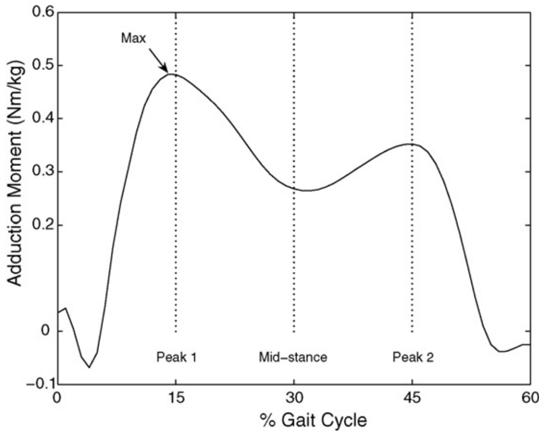

Fig. 2. Representative knee adduction moment waveform. Peak 1 occurs at 15% gait cycle, mid-stance occurs at 30% gait cycle and peak 2 occurs at 45% gait cycle. Max is the maximum value over the whole adduction moment waveform. (*Note*: in the figure the max value coincides with peak 1, but this is not always the case.)

(peak 1), the second peak (peak 2), the mid-stance trough (mid-stance) and the overall maximum value (max). Asymptomatic and osteoarthritic subject groups have been compared using the maximum adduction moment value [1,3–6,15], peak values [2] and the mid-stance value [4]. Reporting group differences in terms of discrete measures is complicated by the fact that interventions have been found to reduce the adduction moment at certain portions of the gait cycle. Toe-out gait has been shown to lower the knee adduction moment in late stance [12], whereas a medial unloading knee brace has been shown to reduce the adduction moment during early stance [9].

Discrete features, although commonly reported in the literature, are difficult to identify in many subject waveforms and cause group comparisons to be problematic and rather subjective. An alternative to describing waveforms with discrete measures, principal component analysis (PCA) has been shown to be an effective technique for capturing differences in the shape (both amplitude and temporal characteristics) of gait waveforms [19,20]. Landry et al. [14] demonstrated that differences in the adduction moment between moderate osteoarthritic and control subjects can be captured with principal component analysis. Their study demonstrated the importance of both the magnitude and shape of the adduction moment waveform in describing osteoarthritic gait.

To our knowledge no study has tried to determine the effects of different knee coordinate systems in both an asymptomatic and moderate osteoarthritic group. Moreover, no study has examined how changing the knee joint coordinate system can influence adduction moment differences between these two groups. It was hypothesized that: (i) changing the biomechanical model of the knee alters the magnitude and shape of the adduction moment waveform for both asymptomatic and osteoarthritic subjects; (ii) changing the model affects the interpretation of differences between the groups.

2. Methods

2.1. Subjects

The subject groups consisted of 44 asymptomatic and 44 osteoarthritic subjects. Subjects from both groups were 35 years of age or older. The asymptomatic subjects had no history of knee pain and were recruited through postings on the Dalhousie University campus. Subjects with moderate osteoarthritis were recruited from the Orthopaedic and Sports Medicine Clinic of Nova Scotia. All moderate OA subjects were diagnosed clinically and radiographically. Subjects were excluded from the study if they had other forms of arthritis, gout, neuromuscular disorders, trauma or major surgery to the lower limb, or a history of stroke or cardiovascular disease.

2.2. Gait

Gait data were collected for five walking trials for each subject. Each subject was instructed to walk in a straight line at a self-selected speed. The three-dimensional orientation of the lower limb of interest was tracked using the Optotrak 3D motion analysis system operating at 100 Hz (Northern Digital Inc., Waterloo, ON). The markers were placed over the greater trochanter, lateral epicondyle, and lateral malleolus along with a cluster of three markers on each of the foot, shank and femur. Virtual points were digitized to identify bony land-marks, including: medial epicondyle, fibular head, tibial tuberosity, medial malleolus, second metatarsal head and calcaneus [21]. Ground reaction forces and moments (collected at 1000 Hz) were recorded from an AMTI force platform (Advanced Mechanical Technology Inc., Watertown, MA).

