

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

Robyn S. Newell and Kevin J. Deluzio
School of Biomedical Engineering
Dalhousie University
Halifax, Canada
rnewell@dal.ca

Abstract—The adduction moment measured at the knee during gait is important to the study of osteoarthritis. Various knee adduction models have been used to demonstrate differences between osteoarthritic and asymptomatic populations and there is also an inconsistency as to which part of the gait cycle differences are being reported. Several noninvasive treatments have been shown to decrease the adduction moment; however, only at certain portions of the gait cycle. It was hypothesized that the adduction moment is sensitive to changing the biomechanical model characterizing the knee, and in specific, changing the model affects the interpretation of differences between the two populations. Gait was measured for 44 asymptomatic subjects and 44 moderate osteoarthritic subjects. The adduction moment was calculated and compared using the three common biomechanical models reported in previous studies: a 2D coordinate system model, a 3D tibial based coordinate system model, and a 3D floating axis coordinate system model. Several portions of the gait cycle waveform were compared between the two populations. It was found that the choice of biomechanical model changes the overall magnitude of the adduction waveform. More importantly, the shape of the adduction moment waveform is significantly altered by changing the model. Significant differences between the study groups were found for each model applied; however, the portions of the gait cycle exhibiting the differences depended on the model. These findings support the importance of standardization for comparing studies and assessing noninvasive interventions for the osteoarthritic knee.

Keywords- *adduction moment; model; coordinate system; osteoarthritis; waveform features; principal component analysis*

I. 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 [1,2,3]. There is evidence that disease severity is associated with maximum knee adduction moment, with a more severe OA subject group having a significantly greater maximum adduction moment than moderate OA and control subjects [4]. One study correlated the adduction moment at the knee with K-L grade score and joint space width [5].

Furthermore, successful results of a proximal tibial osteotomy have been associated with a lower adduction moment [6,7].

Although in many studies, an association between osteoarthritis and peak knee adduction moment has been demonstrated, there is an inconsistency in which part of the gait cycle differences are identified. Asymptomatic and osteoarthritis subject groups have been compared using the maximum adduction moment peak [1,4,5,8]. Weidenhielm, et al. found the midstance value (50% of the gait cycle) was more sensitive than the maximum peak [2]. Hurwitz, et al. reported that the 1st peak of the adduction moment in OA subjects was significantly higher than that of the control subjects and that the 2nd peak had no significant difference [3]. The study also demonstrated that 52% of OA subjects did not have a definitive 2nd peak of the adduction moment compared to 29% control subjects.

There are several proposed noninvasive interventions aimed at reducing medial joint loading by lowering the adduction moment at the knee. Toe-out gait, in which the foot is angled outward during the stance phase of gait, has been proposed as a promising intervention [6,7]. Andrews, et al. established that subjects who walked with a toe-out gait tended to have a lower knee adduction moment; however, this relationship was only found during late stance [9]. One study reported a successful reduction in the adduction moment at the knee with a valgus loading knee brace, yet the moment was only significantly reduced during early stance [10].

While the adduction moment is linked with knee OA, there is still a lack of a standard biomechanical model to characterize this moment. The anatomy of the knee does not suggest an obvious axis to describe the moment in the frontal plane. Manal, et al. provided evidence that the choice of coordinate system in the tibia changes the overall magnitude of the abduction/adduction waveform [11]. More importantly, it was shown that the selection of the coordinate system significantly affects the adduction moment profile. The 1st peak adduction moment was significantly different between coordinate systems; however, the 2nd peak illustrated no significant difference. These findings confirm that various methods of describing the knee adduction moment could result in

conflicting results between studies. Three common models have been used to describe the external adduction moment at the knee: a 2D coordinate system model [1,3,4,5,6,7,9], a 3D tibial based coordinate system model [8, 12], and a 3D floating axis coordinate system model [13, 14]. The objective of the study was to determine if the choice of the biomechanical model characterizing the external adduction moment of the knee affects the interpretation of differences between osteoarthritic and asymptomatic populations.

