Lower Extremity Walking Mechanics of Young Individuals with Asymptomatic Varus Knee Alignment

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ABSTRACT: Varus knee alignment is associated with an increased risk for developing medial knee osteoarthritis (OA). Medial knee OA is commonly associated with altered walking mechanics in the frontal and sagittal planes, as well as altered ground reaction forces. It is unknown whether these mechanics are present in young, asymptomatic individuals with varus knees. We expected that varus-aligned individuals would generally present with frontal plane mechanics that were similar to those reported for individuals with medial knee OA. The gait mechanics of 17 asymptomatic individuals with varus knees and 17 healthy, normally aligned controls were recorded. Gait parameters associated with medial knee OA were compared between groups. The individuals with varus knees exhibited greater knee external adduction moments, knee adduction, eversion, and lateral ground reaction force than the normally aligned individuals. In addition, those with varus knees also demonstrated increased knee flexion and external knee flexor moments during midstance. These results suggest that individuals with varus knees exhibit some, but not all, of the altered mechanics seen in medial knee OA. © 2009 Orthopaedic Research Society. Published by Wiley Periodicals, Inc. J Orthop Res 27:1414–1419, 2009

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Knee osteoarthritis (OA) is a growing problem in the aging population. The probability of developing knee OA by age 85 is nearly one in two.1 Knee OA can occur in either compartment of the tibiofemoral joint, but is most common in the medial compartment.2 Knee OA has no known cure, and is one of the most disabling conditions of the elderly population.3 As a result, understanding risk factors associated with knee OA is a high priority. Recent literature suggests that individuals with varus, but otherwise healthy, knees have an increased risk of developing medial knee OA.4 However, the gait mechanics of this at-risk population have not been studied.

Individuals with diagnosed medial knee OA walk with aberrant gait mechanics in the frontal and sagittal planes, including high knee adduction moments and decreased knee flexion.5–7 Altered frontal plane mechanics in the presence of medial knee OA are likely driven by underlying structure. However, altered sagittal plane mechanics are likely compensatory in response to pain and weakness associated with OA.

Varus knee alignment likely influences frontal plane mechanics locally at the knee, distally at the foot, and proximally at the hip. At the knee, a greater adduction moment was reported in individuals with medial knee OA compared to healthy controls.8 This moment increases the risk of disease progression6 and is related to increased radiographic disease severity, as well as greater in vivo medial knee contact forces.9,10 Distally, a structural consequence of varus knee alignment is a deviated tibial mechanical axis from vertical.11 Thus, varus alignment may be associated with compensatory rearfoot pronation to obtain a plantigrade foot. Another possible consequence of varus angulation at footstrike is that the applied force to the ground is directed more medially, resulting in an increased lateral ground reaction force. Finally, varus knee alignment likely induces a more abducted hip, which may alter hip adduction moments and affect pelvic drop mechanics.12,13

Patients with symptomatic medial knee OA often stiffen their knees to reduce the demands on the quadriceps muscles and diminish pain.5,12,14–18 Reduced hip extension angles and moments have also been noted. Stiffer gait patterns lead to greater vertical ground reaction force load rates as well.12 Recently, dynamic joint stiffness, the change in sagittal plane knee moment versus angle during weight acceptance, has been found to relate positively to knee OA disease severity.19

Thus, some abnormal mechanics in individuals with knee OA appear related to malalignment, while others appear compensatory in nature. Those related to alignment should be present in healthy, but varus-aligned knees, and mechanics related to OA impairments should be absent in an asymptomatic individual. Therefore, the aim of this cross-sectional study was to compare gait mechanics between those with varus knee alignment (varus group) and those with normal knee alignment (normal group). We hypothesized that the varus group would ambulate with greater hip abduction, knee adduction, and rearfoot eversion. We also anticipated greater knee and hip adduction moments and greater lateral ground reaction forces. As neither group had symptomatic knee OA, we theorized that sagittal plane joint kinematics, vertical load rates, and dynamic knee joint stiffness would be similar between the groups.