2.3. Kinetics

The adduction moment at the knee was calculated using the kinematic and kinetic data gathered during the walking trials. Ground reaction forces and moments, along with segment weights and inertial properties were used to calculate the resultant external joint moment at the knee [22] using custom software written in Matlab^{TM}.

Moments were amplitude normalized to body mass (Nm/kg), as is commonly reported [3,14,19,23,24]. In addition the moments were reported for the stance phase only and were time normalized from heel strike to toe-off (0–60% gait cycle). The external knee joint moment was initially calculated in the 3D global coordinate system of the lab. To describe the adduction moment in an anatomically relevant frame of reference, the moment was described in three different coordinate systems in the lower limb. These coordinate systems correspond to the three models regularly used in the literature. The three models that were used to calculate the adduction moment included a 2D model and two 3D model (a floating axis model and a tibial axis model) representations (Fig. 1).

2.4. Modeling

The 2D coordinate system model is based on a planar representation of the lower limb [7]. The adduction moment was calculated in the frontal plane of the leg about an axis (Y_T) that is parallel to the sagittal plane of the subject.

The floating axis model is established by a coordinate system that is described in both the tibia and femur [25]. The floating axis (Y_{FA}) is created by taking the common perpendicular of the axis through the epicondyles of the femur (Z_F) and the long axis of the tibia (X_T).

The tibial axis model is based on a coordinate system described in the tibia [16]. By taking the common perpendicular of the axis through the malleoli (Z_T) and the long axis of the tibia (X_T), an adduction axis (Y_T) is created.

2.5. Waveform features

There were several features examined in the adduction moment waveforms, corresponding to features reported in the literature (Fig. 2). Since many subjects did not have a typical waveform shape, it was assumed that individual peaks occurred at the location where the ensemble averaged curves had peaks: peak 1 (15% of the total gait cycle), peak 2 (45% of the total gait cycle) and mid-stance (30% of the total gait cycle). The max value was the maximum adduction moment value in the waveform, regardless of its location in the gait cycle.

2.6. PCA

Principal component analysis was applied to the ensemble averaged adduction moment waveforms for each of the three models for all subjects [20]. PCA linearly transforms the original variables into new, mutually, orthogonal representations of those variables. A principal component score is associated with each subject based on the projection of that subject's data onto a particular loading vector. This data reduction technique was used to extract features of the waveforms corresponding to shape and magnitude.

2.7. Statistics

Minitab^{TM} was used to apply a two-way ANOVA to the discrete waveform features and PCA scores with group (between-subjects: OA, asymptomatic) and adduction model (within-subjects: 2D, 3D tibial axis, 3D floating axis) as factors and subject as a random variable. The ANOVA tested for group and model main effects as well as group–model interactions ($\alpha = 0.5$). Post-hoc Tukey tests were used to test all pair-wise comparisons.

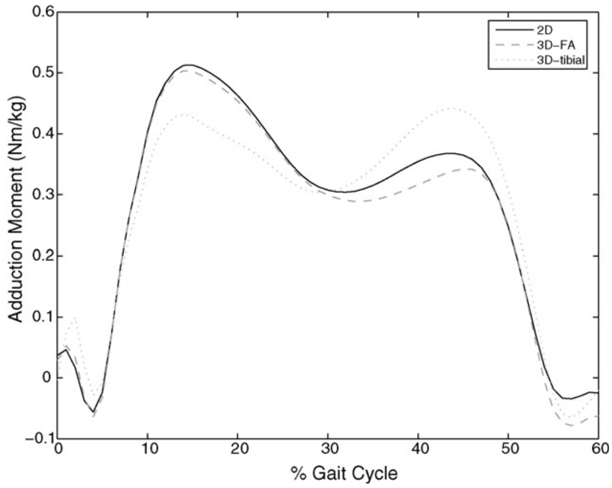

Fig. 3. Plot of the knee adduction moment calculated for the three knee models (black solid = 2D, grey dashed = 3D floating axis, light grey dotted = 3D tibial axis) for the asymptomatic group only.