II. METHODS

A. Subjects

The study included 44 asymptomatic subjects (24 males, 20 females) who had no history of knee pain. Forty-four moderate osteoarthritic subjects (23 males, 21 females), who were diagnosed clinically and radiographically, were also included in the study.

B. Data Collection

Kinematic and kinetic data were captured for 5 walking trials for each subject. Each subject was instructed to walk in a straight line at a self selected speed. The three dimensional (3D) orientation of the lower limb of interest was tracked using infrared markers (collected at 100Hz) with an Optotrak 3D motion analysis system (National Digital Inc., Waterloo, ON). The markers were placed on 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 landmarks, including: medial epicondyle, fibular head, tibial tuberosity, medial malleolus, second metatarsal head and calcaneus. Ground reaction forces and moments (collected at 1000Hz) were also recorded for the full gait cycle using an AMTI force platform (Advanced Medical Technology Inc., Watertown, MA). Gait measures were normalized to 100% gait cycle (first heel strike to second heel strike).

C. Kinetics

The adduction moment at the knee was calculated using the kinematic and kinetic data gathered during the walking trials. Using the 3D position of the markers, the orientation of each of the three segments of the lower limb was computed. The joint center for the knee was determined to be the mid-point between the medial and lateral epicondyles. The joint center for the ankle was determined to be the mid-point between the medial and lateral malleoli. Ground reaction forces and moments, along with segment weights were used to calculate the resultant external joint moment at the knee using the following equation:

$$\mathbf{M}_k = [\mathbf{r}_1 \times \mathbf{F}_{g1}] + [\mathbf{r}_2 \times \mathbf{F}_{g2}] + [\mathbf{r}_3 \times \mathbf{F}] + \mathbf{M}_z \quad (1)$$

Where \mathbf{M}_k is the resultant external joint moment vector at the knee, \mathbf{F}_{g1} and \mathbf{F}_{g2} are the weights of the femur and tibia respectively, \mathbf{r}_1 is the distance from knee joint center to the femur center of mass, \mathbf{r}_2 is the distance from knee joint center to the tibia center of mass, \mathbf{r}_3 is the distance from knee joint center to the center of pressure of the ground reaction force, \mathbf{F}

is the ground reaction force (X, Y, and Z components), and \mathbf{M}_z is the ground reaction moment (about the global Z-axis).

The external knee joint moment calculation was a quasi-static analysis. This was a reasonable assumption for these computations since the inertial effects on each segment are minimal for the stance phase of gait. Moments were normalized to body mass (N/kg). The external knee joint moment was calculated in the 3D global coordinate system of the lab (Fig. 1). To describe the adduction moment as an anatomically relevant moment, the moment was described in three different coordinate systems in the lower limb. These coordinate systems correspond to 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.

The 2D coordinate system model is based on a planar representation of the lower limb [6]. The adduction moment was calculated in the frontal plane of the leg about an axis that is perpendicular to the frontal plane. It was assumed that there was minimal tibial and femoral internal/external rotation (motion in the transverse plane). Motion perpendicular to the sagittal plane was also assumed to be negligible and was projected onto the sagittal plane. The third assumption was that each subject walked in a straight line along the X-axis of the global coordinate system.

The tibial axis (Fig. 2) was based on a coordinate system described in the tibia [12]. The flexion/extension axis (Z_T) of this coordinate system was produced by creating a vector that points medially through the lateral and medial malleoli. The long axis of the tibia (X_T) was formed by a vector joining the fibular head and lateral malleolus, pointing proximally. By taking the common perpendicular of the flexion/extension axis and the long axis of the tibia, an adduction axis (Y_T) is created pointing anteriorly. The adduction moment was calculated by finding the component of the global 3D moment about the tibial axis.

