Dynamic Versus Radiographic Alignment in Relation to Medial Knee Loading in Symptomatic Osteoarthritis

Joaquin A. Barrios,1 Todd D. Royer,2 and Irene S. Davis3
1University of Dayton; 2University of Delaware; 3Harvard Medical School

Dynamic knee alignment is speculated to have a stronger relationship to medial knee loading than radiographic alignment. Therefore, we aimed to determine what frontal plane knee kinematic variable correlated most strongly to the knee adduction moment. That variable was then compared with radiographic alignment as a predictor of the knee adduction moment. Therefore, 55 subjects with medial knee OA underwent three-dimensional gait analysis. A subset of 21 subjects also underwent full-limb radiographic assessment for knee alignment. Correlations and regression analyses were performed to assess the relationships between the kinematic, kinetic and radiographic findings. Peak knee adduction angle most strongly correlated to the knee adduction moment of the kinematic variables. In comparison with radiographic alignment, peak knee adduction angle was the stronger predictor. Given that most epidemiological studies on knee OA use radiographic alignment in an attempt to understand progression, these results are meaningful.

Keywords: gait analysis, biomechanics, kinematics, kinetics

Knee osteoarthritis (OA) is one of the most disabling conditions of the elderly population, and most commonly affects the medial compartment of the knee (Guccione et al., 1994). Varus knee alignment is a risk factor for the development and progression of medial knee OA (Brouwer et al., 2007; Sharma et al., 2001; Felson et al., 2003). Increased varus knee alignment is thought to increase medial compartment loads during gait by medially shifting tibiofemoral load distribution (Andriacchi, 1994). Most often, the external adduction moment at the knee, extracted from instrumented gait analysis, is used as an indirect measure of medial joint loading (Zhao et al., 2007). This moment has been associated with radiographic disease severity and progression, lending further support to its use (Sharma et al., 1998; Miyazaki et al., 2002). However, our understanding of the relationship between knee alignment and knee adduction moment remains incomplete. This is partly due to the preponderance of studies evaluating static, usually radiographic, measures of knee alignment, with far less attention focused on dynamic parameters.

The strength of the relationship between static knee alignment and the knee adduction moment has been found to be quite variable across studies (Goh et al., 1993; Wang and Olney, 1994; Weidenhielm et al., 1994; Hurwitz et al., 2002, Miyazaki et al., 2002). In a small sample of normal healthy subjects, a moderately strong correlation has been reported between radiographic alignment and the peak knee adduction moment ($r = 0.69$) (Andrews et al., 1996). In 12 elderly individuals, Wang and Olney (1994) also found moderate correlations ($r = 0.58–0.59$). In individuals with medial knee OA, radiographic alignment has been found to explain approximately 50% of the variation in the peak knee adduction moment (Hurwitz et al., 2002; Thorp et al., 2007). However, Specogna et al. (2007) and Weidenhielm et al. (1994) reported weaker relationships ($r = 0.46, 0.32$, respectively). Even weaker radiographic results ($r = 0.23$) were found by Miyazaki and colleagues (2002). Beyond radiography, static clinical measures of alignment, such as tibial axis (inclinometry) and the distance between the knees (calipers), have also been related to the knee adduction moment and found to have moderately strong relationships ($r = 0.74, 0.64$, respectively) (Barrios et al., 2009a). The wide variation in the strengths of these relationships makes it difficult to confidently infer medial knee loads from static frontal plane measures.