3. Results

The radiographic data confirmed the moderate classification of the OA subjects, because 84% had a Kellgren–Lawrence (KL) score of 2 or 3 (5-KL = 1, 20-KL = 2, 17-KL = 3, and 2-KL = 4). Table 2 is a summary of the speed and anthropometric data for the two groups.

It was found that the shape and magnitude of the adduction moment waveform depended on which adduction moment axis model was used for the moment calculation. Fig. 3 is a plot of the moment reported about the three different coordinate systems for the asymptomatic group only. From Fig. 3 it can be seen that the 3D tibial axis model behaves very differently from the other two models since the second peak is the largest for the 3D tibial axis model and the first peak is the largest for the other two joint coordinate systems. The adduction moment magnitude for the three models was found to be significantly different for both peaks ($p < 0.05$), with the exception of the 2D and floating axis model comparison at peak 1 ($p < 0.05$). There was no difference between the three models for the mid-stance magnitude ($p > 0.05$).

Differentiating between the osteoarthitic and asymptomatic subjects' adduction moment was influenced by the adduction moment model. It is evident from Fig. 4 and

Table 2
Average (and standard deviation) values for age, speed, mass, height and BMI for the two groups (p-value is reported for group differences)

	N	Age (years)	Speed (m/s)	Mass (kg)	Height (m)	BMI (kg/m^2)
Asymptomatic	44	51.9 (9.7)	1.32 (0.14)	74.53 (12.5)	1.70 (0.09)	25.87 (3.7)
Moderate OA	44	57.1 (10.5)	1.28 (0.17)	92.45 (16.5)	1.74 (0.10)	30.39 (4.6)
p-Value		0.018	0.22	0.025	0.001	0.001

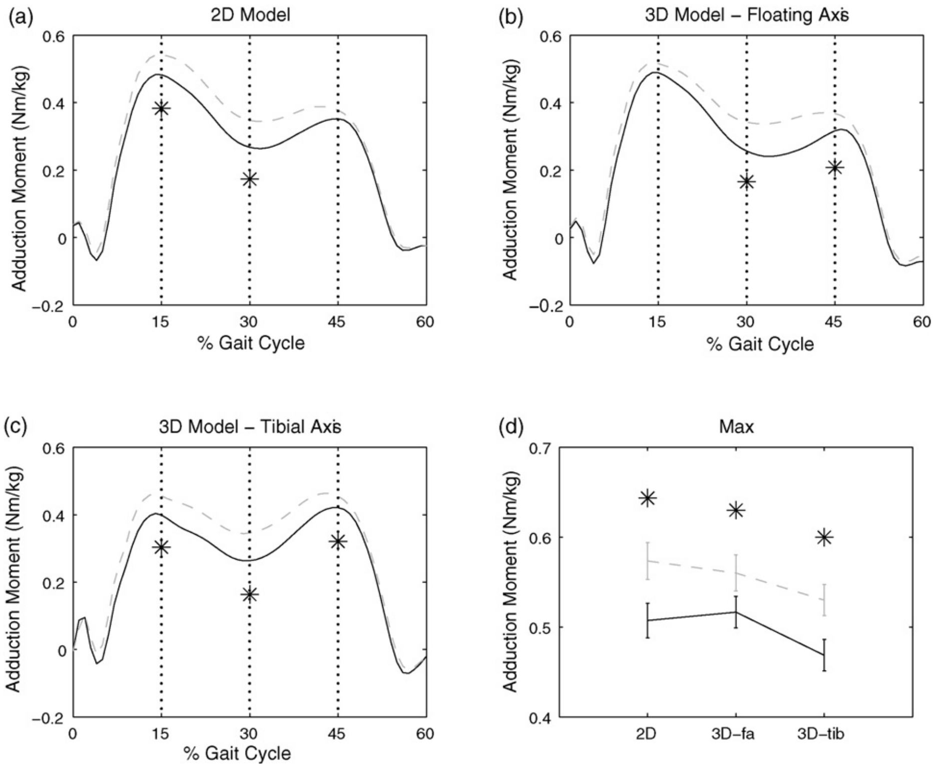

Fig. 4. Plots of the knee adduction moment calculated for the three knee models (a–c) for the two subject groups (black solid = asymptomatic, grey dashed = moderate OA). Interaction plot (d) for the max value with the mean and standard error for each of the three models (black solid = asymptomatic; grey dashed = moderate OA). Significant differences between the groups for each feature (peak 1, mid-stance, peak 2 and max) are indicated directly on the plots. $^{*}p < 0.05$.