The floating axis model (Fig. 2) is established by a coordinate system that is described in both the tibia and femur [15]. A vector joining the medial and lateral epicondyles, which points medially is used to establish a flexion/extension axis based (Z_F) in the femur. The floating axis (Y_{FA}) is created by taking the common perpendicular of the flexion/extension

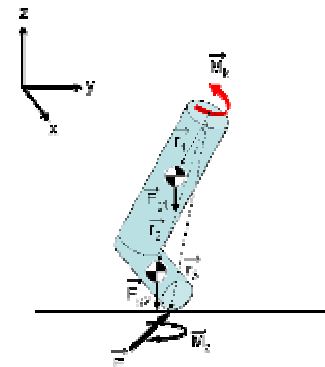


Figure 1. Free body diagram of forces and moments acting on the tibia and foot in a global lab coordinate system.

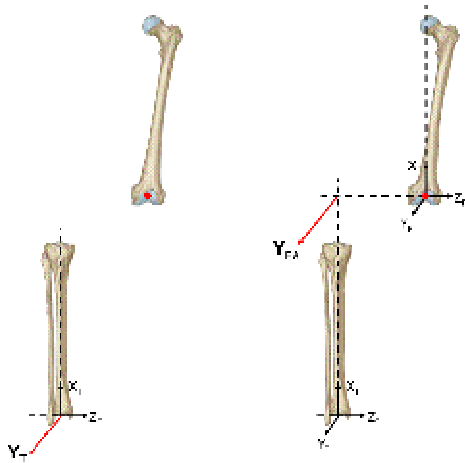


Figure 2. The tibial axis (Y_T) adduction moment model (left) and the floating axis (Y_{FA}) adduction moment model (right).

axis of the femur and the long axis (X_T) of the tibia. The adduction moment was calculated by finding the component of the global 3D moment about the floating axis.

D. Data Analysis

There were several features examined in the adduction moment waveform for group comparisons. The three major features of the adduction moment waveform were the first maximum peak (10-25% gait cycle), the second maximum peak (35-50% gait cycle) and the dip (25-35% gait cycle) in the waveform at mid-stance (Fig. 3). The maximum peak throughout the complete waveform was also analyzed.

Principal component analysis (PCA), a descriptive multivariate statistical technique, has been shown to be an effective technique for capturing differences in the shape of gait waveforms [16]. PCA was applied to the adduction moment waveforms for each of the three models for all 88 subjects. This orthogonally transforms the data into uncorrelated loading vectors and principal component score is given to each subject based on the projection of that subject's data onto a particular loading vector.

A t-test with a 0.05 significance level was performed in comparing the two groups for each of the waveform features.

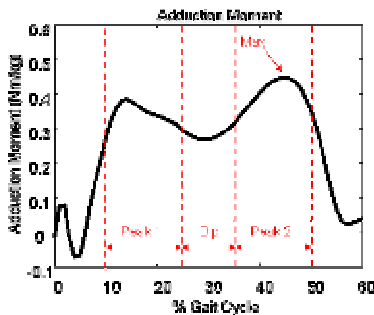


Figure 3. Representative knee adduction waveform. The first peak occurs between 10-25% gait cycle, the dip occurs between 25-35% gait cycle and the second peak occurs between 35-50% gait cycle.

III. RESULTS

The average body mass index (BMI) of the asymptomatic and osteoarthritic groups were $25.9 \text{ kg/m}^2 (\pm 3.7)$ and $30.4 \text{ kg/m}^2 (\pm 4.6)$ respectively. 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) [17]. There were no differences in walking speeds for the two study groups. The asymptomatic group walked with an average speed of 1.32 m/s ($\pm 0.14 \text{ m/s}$) and the moderate osteoarthritic group walked with an average speed of 1.28 m/s ($\pm 0.17 \text{ m/s}$).

It was found that the shape and magnitude of the adduction moment waveform depended on which adduction moment axis model was applied to the moment calculation (Fig. 4). The maximum peak was found to occur at the first peak of the waveform for the 2D axis and floating axis calculations; however, the maximum peak was found to occur at the second peak for the tibial axis calculation.