It has been suggested that the knee adduction moment would be more strongly related to dynamic measures of knee alignment than to radiographic alignment (Sharma et al., 2006). Dynamic knee alignment can be represented by frontal plane knee kinematics obtained during three-dimensional gait analysis. Indeed, peak knee adduction angle during stance has been found to be highly correlated to radiographic alignment (Hunt et al., 2008). Recently, Foroughi and colleagues (2010) found that shank adduction angles at 30% of stance explained 61% of peak knee adduction moment.
variation in women with medial knee OA. Interestingly, these authors chose to focus on segmental shank angles rather than knee angles, and did not include males in the study. Barrios and colleagues (2009a) reported that knee adduction angle at the time of peak knee adduction moment explained 46% of the variation in the moment. In this study, however, kinematic data were extracted at the instance of the peak in the moment data, making the kinematic variable reliant on the moment data. Further, only healthy individuals were studied. Consequently, the existing literature relating dynamic alignment to the knee adduction moment is rather incomplete. Stance-phase variables representative of dynamic alignment, such as peak knee adduction angle, mean knee adduction angle, and knee adduction angle excursion have not been assessed for their unique contributions to knee adduction moment variation. Peak knee adduction is of interest as this is the greatest instance of limb malalignment. The mean adduction angle merits interest as a value representing alignment throughout stance. Finally, the adduction excursion merits evaluation as a kinematic indicator of overall frontal plane knee motion associated with loading. As a target variable, analyses should include frontal plane knee angular impulse, in addition to the peak knee adduction moment, as an indicator of medial knee joint loading across stance (Thorp et al., 2006, 2007). Finally, these relationships need to be evaluated in a cohort that includes males with medial knee OA.

In result, the primary aim of this study was to determine which of three variables related to dynamic alignment (peak adduction angle, mean adduction angle, and adduction excursion [initial contact to peak adduction angle]) most strongly correlated to peak knee adduction moment and angular impulse in a medial knee OA cohort. We hypothesized that peak adduction angle would be most strongly correlated to peak knee adduction moment. We also hypothesized that that mean adduction angle would relate most strongly to the angular impulse, as both are determined from the entirety of stance. As a secondary aim, we assessed the relationships of radiographic and kinematic measures of frontal plane knee alignment to the knee adduction moment variables. We hypothesized that the kinematic measure(s) identified in the primary aim would be more strongly related to the moment variables than the radiographic measure.

Methods

Subjects
An a priori power assessment was conducted to determine the sample size for the primary aim of this study. Given three predictor variables, an alpha level of 0.05 and beta of 0.20, at least 48 subjects were needed to power the regression analyses. In result, 55 subjects between 40–75 years of age participated. These individuals were a subsample from a larger longitudinal study examining laterally wedged foot orthoses in the management of knee OA (Barrios et al., 2009b). These subjects reported medial knee pain during walking of ≥ 3/10 on a numerical rating scale. Diagnostic radiographs were obtained with the knee in a 30° flexed position, and evaluated by a single rheumatologist. To be included, subjects had to be diagnosed with medial tibiofemoral OA of at least Kellgren-Lawrence grade II (Kellgren & Lawrence, 1957). Exclusion criteria included any neurological or musculoskeletal condition that could affect ambulation, as well as any use of an assistive device for gait. All subjects granted informed written consent in accordance with the University of Delaware Institutional Review Board.

Gait Analysis

Subject preparation included the donning of standardized shoes (Nike Air Pegasus, Beaverton, OR, USA) and neutral foot inserts (KLM Cal-Pre, Valencia, CA) to minimize variability in footwear. Reflective surface markers were then applied. Anatomical markers were placed on the greater trochanters, the medial and lateral femoral condyles, the medial and lateral malleoli, on the shoe over the bases of the 1st and 5th metatarsals, and the distal tip of the shoe. Four rigid tracking markers, mounted on thermoplastic shells, were strapped to the shank and thigh. Individual tracking markers were placed over the L5-S1 interspinous space, the ipsilateral iliac crest, and the ipsilateral anterior superior iliac spine. Three individual markers tracking calcaneal motion were placed directly on the skin and projected through holes in the heel counters. The anatomical markers were used to determine segment coordinate systems for the pelvis, thigh, shank and foot, and were removed after a standing calibration trial. The hip joint center was identified as a quarter of the distance between the greater trochanters. For each segment, the z-axis was oriented from the distal segment end to the proximal end. The y-axis was oriented from posterior to anterior in the segment. Lastly, the x-axis was oriented from medial to lateral. We have found use of this marker set to be reliable (Ferber et al., 2002). During the standing calibration, paper foot maps were used to record foot position.