Table 3 that not only were group differences found to depend on which model was used; differences were also found to depend on which waveform feature was analyzed.

3.1. Discrete waveform features

The mid-stance and max values revealed significant differences between the two groups, regardless of which model was used (Fig. 4). However, the max value demonstrated a model effect ($p < 0.05$), since the tibial model was different than the others. An interaction between model and group was observed for the first and second peaks. Pair-wise comparisons were performed to contrast the two groups for each of the three models. Peak 1 differed between the two groups for both the 2D and tibial axis models ($p < 0.05$), but not the 3D floating axis model ($p = 0.26$). For peak 2, the two groups were different for the floating axis model and the tibial axis model ($p < 0.05$) but not the 2D model ($p = 0.12$). In order to capture these changes to the waveform magnitude and shape associated with ostoarthritic gait, and the different knee models, PCA was used as an alternative to discrete waveform measures.

3.2. PCA

The first three principal components were extracted from the waveform data. To help interpret the PCs, the extreme z-scores were plotted [20] and the PC loading vectors were examined (Fig. 5). To determine which feature(s) of variability a specific PC captured, the waveforms of subjects that have high scores for that particular PC are compared to subjects that scored low. The first PC extracted from the waveforms described the overall magnitude of the adduction moment across the whole gait cycle (analogous to an area

Table 3
Average adduction moment values (and standard deviations) for each group (asymptomatic and OA) and each model (2D axis, floating axis and tibial axis) for all discrete waveform measures (peak 1, peak 2, max and mid-stance)

	2D axis (nm/kg)			3D floating axis (nm/kg)			3D tibial axis (nm/kg)		
	Asym	OA	% diff.	Asym	OA	% diff.	Asym	OA	% diff.
Peak 1	0.483 (0.13)	0.543 (0.14)	12.4*	0.489 (0.13)	0.516 (0.11)	5.5	0.399 (0.13)	0.456 (0.14)	14.2*
Peak 2	0.352 (0.08)	0.378 (0.10)	7.2	0.317 (0.11)	0.368 (0.13)	16.1*	0.421 (0.09)	0.455 (0.11)	8.1*
Max	0.507 (0.08)	0.574 (0.14)	13.0*	0.517 (0.08)	0.560 (0.14)	8.4*	0.469 (0.08)	0.530 (0.13)	13.1*
Mid-stance	0.268 (0.13)	0.347 (0.14)	29.8*	0.257 (0.12)	0.342 (0.13)	33.3*	0.264 (0.12)	0.346 (0.12)	31.0*

Percent difference between asymptomatic and OA groups is also reported (* is for significant group differences for $p < 0.05$).