METHODS

An a priori power calculation was performed to estimate the number of subjects needed to ascertain group differences in the variables of interest. Using estimates of variability from
the literature, \( \alpha = 0.05 \), and \( \beta = 0.20 \), we found that 17 subjects per group would be necessary to find group differences.20

All subjects were between 18 to 35 years old with no history of knee pain or injury. Subjects with current or previous ligamentous, meniscal, chondral, patellofemoral, or bony defects that would affect knee function were excluded. All subjects completed the Sports and Recreational Activities subscale of the Knee Injury and Osteoarthritis Outcome Score Knee Survey (KOOS-SR).21 Answers to the five items were based on the previous week. A Likert scoring system, from 0 to 4, quantified the degree of difficulty with each activity. A score of 0 indicated no symptom, and a score of 4 indicated extreme symptoms. Individuals who scored greater than a 2/20 for the subscale were excluded.

The mechanical axes of both tibias (with respect to the vertical) were measured using a caliper-inclinometer device (Acuangle, Isomed, Portland, OR). This measure strongly correlates \( (r = 0.80) \) to frontal plane knee alignment from radiographs.13 Individuals were positioned in tandem stance and instructed to stand with their weight evenly distributed between both feet while maintaining full knee extension. For a single measure, one end of the caliper arms was placed at the most prominent aspect of the tibial tuberosity (Fig. 1); the other end was placed over the neck of the talus. The mechanical axis in the frontal plane was then recorded to the nearest degree. Tibial mechanical axes \( > 10^\circ \) from vertical qualified for the varus group. This value was 1.5 standard deviations above the mean for a normative database of 30 healthy individuals (mean age 26.5 years, mean axis \( 8.0 \pm 1.9^\circ \)) collected in the laboratory. Axes between 7 and 9° (representing \( \pm 0.5 \) standard deviations about the database mean) qualified for the normal group.

Subjects with at least a single limb meeting the above criteria and willing to participate in the study were invited to the Motion Analysis Laboratory at the University of Delaware. Following authorization of informed consent, the height and weight of each subject were recorded. Kinematic and kinetic data during level walking were then collected. The gait mechanics of the more malaligned lower extremity was collected for the varus subjects, and the mechanics of the more normally aligned limb was tested for the normal group. Test limbs were chosen at random for subjects whose alignment was not different bilaterally.

Anatomical markers were placed over the iliac crests, the greater trochanters, the femoral condyles, the tibial plateaus, the malleoli, the first and fifth metatarsal heads, and the distal aspect of the shoe (Nike Air Pegasus, Beaverton, OR). Individual tracking markers were positioned bilaterally on the anterior superior iliac spines and the L5–S1 interspinous space. A cluster of three tracking markers was placed on the rearfoot. In addition, rigid clusters of four markers were placed on the distal posterior shank and the distal postero talateral thigh. Then, a standing calibration trial and a hip motion trial (to establish a functional hip joint center) were collected to establish the pose for the pelvis, thigh, shank, and foot segment coordinate systems.22,23 The anatomical markers were then removed, leaving the tracking markers for the walking trials. The 3D marker trajectories were captured using an eight-camera Vicon motion analysis system (VICON, Oxford Metrics, UK) at rate of 120 Hz. Analog data from a floor-embedded force plate (BERTEC Corp., Worthington, OH) were captured at 1,080 Hz as subjects walked along a 23 m walkway at 1.46 m/s (±2.5%). Walking velocity was monitored with two photoelectric cells linked to a timer. The stance phases of eight usable trials were collected.

A frequency content analysis was conducted to establish a low-pass cut-off frequency that retained 95% of the original power of the signals of interest.24 As a result, a 4th-order, phase-corrected, low-pass Butterworth filter with a cut-off frequency of 8 Hz for the marker trajectory data and 50 Hz for the analog data was used. Visual 3D software (Version 3.91, C-Motion Inc, Rockville, MD) was used for all signal processing and inverse dynamics calculations of joint kinetics. The segments were modeled as frustra of right cones, and the inertial characteristics were derived from established anthropometric data.25 An X-Y-Z Euler rotation sequence was used to derive joint angles. Joint moments were expressed as external moments and normalized to mass (kg) and height (m). Ground reaction forces were normalized to mass (kg). Custom software extracted the discrete variables from the time-series data (Labview 8.2, National Instruments, Austin, TX). These variables were averaged over five trials for each subject. The stance-phase data were time normalized to 100 points to generate ensemble curves.