The walking trials were then conducted. Photocells were used to determine self-selected walking speed for each subject, and this speed was held within ±5% for all walking trials. The marker trajectories were collected at 120 Hz using a six-camera motion analysis system (Vicon, Oxford Metrics, UK). The subjects traversed a floor-embedded force platform (Bertec Corp., Worthington, OH, USA), the outputs of which were sampled at 1080 Hz. The analog data were down-sampled to match the video rate for analysis.

Data were processed offline using Visual 3D software (C-Motion, Bethesda, MD, USA). The marker data were low-pass filtered at 8 Hz with a phase-corrected, fourth-order Butterworth filter. The kinetic data from the force platform was low-pass filtered at 50 Hz. An X-Y-Z rotation sequence was used to derive the joint kinematics.
External joint moments were normalized to height and weight. The five stance-phase variables of interest were peak adduction angle, mean adduction angle, adduction excursion, peak knee adduction moment (first half of stance) and the net adduction angular impulse. These variables were extracted and averaged from five individual trials for each subject.

Radiographic Knee Alignment

Full-length lower extremity anterior-poster radiographs to assess radiographic alignment were also collected in a subset of 21 subjects, who voluntarily agreed to the additional radiography. Subjects stood with their knees fully extended and their feet in natural stance, using the paper foot maps from the gait analysis. A single investigator identified the mechanical axes of the femur and tibia, and then measured the angle between the axes. The landmarks used to determine the femoral mechanical axis were the center of the femoral head and the midcondylar notch (Moreland et al., 1987). For the tibial mechanical axis, the center of the tibial spines and the center of the tibial plafond were used (Moreland et al., 1987; Yoshioka et al., 1989). The radiographic alignment angle was then recorded to the nearest degree. A radiographic alignment angle between 178° and 180° was classified as normal (Moreland et al., 1987; Brouwer et al., 2007). Angles <178° were considered varus, and angles >180° were considered valgus. Reliability testing revealed a standard error of the measure of 0.2°.

Statistical Analysis

Data were analyzed using SPSS version 15.0 (SPSS Inc, Chicago, IL, USA). An alpha level of 0.05 was used for all statistical analyses. For the primary aim, Pearson’s correlation coefficients were used to examine the relationships between the five variables of interest from the gait data of all 55 subjects. Separate hierarchical linear regressions were then used to determine the amount of variation explained in the two knee adduction moment variables by the three kinematic variables. Two stepwise multiple linear regression models ($p_{\text{enter}} \leq 0.05, p_{\text{remove}} \geq 0.10$) were performed. The first model used the peak knee adduction moment during the first half of stance as the dependent variable, and second used the angular impulse. The kinematic predictor explaining the most variation in the knee adduction moment variables was carried forward to the secondary aim.

The secondary aim involved the direct comparison between radiographic and kinematic prediction of the knee adduction moment variables. For this aim, data from the subset of subjects who also provided radiographs were used. Pearson’s correlation coefficients were first used to correlate radiographic alignment to the strongest kinematic predictor from the first aim. Forced entry regressions were then used to test how much variation in peak knee adduction moment and angular impulse was explained by radiographic alignment angle, the kinematic predictor, and both measures together.

Results

The subject demographics and descriptive statistics of the knee variables are presented in Table 1. There was a nearly equal distribution of males and females. Levels of disease severity were also well distributed. Participants were generally obese with a mean BMI of 33.2 ± 7.3 kg/m². All subjects demonstrated a discrete peak in the knee adduction angle and moment waveforms during the first half of stance (Figure 1). In terms of correlations, angular impulse and peak knee adduction moment were strongly related ($r = .817, p < .001$) (Table 2). Regarding the kinematic predictors, moderately weak correlations were observed between adduction excursion and both mean adduction angle ($r = –0.398, p = .001$) and peak adduction angle ($r = .295, p = .014$). Mean and peak adduction angle were not found to be correlated ($r = –0.063, p = .324$).

