Effect of lower limb malalignment in the frontal plane on transverse plane mechanics during gait in young individuals with varus knee alignment

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A R T I C L E   I N F O
Article history:
Received 20 June 2013
Received in revised form 4 March 2014
Accepted 11 March 2014

Keywords:
Gait analysis
Varus malalignment
Knee osteoarthritis
Knee adduction moment
Internal tibia rotation

A B S T R A C T
Background: Varus knee alignment has been identified as a risk factor for the progression of medial knee osteoarthritis (OA). This study tested the hypothesis that not only frontal plane kinematics and kinetics but also transverse plane lower extremity mechanics during gait are affected by varus malalignment of the knee.

Methods: Eighteen, otherwise healthy children and adolescents with varus malalignment of the knee were studied to examine the association between static varus malalignment and functional gait parameters. Kinematic data were collected using a Vicon motion capture system (Vicon Motion Systems, Oxford, UK). Two AMTI force plates (Advanced Mechanical Technology, Inc., Watertown, MA, USA) were used to collect kinetic data.

Results: The results indicated that changes in transverse plane mechanics occur concomitantly with changes in knee malalignment in the frontal plane. A mechanical consequence of varus knee malalignment is obviously an increased endorotation of the foot (internal foot placement) and an increased internal knee rotation (tibia rotation) during stance phase. The linear correlation between the maximum external knee adduction moment in terminal stance and the internal knee rotation in terminal stance (r = 0.823, p < 0.001) shows that this transverse plane gait mechanics is directly in conjunction with intrinsic compressive load on the medial compartment during gait.

Conclusions: Understanding factors that influence dynamic knee joint loading in healthy, varus malaligned knees may help us to identify risk factors that lead to OA. Thus, three-dimensional gait analysis could be used for clinical prognoses regarding the onset or progression of medial knee OA.

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1. Introduction
Mechanical factors, such as varus malalignment of the knee in the frontal plane, have been implicated in the progression of medial knee OA [1–6]. A recent study by Hayashi et al. [6] has shown that varus knee alignment is associated with increased risk of incidence and enlarging bone marrow lesions. Quantitative gait analysis as an adjunct to static radiographic measures of alignment provides an estimate of tibiofemoral load through an inverse dynamic analysis and can be used to gain a better understanding of the biomechanical factors that contribute to the pathogenesis of knee OA [7,8]. The external knee adduction moment is used as the primary parameter for characterizing intrinsic compressive load and articular cartilage degeneration in the medial knee compartment during gait [4,5,9,10].

Previous studies have investigated biomechanical changes during gait in the sagittal and frontal planes in patients with knee OA compared to healthy controls [5,11,12]. For example, patients with medial knee OA make initial contact with the ground with the knee in a more extended position and have a smaller range of knee flexion during the stance phase of walking [11]. However, these studies on patients with established knee OA have made it difficult to determine if biomechanical changes are involved in the development of disease, are in response to degenerative changes in the joint, or are compensatory mechanisms in response to these degenerative changes or to joint pain.

In children and adolescents with varus malalignment of the knee without signs of knee OA abnormally increased knee internal rotation and hip external rotation moments were detected [13]. While transverse
plane mechanics can initiate degenerative changes to the articular cartilage and have been implicated in the progression of knee OA [10], there is a lack of research on the relationship between static varus malalignment of the knee and transverse plane lower extremity mechanics during gait. In particular, it is still not known which role the rotational gait profile plays in the progression of knee OA. The purpose of the present study was therefore to investigate the effect of pathological varus alignment of the knee on transverse plane gait parameters of the lower extremity in young individuals without signs of knee OA. The following question should be answered and may have important implications for the progression of knee OA: Does a relationship exist between static lower extremity malalignment in the frontal plane and transverse plane lower extremity mechanics during gait? We hypothesized that (1) the static varus alignment of the knee correlates with internal knee rotation (tibial rotation) and endorotation of the foot (internal foot placement) during the stance phase of gait, and (2) the rotational gait profile has an influence on the external knee adduction moment and thus also leads to degenerative changes in the knee joint in young patients with varus malalignment of the knee.

2. Methods

2.1. Subjects

Eighteen, otherwise healthy children and adolescents with varus malalignment of the knee 12–19 years of age were consecutively selected during clinical visits between January 2008 and October 2012 (Table 1). Solely patients were included with a clinical indication for a full-length standing anteroposterior radiograph and a pathological varus alignment of at least one knee according to the mechanical axis angle (MAA) of the lower limb [14]. Alignment was defined as pathological varus when the angle was more than 1.3° [14]. Patients were excluded if they had signs of OA or rheumatoid arthritis, anterior cruciate ligament (ACL) deficiency, neuromuscular dysfunction, achondroplasia, sagittal or transverse plane deformities of the leg, flexion contractures in the knee or hip joint, leg length discrepancy of more than 1 cm, avascular necrosis, history of major trauma or a sports injury of the lower extremity, knee surgery within the last 12 months, chronic joint infection, intraarticular corticosteroid injection, or morbid obesity according to the body mass index [15].