The kinematic variables of interest included peak knee flexion during early midstance, peak knee adduction, knee flexion at footstrike, peak hip extension, peak rearfoot eversion, and contralateral pelvic drop during early stance. The kinetic variables of interest included peak hip extension and abduction moments, peak knee adduction moment, and the peak knee flexion moment during early midstance. From the force data, peak lateral ground reaction force during loading was extracted, as was the maximum loading rate of the vertical ground reaction force over the first 10% of stance. Dynamic knee joint stiffness during weight acceptance was calculated as the change in sagittal plane moment divided by the change in sagittal plane angle.

Group means and standard deviations were calculated for all variables. Data between groups were analyzed using independent samples t-tests \( (p < 0.05) \).
RESULTS
The groups were similar with respect to age, BMI, and KOOS-SR score (Table 1). The majority of subjects were men, with two women in the varus group and three in the normal group. Average tibial mechanical axis relative to vertical was 11.5° (SD = 0.6°) for the varus group and 7.7° (SD = 0.7°) (p < 0.001) for the normal group.

In the frontal plane, group differences were detected in the expected directions for most variables. At the hip, the peak adduction moments were not different between the groups (p = 0.40). Peak hip adduction angle did not differ between groups (p = 0.41), nor did contralateral pelvic drop (p = 0.77). At the knee, the peak adduction moment was 42% greater in the varus group (p < 0.001) (Fig. 2), and the associated peak knee adduction angle was 5.5° greater (p < 0.001) (Table 2). For the rearfoot, peak eversion angle was about 3° greater in the varus group (p < 0.001) than the normal group. The varus group produced a 51% larger peak lateral ground reaction force after footstrike (p = 0.02) than the normal group (Fig. 3).

For the sagittal plane variables, fewer differences were observed. For the knee, the peak flexion moment during early midstance was 21% greater in the varus group (p = 0.07), and the associated peak knee flexion angle during early midstance was approximately 4° greater (p = 0.03) (Table 2, Fig. 4). However, no difference was found in knee flexion at footstrike. Additionally, no differences were found in the sagittal hip variables, vertical load rate, or dynamic knee joint stiffness.

DISCUSSION
Our overall purpose was to compare selected gait mechanics between young individuals with varus knees and those with normal knee alignment. The mechanics of interest were those previously reported to be altered in people with medial knee OA. Increased knee adduction moment and knee adduction angle were found, along with increased rearfoot eversion. These findings generally supported our expectation that varus knee alignment is largely responsible for the altered frontal plane mechanics associated with medial knee OA. Sagittal plane-oriented variables were similar between groups, with the exception of the increased knee flexion angle and moment. These results again generally supported our hypotheses. The findings also suggest that the stiffer, more extended gait pattern associated with medial knee OA is not necessarily present in individuals with healthy, varus knees who may eventually develop disease.

Previous studies have reported that individuals with medial knee OA ambulate with elevated knee adduction moments and knee adduction angles. As knee adduction moments relate to disease progression, this variable might also relate to disease development. Notably, the average peak knee adduction moment for the varus group in our study was remarkably similar to previously reported values for individuals with medial knee OA. This provides indirect evidence that knee adduction moments are significantly influenced by frontal plane lower extremity structure, regardless of the presence of established medial knee OA.

Frontal plane hip mechanics were similar between the varus and normal groups. This was contrary to our hypothesis that reduced hip adduction is associated with varus knee alignment. Furthermore, Weidow and colleagues reported less hip adduction in individuals with medial knee OA compared to asymptomatic controls. However, individuals with less severe medial knee OA ambulate with similar hip adduction moments as healthy controls, suggesting that those with mild disease have sufficiently strong hip abductor musculature to counterbalance the hip adduction moment. This was likely the case for both groups in the present study, as all subjects were young and healthy.