Table 1 Description characteristics of the 55 subjects ($M \pm SD$ unless noted)

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gender (M/F)</td>
<td>28/27</td>
</tr>
<tr>
<td>Age (years)</td>
<td>61.7 ± 8.9</td>
</tr>
<tr>
<td>BMI (kg/m²)</td>
<td>33.2 ± 7.3</td>
</tr>
<tr>
<td>Kellgren–Lawrence grade</td>
<td></td>
</tr>
<tr>
<td>II (# of subjects)</td>
<td>21</td>
</tr>
<tr>
<td>III (# of subjects)</td>
<td>20</td>
</tr>
<tr>
<td>IV (# of subjects)</td>
<td>14</td>
</tr>
<tr>
<td>Frontal plane knee angular impulse (Nm·s·kg⁻¹·m⁻¹)</td>
<td>0.14 ± 0.04</td>
</tr>
<tr>
<td>Peak knee external adduction moment (Nm·kg⁻¹·m⁻¹)</td>
<td>0.37 ± 0.11</td>
</tr>
<tr>
<td>Peak knee adduction angle (degrees)</td>
<td>3.1 ± 4.3</td>
</tr>
<tr>
<td>Mean knee adduction angle (degrees)</td>
<td>–0.3 ± 4.0</td>
</tr>
<tr>
<td>Knee adduction angle excursion (degrees)</td>
<td>6.1 ± 2.3</td>
</tr>
</tbody>
</table>
Of the three kinematic predictors used for the first aim, peak adduction angle explained the most variation in peak knee adduction moment ($R^2 = .498$, $p < .001$), as well as angular impulse ($R^2 = .511$, $p < .001$) (Table 3). Neither mean adduction angle nor adduction excursion contributed significantly to either model. The possibility of multicollinearity was examined using the tolerance statistic. In both models, the tolerance was $\geq 1$, suggesting that excessive multicollinearity was not present.

For the secondary aim, full-length lower extremity radiographs were available for 21 subjects (10 males, 11 females). The mean radiographic alignment angle was $176 \pm 3^\circ$. Fifteen subjects demonstrated varus alignment, four demonstrated normal alignment, and two were valgus-aligned. A weak, nonsignificant correlation between peak adduction angle and radiographic alignment was observed ($r = .326$, $p = .075$) (Figure 2). Peak KADD and radiographic alignment angle were then used to predict peak knee adduction moment and angular impulse variation (Figure 3). Similar to the regression results from all 55 subjects, peak adduction angle remained a strong predictor of both peak knee adduction moment ($R^2 = .659$, $p < .001$) and angular impulse ($R^2 = .534$, $p < .001$). Radiographic alignment alone was a weak predictor of peak knee adduction moment ($R^2 = .096$, $p = .171$), and a moderate predictor of angular impulse ($R^2 = .319$, $p = .008$). Together, peak adduction angle and radiographic alignment explained a similar amount of variation in peak knee adduction moment ($R^2 = .661$, $p < .001$) and angular impulse ($R^2 = .653$, $p < .001$) compared with peak adduction angle alone.

**Table 2** Correlation coefficients of gait data (55 subjects)

<table>
<thead>
<tr>
<th></th>
<th>Frontal plane knee angular impulse</th>
<th>Peak knee external adduction moment</th>
<th>Peak knee adduction angle</th>
<th>Mean knee adduction angle</th>
<th>Knee adduction angle excursion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frontal plane knee angular impulse</td>
<td>$r$ 1.000</td>
<td>$p$ —</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak knee external adduction moment</td>
<td>$r$ 0.817 1.000</td>
<td>$p$ &lt;0.001 —</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak knee adduction angle</td>
<td>$r$ 0.715 0.706 1.000</td>
<td>$p$ &lt;0.001 &lt;0.001 —</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean knee adduction angle</td>
<td>$r$ 0.021 0.065 –0.063 1.000</td>
<td>$p$ 0.439 0.320 0.324 —</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Knee adduction angle excursion</td>
<td>$r$ 0.203 0.348 0.295 –0.398 1.000</td>
<td>$p$ 0.069 0.005 0.014 0.001 —</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The values in italic are statistically significant ($p \leq .05$).
The primary purpose of this study was to examine the relationship between the knee adduction moment (peak and impulse) and both radiographic and dynamic knee alignment in individuals with medial knee OA. In the primary aim, peak adduction angle was identified as the kinematic variable with the strongest relationship to the knee adduction moment, regardless of predicting the peak or the impulse. In the secondary aim, peak adduction angle was found to be more strongly related to the knee adduction moment than radiographic alignment. In previous epidemiological studies, researchers have quantified radiographic knee alignment in an attempt to evaluate the influence of alignment on disease progression. Thus, these results are important in that dynamic, rather than radiographic, knee alignment may relate more closely to disease progression.