Fifteen healthy subjects were recruited as control group (Table 1). All subjects had undergone a clinical examination, including passive hip, knee and ankle range of motion (Table 1). The patients and the healthy subjects had normal strength and full range of motion in the lower extremities.

All subjects, and their parents in the case of subjects under age 18, were thoroughly familiarized with the gait analysis protocol. Subjects 18 and over gave written informed consent. Subjects younger than 18 gave verbal assent to study participation, and their parents provided written informed consent to participate in this study, as approved by the local ethics committee and in accordance with the Helsinki Declaration.

2.2. Gait analysis methods

Three-dimensional gait analysis was carried out using a Vicon motion capture system (Vicon Motion Systems, Oxford, UK) operating at a sampling rate of 200 Hz (Fig. 1). The level walkway was 15 m long and viewed by eight infrared cameras. Two AMTI force plates (Advanced Mechanical Technology, Inc., Watertown, MA, USA) were situated at the mid-point of the walkway to collect kinetic data at 1000 Hz.

To improve the reliability and accuracy when analyzing frontal and transverse plane gait data, a custom made lower body protocol described in a previous investigation [16] was used. In addition to the standardized Helen Hayes marker set [17], reflective markers on the medial malleolus, medial femoral condyle and major trochanter were applied to determine positions of joint centers of rotation for the hip, knee and ankle. In contrast to the Helen Hayes marker set [17], the centers of rotation for the knee and ankle joints were defined statically as the midpoint between the medial and lateral femoral condyle and malleolar markers. This eliminates the reliance on the subjective palpation of the thigh and tibia wand markers, which is difficult to handle and less reliable within or between therapists than manual palpation [18]. The center of the hip joint was calculated using a geometrical prediction method [17]. The major trochanter marker was used to improve the prediction of the hip joint center by immediately calculating the distance between the anterior superior iliac spine and the major trochanter by anatomical landmarks [16]. Varus/valgus alignment of all knee joints was determined by rotating the local shank coordinate system about the y-axis of the thigh (vector from the lateral knee to the medial knee) until the x-axis of the Shank (vector from the knee center to the ankle center) fell in line with the x-axis of the thigh (vector from the knee center to the hip center). According to Hunt et al. [7] using the same marker set for a similar purpose, this varus angulation provided an accurate, marker-based measure of lower limb alignment in the frontal plane. It has been shown that adding these few extra markers to the standard Helen Hayes marker set increases the repeatability in three-dimensional gait analysis, reduces the measurement errors when analyzing frontal and transverse plane gait data, and improves the accuracy of the knee joint axis by reducing the knee axis cross-talk phenomenon [16,19,20]. Furthermore, our lower body protocol enables the detection of significant effects in the tibiofemoral angles and moments in the frontal and transverse plane between three different patterns of movement [21]. Further processing incorporating force plate data allowed external moments (normalized to body weight) about the mathematically derived joint centers to be calculated.

Discrete variables of interest (Table 2) were calculated for five barefoot trials at a self-selected speed and then averaged for further analysis on the basis of complete marker trajectories and a clear foot-forefoot contact. In the case of bilateral involvement, measurements were performed only on the limb with greater malalignment. This ensures that the statistical calculations were independent from each other. No significant differences were found in the discrete variables of interest comparing the left and right sides in the control group. Therefore, only one side — the left side was chosen here — was used for further analysis of the controls.

After each acquisition session, missing frames were handled with a fill-gap procedure using the Vicon-Nexus software version 1.7.1 (Vicon Motion Systems, Oxford, UK). The data were smoothed with a Woltring filter and using a smoothing spline [22]. The external knee adduction moment as well as the transverse plane gait parameters during stance phase were automatically determined by a custom made algorithm in Matlab 7.12.0 (The MathWorks, Inc., Natick, MA).
According to Perry [23], loading response was defined as a subphase of the gait cycle, i.e. 2–12% of the gait cycle. This phase follows the initial contact of the foot with the floor and continues until the contralateral limb is lifted for swing. Mid stance (12–31% of the gait cycle) begins as the contralateral foot is lifted and continues until body weight is aligned over the forefoot. Terminal stance (31–50% of the gait cycle) begins with heel rise and continues until the contralateral foot strikes the ground. To determine the foot progression angle, the angle of the long axis of the foot segment in the global (lab) coordinate system relative to the walking directions axis was computed.