Increases in peak frontal plane rearfoot angles of 3° were seen in the varus group. This increased eversion is likely a compensation for the greater inclination of the tibia. However, this motion may also help reduce the knee adduction moment. Interestingly, laterally wedged orthoses have the same effect of increasing rearfoot

**Table 1. Subject Demographics for Normal and Varus Knee Alignment Groups**

<table>
<thead>
<tr>
<th></th>
<th>Varus (SD)</th>
<th>Normal (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>23.6 (3.6)</td>
<td>23.8 (4.6)</td>
</tr>
<tr>
<td>Gender (M/F)</td>
<td>15/2</td>
<td>14/3</td>
</tr>
<tr>
<td>Body Mass Index (kg/m²)</td>
<td>23.2 (2.4)</td>
<td>25.4 (5.0)</td>
</tr>
<tr>
<td>KOOS-SR score (0–20)</td>
<td>0.3 (0.6)</td>
<td>0.2 (0.5)</td>
</tr>
<tr>
<td>Tibial Mechanical Axis (degrees)</td>
<td>11.5 (0.6)</td>
<td>7.7 (0.7)</td>
</tr>
</tbody>
</table>

**Figure 2.** Composite group curves of knee frontal plane moment. The error bars above and below the mean at each time point represent the standard deviation.
These orthoses have been shown to reduce the knee adduction moment.

There was a 54% greater peak lateral ground reaction force during early stance in the varus subjects. Mundermann and colleagues also reported a 54% greater peak lateral ground reaction force in their cohort of patients with medial knee OA in comparison to controls. The similarities in these data suggest that differences in mediolateral ground reaction forces may be closely related to frontal plane knee alignment.

Interestingly, the medial-lateral force data demonstrated a lateral bias throughout stance (Fig. 3), suggesting that the varus individuals imparted a more medially directed force to the ground throughout stance, likely a consequence of their more inclined tibias.

Numerous studies reported alterations in sagittal plane knee mechanics in individuals with medial knee OA in comparison to controls. The similarities in these data suggest that differences in mediolateral ground reaction forces may be closely related to frontal plane knee alignment. Interestingly, the medial-lateral force data demonstrated a lateral bias throughout stance (Fig. 3), suggesting that the varus individuals imparted a more medially directed force to the ground throughout stance, likely a consequence of their more inclined tibias.

Table 2. Group Results for Variables of Interest

<table>
<thead>
<tr>
<th>Pelvis/hip</th>
<th>Varus</th>
<th>Normal</th>
<th>p-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contralateral pelvic drop excursion</td>
<td>4.7 (1.0)</td>
<td>4.9 (1.8)</td>
<td>0.772</td>
</tr>
<tr>
<td>Peak extension moment</td>
<td>0.65 (0.15)</td>
<td>0.69 (0.12)</td>
<td>0.396</td>
</tr>
<tr>
<td>Peak adduction moment</td>
<td>0.57 (0.10)</td>
<td>0.55 (0.10)</td>
<td>0.491</td>
</tr>
<tr>
<td>Peak extension angle</td>
<td>18.4 (6.0)</td>
<td>19.5 (6.7)</td>
<td>0.605</td>
</tr>
<tr>
<td>Peak adduction angle</td>
<td>8.5 (2.1)</td>
<td>9.2 (2.9)</td>
<td>0.411</td>
</tr>
<tr>
<td>Knee</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak flexion moment</td>
<td>0.39 (0.11)</td>
<td>0.33 (0.09)</td>
<td>0.067</td>
</tr>
<tr>
<td>Flexion angle (footstrike)</td>
<td>−0.2 (3.5)</td>
<td>−1.1 (3.2)</td>
<td>0.429</td>
</tr>
<tr>
<td>Flexion angle (midstance)</td>
<td>19.1 (4.8)</td>
<td>15.3 (5.0)</td>
<td>0.031</td>
</tr>
<tr>
<td>Flexion excursion</td>
<td>19.3 (4.0)</td>
<td>16.5 (4.8)</td>
<td>0.068</td>
</tr>
<tr>
<td>Peak adduction moment</td>
<td>0.40 (0.06)</td>
<td>0.28 (0.05)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Peak adduction angle</td>
<td>6.4 (2.9)</td>
<td>0.9 (2.1)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Peak internal rotation angle</td>
<td>14.1 (8.2)</td>
<td>12.8 (9.0)</td>
<td>0.662</td>
</tr>
<tr>
<td>Dynamic joint stiffness</td>
<td>0.038</td>
<td>0.037</td>
<td>0.787</td>
</tr>
<tr>
<td>Rearfoot/ground reaction force</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak eversion angle</td>
<td>8.8 (2.3)</td>
<td>5.7 (2.0)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Peak lateral reaction force</td>
<td>0.06 (0.03)</td>
<td>0.04 (0.02)</td>
<td>0.022</td>
</tr>
<tr>
<td>Vertical load rate (maximum)</td>
<td>11.4 (1.8)</td>
<td>10.7 (1.8)</td>
<td>0.303</td>
</tr>
</tbody>
</table>