It is sensible that peak adduction angle would be highly correlated with peak knee adduction moment. Based on previously published modeling data, a greater varus angle at the knee will shift the overall knee load further onto the medial tibiofemoral compartment (Andriacchi, 1994). Temporally, we found the peak adduction angle, which occurred at ~22% of stance on average, to be nearly simultaneous to peak knee adduction moment (~23% of stance). Thus, the similar timing of the angle and moment peaks suggests a relationship that is not only magnitude-related, but also temporally related. It is less obvious why peak adduction angle related so well to the angular impulse, as the former is extracted at a discrete instant during stance, and the latter is reflects the entirety of stance.

Adduction excursion did not significantly relate to the knee adduction moment variables. In this study, adduction excursion was determined as the difference between the knee adduction angle at initial contact and initial contact and initial contact.

**Table 3** Summary of forced entry regression outputs for the KEAM variables (Aim 1)

<table>
<thead>
<tr>
<th>Model</th>
<th>$R$</th>
<th>$R^2$</th>
<th>Adj $R^2$</th>
<th>$R^2\Delta$</th>
<th>$p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>First Peak KEAM ($n = 55$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak (adduction angle)</td>
<td>0.706</td>
<td>0.498</td>
<td>0.489</td>
<td>—</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Peak + Excursion (adduction angle)</td>
<td>0.721</td>
<td>0.519</td>
<td>0.501</td>
<td>0.021</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Peak + Excursion + Mean (adduction angle)</td>
<td>0.722</td>
<td>0.521</td>
<td>0.493</td>
<td>0.002</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Frontal Plane KAI ($n = 55$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak (adduction angle)</td>
<td>0.715</td>
<td>0.511</td>
<td>0.501</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Peak + Excursion (adduction angle)</td>
<td>0.715</td>
<td>0.511</td>
<td>0.492</td>
<td>—</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Peak + Excursion + Mean (adduction angle)</td>
<td>0.718</td>
<td>0.515</td>
<td>0.487</td>
<td>0.004</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

**Figure 2** — Relationship between peak knee adduction angle during gait and radiographic knee alignment.
at peak value. In this study, as the lower extremity was loaded during early stance, the knee typically underwent an increase in knee adduction angle, typically on the order of 2–4°. However, these data suggest that this frontal plane excursion, whether larger or smaller, has little bearing on the knee adduction moment in general. We should note that there are other factors that may influence frontal plane excursions in medial knee OA that were not evaluated in the current study. Such factors include co-contraction of the muscles that cross the knee and excessive frontal plane laxity (Schmitt & Rudolph, 2007).

Mean adduction angle was also a poor predictor of the knee adduction moment variables. This was not particularly surprising for peak knee adduction moment. However, since the mean adduction angle was calculated over the entire stance phase, we anticipated a stronger correlation to angular impulse than was observed ($r = .203$). Based on these data, taking a mean adduction angle over a subphase of stance may have been more predictive. For example, since we extracted peak knee adduction moment from the first half of stance, perhaps taking the mean angle over that same time period would have yielded a stronger correlation.

In the secondary aim of our study, radiographic alignment did not relate well to dynamic knee loading. This finding is agreement with some, but not all, previous...
works in this area (Weidenhielm et al., 1994; Miyazaki et al., 2002). A number of factors may help explain the weaker relationship. Perhaps the most influential of these is the two-dimensional nature of radiography, as radiographic measures are prone to perspective errors (Cooke, 2007). In the current study, the same natural stance position was used for both the radiographs and gait analysis (standing calibration) portions of the study, done using paper foot maps. This approach, however, may not have been optimal for the purposes of reducing radiographic perspective error. In the transverse plane, foot placement can be problematic (Hunt et al., 2006; Moreland et al., 1987; Sharma et al., 2001; Hinman et al., 2006). Radiographic measures of knee alignment are also sensitive to positional error in the sagittal plane. If standing in slight knee flexion, lower extremity external rotation may appear as varus angulation, while internal rotation may appear as valgus angulation (Moreland et al., 1987).