2.3. Radiographic methods

Radiographic assessment of lower limb alignment was conducted on the same day as the gait analysis. Patients stood barefoot in a forward knee position with the patella centered over the femoral condyles and feet straight ahead to control for any foot rotation effects [24] and to attain a true full-length weight bearing anteroposterior radiograph [25]. On each radiograph, the joint centers of the hip, knee, and ankle were identified. In accordance with Miyazaki et al. [4], Hunt et al. [7], and Mundermann et al. [8] using the same method for a similar purpose, the MAA of the lower extremity was used to quantify alignment in the frontal plane and obtained with the analysis software Diagnostix-32 (Gemed) by the same investigator. Alignment was measured as the angle formed by the line from the femoral head center to the femoral intercondylar notch center and the line from the ankle talus center to the center of the tibial spine tips. In accordance with the study of Specogna et al. [26], reliability of MAA measurements was high (ICC = 0.97). The MAA measured from standing radiographs uses therefore the same landmarks and definitions like the marker-based three-dimensional gait analysis to measure lower limb alignment in the frontal plane. This enables comparison between these two measurements and can be used as quality assurance of the marker-based lower body protocol.

2.4. Statistical analysis

The normal distribution of the present sample was confirmed using the Kolmogorov–Smirnov test. Means and standard deviations of the variables of interest were calculated. Simple linear regression (Pearson product–moment correlation coefficient; r) was used to examine the association between static varus malalignment and gait parameters as well as between the MAA measured from standing radiographs and the static lower limb alignment measurements in the frontal plane based on reflective markers. The significance level adopted in this study was set at p < 0.05. We interpreted correlation values below 0.30 as low, between 0.30 and 0.65 as medium, and correlations above 0.65 as high [27]. Differences between groups were tested for significance using a Student's t-test. The statistical calculations were carried out using the SPSS version 18.0.0 (Chicago, IL, USA). Post hoc power calculations were determined with the analysis software R (package pwr, version 1.1.1) and according to Cohen [27].

3. Results

Subject group characteristics are summarized in Table 1. No significant differences were observed across groups for self-selected walking speed, passive hip rotation, passive tibial torsion and anthropometric parameters. Post hoc power calculations revealed that a sample size of 18 patients provides 80% power for detecting a correlation coefficient between the MAA and frontal/transverse plane kinematic and kinetic parameters as small as r = 0.62 (p = 0.05, two sided). Fig. 2 shows a strong linear relationship (r = 0.834, p < 0.001, power = 100%) between the MAA measured from standing radiographs and the static lower limb alignment measurements in the frontal plane based on reflective markers and the gait analysis system. Linear correlations between the MAA measured from standing radiographs and gait parameters in the transverse plane are presented in Table 2. High correlations with increased internal knee rotation (tibia rotation; r = 0.696, p = 0.004, power = 88%) and medium correlations with increased endorotation of the foot (internal foot placement; r = 0.584, p = 0.022, power = 74%) during the stance phase of gait were detected. Regarding the kinetic data, significant, high linear correlations with the static MAA are shown for the maximum internal knee rotation moment in terminal stance (r = 0.690, p = 0.007, power = 87%) and the maximum external hip rotation moment in loading response/mid stance (r = −0.661, p = 0.007, power = 87%).

Furthermore, the maximum external knee adduction moment in terminal stance was linearly correlated with maximum internal knee rotation (r = −0.623, p < 0.001, power = 94%) in terminal stance and maximum internal hip rotation during stance phase (r = −0.742, p = 0.002, power = 90%). Differences between the patient and control groups are shown in Fig. 3. Patients with varus malalignment of the knee were walking with a significantly increased endorotation of the foot compared to healthy controls. A post hoc power calculation revealed that the difference in maximum foot endorotation between our study groups (18 patients, 15 controls) has a power of 95%.

Table 2

<table>
<thead>
<tr>
<th>Joint Parameter</th>
<th>r</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angles (°)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Foot Max. endorotation stance phase</td>
<td>0.584</td>
<td>0.022</td>
</tr>
<tr>
<td>Knee Max. internal rotation terminal stance</td>
<td>0.696</td>
<td>0.004</td>
</tr>
<tr>
<td>Hip Max. internal rotation stance phase</td>
<td>−0.459</td>
<td>0.085</td>
</tr>
<tr>
<td>Moments (nm/kg)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Knee Max. internal rotation terminal stance</td>
<td>0.660</td>
<td>0.007</td>
</tr>
<tr>
<td>Hip Max. external rotation loading response/mid stance</td>
<td>−0.661</td>
<td>0.007</td>
</tr>
<tr>
<td>Max. internal rotation terminal stance</td>
<td>0.040</td>
<td>0.986</td>
</tr>
</tbody>
</table>