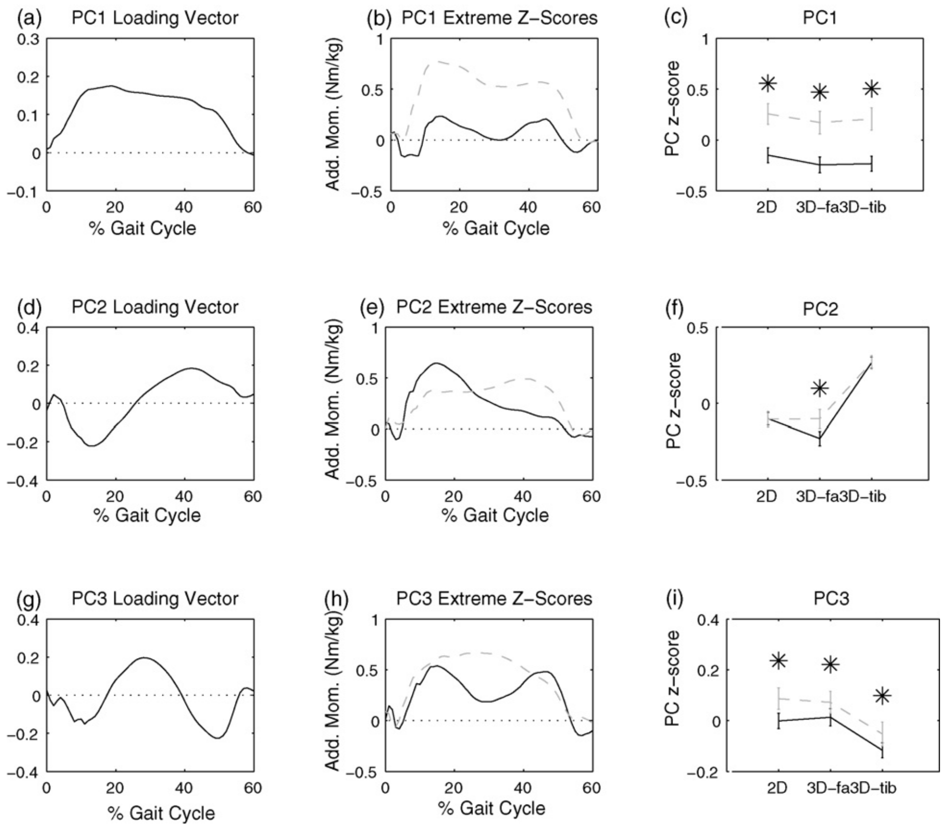

Fig. 5. PCA loading vectors, PCA extreme *Z*-scores and PCA interaction plots. Loading vectors for (a) PC1 (58.1% total variation explained), (d) PC2 (18.9% total variation explained) and (g) PC3 (9.5% total variation explained). Extreme *z*-scores for PC1 (b), PC2 (e), and PC3 (h) (black solid = low *z*-score; grey dashed = high *z*-score). Interaction plots for PC1 (c), PC2 (f), and PC3 (i). The mean and standard error are plotted for each of the three models (black solid = asymptomatic; grey dashed = moderate OA). (*) Significant difference between the two groups ($p < 0.05$).

under the curve calculation). The second PC captured a difference between the first and second peaks in the adduction moment waveform. The third PC captured the shape of the mid-stance portion of the gait cycle.

The overall magnitude of the moment (PC1) did not depend on the joint coordinate system used and revealed significant differences between the two groups for all three models (Fig. 5). The second and third principal components had significant adduction model effects ($p < 0.05$). PC2 was different for all model comparisons for the asymptomatic group ($p < 0.05$), but the 2D axis and floating axis were not different for the OA group ($p = 1.00$). Pair-wise comparisons with PC2 (which referred to the ratio of the two peaks) revealed that there were only differences between the two groups with the floating axis model ($p = 0.03$). For PC3, the 3D tibial axis model was different than the other models ($p < 0.05$). The shape of the mid-stance portion of the waveform (PC3) exhibited group differences for all 3 models ($p < 0.05$).

4. Discussion

This study provides evidence that the adduction moment is in fact sensitive to the biomechanical model applied to the knee. Describing the knee adduction moment about three axes with different orientations in the lower limb resulted in transformation in both the magnitude and shape of the adduction moment waveform. This is consistent with Manal et al. [18], who demonstrated the effects on the adduction moment waveform when adjusting the adduction moment axis in an asymptomatic group. When comparing the two groups, osteoarthritic versus asymptomatic, significant differences relied on which model was applied and which waveform feature was analyzed.