The weak relationship between radiographic alignment and the knee adduction moment can also be influenced by the double-limb support position of the radiographs. In most study designs, bilateral stance from the radiographs is related to single-limb weight-bearing during gait. However, Specogna and colleagues (2007) found that radiographic alignment angles increase in the varus direction when moving from supine to double-limb standing to single-limb standing. Therefore, single-limb support during stance, when peak adduction angle and moment typically occur, might be better represented radiographically using single-limb stance than double-limb stance. Single-limb stance radiographs might then have enhanced the relationship between radiographic alignment and the knee adduction moment in the current study.

Interestingly, radiographic alignment and peak adduction angle were not strongly correlated in this study ($r = .326$). This finding is in contrast to previous data suggesting this relationship is strong in individuals with medial knee OA ($r = .84$) (Hunt et al., 2008). Methodological discrepancies may help explain this difference. Importantly, the current study used a custom marker set with more tracking markers than the Helen Hayes marker set employed by Hunt and colleagues. Related to the marker sets, different algorithms were also used to determine the hip joint centers during gait analyses, which would directly affect thigh kinematics. The current study identified the hip joint center as a quarter of the distance between the greater trochanter markers, whereas Hunt et al. used anthropometric data (Dempster, 1955). In addition, different landmark-based algorithms were used to define the knee and ankle joint centers on the radiographs, although these discrepancies would likely be of minor consequence at the level of data analysis. Finally, as 80 participants were studied by Hunt and colleagues, it is possible that more subjects in our investigation may have significantly altered the correlation coefficients, although a shift from a weak relationship to a much stronger one is highly unlikely.

Based on these two studies, the evidence appears inconclusive regarding the relationship between radiographic and dynamic knee alignment.

This study also combined peak adduction angle and radiographic alignment in forced entry regression models to account for the most variation in the knee adduction moment data. We expected that the addition of radiographic alignment to peak adduction angle would significantly increase the explained variation. However, the addition of radiographic alignment did not significantly improve either model. This finding suggests that radiographic alignment does not provide unique information beyond that of peak adduction angle when examining the alignment-moment relationship. Based on these data, investigators may consider using peak adduction angle in place of radiographic alignment when analyzing this relationship.

As a measure of cumulative rather than instantaneous loading throughout stance, we used net adduction angular impulse as a target variable that might account for the time-dependent features of joint loading (Thorp et al., 2006). However, as an outcome variable in this study, this impulse provided similar results to peak knee adduction moment. Therefore, the addition of angular impulse to this analysis did not reveal additional information regarding the relationship between frontal plane knee alignment, whether static or dynamic, and the knee adduction moment. However, it should be noted that this study did not evaluate patients with lateral knee OA, which is often associated with valgus knee alignment. Biomechanically, in the presence of extreme valgus knee alignment, the weight-bearing axis may fall lateral to the knee joint center during gait. In such an individual, a net abduction angular impulse may better represent the lateralized knee joint load than the peak magnitude of the knee adduction moment.

A key implication of this study is that the peak frontal plane angle during stance can be targeted as surrogate for the knee adduction moment when kinetic data from a force plate are unavailable. When evaluating the success of load-altering interventions, this might be helpful when testing gait modification and orthotic strategies. Indeed, one study evaluating gait modification has used the reduction of the peak adduction angle as a surrogate for the time-dependent features of joint loading (Thorp et al., 2006). However, as an outcome variable in this study, this impulse provided similar results to peak knee adduction moment in the presence of knee malalignment (Barrios et al., 2010).

In conclusion, peak adduction angle during gait was the strongest predictor of knee adduction moment variation when compared with other knee adduction kinematic variables. These data also suggest that peak adduction angle explains more variation in the knee adduction moment than radiographic measures. Future research investigating the relationship between frontal plane knee alignment and tibiofemoral joint loading may consider using frontal plane knee kinematics in lieu of obtaining radiographic measures. In addition, future research on interventions may also consider targeting frontal plane kinematics in the absence of kinetic data.
Acknowledgments

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