The peak differences between the study groups were found to be sensitive to which adduction moment axis model was used. Table I summarizes the peak adduction moment values calculated for each waveform feature. It was found that the first peak (10-25% gait cycle) was statistically different between the asymptomatic and moderate OA groups for the 2D model ($p = 0.01$) and the tibial axis model ($p = 0.02$) but not the floating axis model. The second peak (35-50% gait cycle) was statistically different between the two groups for the floating axis model ($p = 0.02$) and was not significantly different for the 2D model and the tibial axis model. The dip (25-35% gait cycle) in the adduction moment profile was statistically different between the two groups for each of the three models ($p < 0.001$).

The first principal component feature extracted from the waveforms described the overall magnitude of the adduction moment across the whole gait cycle (analogous to an area under the curve calculation). This feature was significantly different between the asymptomatic and OA groups for each of the three models ($p < 0.005$).

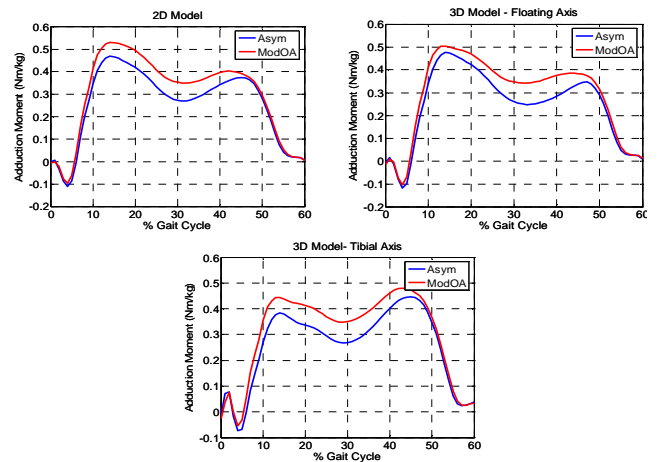


Figure 4. The knee adduction moment calculated from the three knee models. 2D model top left, 3D tibial axis model top right, and 3D floating axis model bottom. (Blue = Asymptomatic, Red = Moderate OA).

TABLE I. PEAK VALUES FOR KNEE ADDUCTION MOMENT WAVEFORM FOR EACH KNEE MODEL

Group	Model	1 st Peak	Midstance Peak	2 nd Peak	Overall Peak
Asym	2D	0.493*	0.261*	0.388	0.499*
Mod OA	2D	0.567*	0.339*	0.425	0.568*
Asym	3D-tibial	0.412*	0.256*	0.462	0.486*
Mod OA	3D-tibial	0.486*	0.335*	0.497	0.542*
Asym	3D-FA	0.502	0.240*	0.363*	0.511
Mod OA	3D-FA	0.546	0.329*	0.419*	0.560

* A significant difference was found when comparing the two groups (p<0.05)

IV. DISCUSSION

This study suggests that the adduction moment is in fact sensitive to the biomechanical model applied to the knee. By describing the adduction about three axes with various orientations in the lower limb, not only does the magnitude of the adduction moment waveform change but the shape is altered as well. In comparing two populations, osteoarthritic versus asymptomatic, significant differences relied on which model was applied and which waveform feature was analyzed. Even when examining the overall peak, as many authors do, a similar dependency on the adduction model was concluded. This is consistent with Manal, et al., who demonstrated the effects on the adduction moment waveform when adjusting the adduction axis in a normal population [11].

A noteworthy finding in this study was that there were two waveform features found to be significantly different between the two groups regardless of which model was applied. One of these features was the midstance adduction moment value (located at 25%-35% of the gait cycle). Principal component analysis also found group differences despite changing the model. The first principal component captured the overall magnitude of the adduction moment during stance. These findings suggest that there are waveform descriptors that are insensitive to the choice of the biomechanical model when measuring group differences. The clinical relevance of the midstance adduction moment value and the first principal component should be explored further.

These results question the ability to compare studies where different methods of calculating the adduction model are employed. If differentiating between osteoarthritic and asymptomatic joint loading cannot be done with a significant degree of confidence, then the biomechanical evaluation of noninvasive interventions is difficult. Future efforts should be directed toward standardizing the biomechanical model that describes the external adduction moment at the knee.

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