The findings of this study are consistent with the literature that has reported adduction moment differences between an asymptomatic and osteoarthritic group. Hurwitz et al. [2] found an osteoarthritic group had a higher first peak adduction moment and no difference for the second peak using a 2D model. Gok et al. [3] and Baliunas et al. [1] both reported the maximum adduction moment value to be higher in an OA group, with the former study using a 3D tibial axis model and the latter study using a 2D model. Weidenhielm et al. [4] was able to differentiate the groups using both the max and mid-stance adduction moment value. Landry et al. [14] found that the first principal component (overall adduction moment over the entire waveform) was significantly different between the two groups using the 3D floating axis model. When considering this sample of the literature, it can be seen that the results of a study depend on the adduction moment model and waveform feature used.

It was found that differences could be detected between the osteoarthritic and asymptomatic group by using certain model and waveform feature combinations. However, it is important to observe that not only were these differences statistically significant but they were also of a clinically significant magnitude. The adduction moment has been reported to be 13% [2] and 27% [1] higher in an osteoarthritic group versus a control group. Reductions of the adduction moment of 14% [9], 13% [10] and 10% [11] were considered successful reductions when evaluating knee braces. In the present study, large group differences were detected when examining the mid-stance portion of the gait cycle (29–34%) and the max value (8–14%). The group differences found at peak 1 (5–15%) and peak 2 (7–17%) were also sizable.

A noteworthy finding was that there were four waveform features found to be significantly different between the two groups regardless of which model was applied. These features were the overall magnitude of the moment (PC1), the shape of the mid-stance portion of the waveform (PC3), mid-stance and max. The first principal component captured the overall magnitude of the adduction moment during stance. Group separation with PC1 may imply that the moderate osteoarthritic group is loading the medial compartment of the knee more than the control group throughout the entire stance phase of the gait cycle. The magnitude difference between the two groups at the mid-stance portion of the gait cycle tends to support a notion that osteoarthritic subjects are not unloading the medial compartment of the knee at full weight acceptance as well as their asymptomatic counterpart. A concern with reporting the max value is that even though it does separate the groups for all models, this measure occurs at different portions of the gait cycle for each subject. Another problem with the max value is that its magnitude and location in the gait cycle changes when a different joint coordinate system is used. Even though both the max and PC3 values separated the two groups for all models, both features revealed a model dependency. There were only two waveform features that could separate the groups for all three models and had no model dependency: PC1 and mid-stance. These two features appear to be more robust measures for evaluating osteoarthritic gait; therefore, the clinical relevance of each should be examined further.

Since the main difference between the three models involves orientation in the transverse plane, this provides a good opportunity to investigate potential mechanisms for group differences. Orientation differences in the transverse plane among the three models are attributed to two factors: the fixed offset between the malleoli and the epicondyles in addition to knee internal/external rotation. These orientation differences in the model axes are responsible for the shape changes in the adduction moment waveform when changing the model. Examining the role of axis orientation in model-dependent group differences is important to understanding the mechanisms behind the involvement of the adduction moment in knee OA.

These finding suggest that there are waveform descriptors that are insensitive to the choice of the biomechanical model when measuring group differences. As well they show that caution should be exercised when interpreting results among studies where different methods of calculating the adduction model are employed. It is evident that there is a need for improvement in our understanding of the nature of the adduction moment at the knee. Without a better understanding of the axis about which the adduction moment occurs, the mechanisms related to the presence and progression of osteoarthritis cannot be fully understood. Proper evaluations of noninvasive interventions for the disease are challenging without a better understanding of the biomechanical model for the knee.

5. Conclusion

It was concluded that the waveform characteristics (magnitude and shape) of the adduction moment at the knee depend on which axis was used for the moment calculation. Not only was it found that changing the model had an effect on the waveform shape, it also had an influence on detecting differences between an asymptomatic and a moderate osteoarthritic group. There were certain waveform features used to describe the adduction moment that identified differences between groups, no matter which of the biomechanical models was employed. The overall magnitude of the adduction moment throughout stance (PC1) and the mid-stance value demonstrated no model dependence and could separate the two groups for all three joint coordinate systems.

Acknowledgements

This work was funded by Natural Sciences and Engineering Research Council (NSERC) and Canadian Institutes of Health Research (CIHR).

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