Angles/excursions in degrees, moments in Nm·kg⁻¹·m⁻¹, stiffness as Nm·kg⁻¹·m⁻¹·degrees⁻¹, forces in N·kg⁻¹, load rate in N·s·kg⁻¹. Data presented as mean (SD); significant results in italics.

Figure 3. Composite group curves of mediolateral ground reaction force. The error bars above and below the mean at each time point represent the standard deviation.

Figure 4. Composite group curves of knee sagittal plane angle. The error bars above and below the mean at each time point represent the standard deviation.
contrary to our expectations, the varus group appeared to ambulate with more knee flexion during early midstance. Additionally, the varus group underwent about 3° greater knee flexion excursion to achieve the greater peak knee flexion, with no differences at initial contact. Greater knee flexion could predispose these varus-aligned knees to problems, as greater knee flexion is associated with greater tibiofemoral loads.27 A potential factor associated with the difference in knee flexion seen in our study is the role of the quadriceps. Perhaps greater quadriceps strength or activation would allow for more knee flexion during weight acceptance. Future studies might consider investigating the role of quadriceps muscle strength and activation in those with healthy, varus knees.

At the hip, those with medial knee OA walk with reduced peak extension angles and extension moments in late stance compared to healthy controls.12,15,16 Healthy older adults also demonstrate this pattern compared to younger individuals.28 In the current study, the varus individuals demonstrated similar sagittal plane peak hip angles and moments in late stance in comparison to the normal group. This suggests that alterations in hip mechanics are secondary to either the aging process or the onset of OA.

Dynamic knee joint stiffness during weight acceptance was similar between groups, despite the increased knee flexion in the varus group. This finding suggests that the stiffer, more extended gait pattern seen in those with medial knee OA is not inherently associated with varus knee structure.19 However, the similarity in stiffness helps to explain the similarity in vertical load rate between the groups. Had there been differences in knee flexion at footstrike, the group with the more extended knee would likely have produced a greater load rate.12

This study has limitations. One limitation was the cross-sectional study design, limiting our ability to infer cause and effect. A longitudinal study of gait mechanics of individuals with healthy, varus knees is warranted. This would help to establish aberrant gait mechanics as risk factors for disease development. Secondly, as radiographs were not obtained, we were unable to confirm that all participants were free of radiographic OA. Some individuals might have had mild radiographic disease without symptoms. Finally, given the large proportion of male subjects in the study, it is difficult to generalize these findings to females with asymptomatic, varus knees. Future studies should recruit these females, as knee OA is more prevalent in women.

In summary, differences were observed between normally aligned and varus-aligned knees in the frontal plane. The knee adduction moment was substantially higher in healthy varus knees and similar to previously reported values for individuals with medial knee OA. These high values support the notion that this moment functions as a causal factor for the onset of OA. Interestingly, the varus group ambulated with greater knee flexion, a somewhat surprising finding as those with established OA typically ambulate with more knee extension. Dynamic knee joint stiffness, however, was similar between groups. Overall, these data suggest that individuals with healthy varus knees exhibit some, but not all, of the altered mechanics seen in medial knee OA.

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