Internal rotation is positive; external rotation is negative.
4. Discussion

The primary objective of the present study was to investigate the correlation between static varus malalignment of the knee and dynamic measures of the lower extremity during gait in the transverse plane. The results suggest that a linear association exists between lower extremity varus malalignment and an increased endorotation of the foot as well as an increased maximum internal knee rotation (tibia rotation). Patients with varus malalignment of the knee showed a significantly increased internal foot placement (9.0°) during stance phase compared to the control subjects without varus malalignment (1.3°), which could be caused by the tendential increased tibia rotation in the patient group (7.9°) compared to the control group (3.7°). Due to the fact that the passive hip rotation and passive tibial torsion were not significantly different between groups (Table 1), the observed differences in transverse plane rotations during gait may either be a potential gait mechanism to compensate for excessive varus malalignment of the knee or essential in response to the altered MAA. As a result, this modified gait pattern in patients with varus malalignment may explain the increased internal knee rotation moments compared to normally aligned controls in a previous study [13]. Astephen et al. [28] also reported a greater knee internal rotation moment coupled with a net hip external rotation moment in patients with knee OA compared to a healthy control group.

Regarding the accuracy of three-dimensional gait parameters, the strong linear relationship between the MAA (radiologically) and the MAA (based on reflective markers) suggests the suitability of the used marker-based lower body protocol to analyze patients with varus malalignment of the knee. No significant differences were observed between patients and controls for self-selected walking speed. Thus,
differences in gait patterns could not be attributed to differences in walking speed.

The external knee adduction moment was linearly correlated with internal knee (positive correlation) and hip rotation (negative correlation) during the stance phase. This suggests that transverse plane gait mechanics in patients with varus malalignment of the knee but no signs of knee OA are directly in conjunction with the external knee adduction moment which is a contributing factor to articular cartilage degeneration and disease progression in the medial knee compartment [4,5,9,10] (second part of the hypothesis). This assumption is confirmed with the studies of Davids et al. [29] and MacWilliams et al. [30] that demonstrated that an increased knee rotation in children with symptomatic intoeing gait leads to an increased knee adduction moment in the coronal plane during the stance phase of gait. These findings lead to the conclusion that transverse plane bone morphology is associated with coronal knee loading during gait, which may have important implications for the progression of OA in this patient group. It has been suggested that changes in transverse plane mechanics at the knee can initiate degenerative changes by placing altered loads on regions of the articular cartilage that were previously conditioned for different load levels [10]. Internal tibia rotation is thought to increase compressive shear loading in the medial compartment of the knee [31] and strong associations have been shown between the foot progression angle and medial knee loading [9, 29, 30, 32]. In particular, internal foot placement shifts the loads more onto the knee’s medial compartment [9,29,30], which may create an uncomfortable environment in the knee joint. Studies of patients with ACL injury support the observation that rotational changes are a major factor in the progression of knee OA [33–35]. In ACL deficient knees, the tibia remained internally rotated throughout the stance phase compared to the control limb. This offset led to loading of cartilage regions not typically loaded prior to the ACL injury (for an overview see e.g., Vincent et al. [35]). In addition to the varus malalignment of the knee, we believe therefore that the transverse plane gait mechanics in the analyzed patient group later lead to increased ligament forces and degenerative changes in the knee joint.

However, our results should be treated with some caution. Due to the small sample size, some results of the present study may be underpowered and the results could be significant with greater sample sizes. Further studies with an enlarged sample size should also investigate the effect of surgical interventions to correct excessive varus alignment, especially on transverse plane mechanics during gait. If a preoperatively increased internal knee rotation were not reduced after surgery, the correction of the rotational gait profile should be taken into account for surgical planning of varus knees in young patients. Davids et al. [29] and MacWilliams et al. [30] have shown that the correction of the pathologically increased internal knee rotation by rotation osteotomy normalized the knee adduction moment. A non-invasive gait modification to reduce the knee adduction moment is a toe out foot position [9, 36]. This mechanism of gait compensation reduces the moment arm length of the net ground reaction force vector with respect to the knee joint center in the frontal plane and shifts the load onto the non-diseased compartment. This may also help to reduce the knee adduction moments at this early stage and could be a potential strategy to slow disease progression and delay the evolution of later medial knee OA [4].

Understanding factors that influence dynamic knee joint loading in healthy, varus malaligned knees may help us to identify risk factors that lead to OA. Recent literature has been shown that the amount of varus thrust measured quantitatively using skin markers correlates with X-ray joint degeneration and thus appears to offer a simple dynamic assessment of knee OA severity in clinics [37]. Clinical gait analysis is therefore a powerful tool for clinical prognoses regarding the onset or progression of medial knee OA. Nevertheless, to understand the complexity of knee OA and to develop earlier and more appropriate treatment strategies for the disease will require continued study on the interrelationships between risk factors for the disease and appropriate models of disease progression.

In conclusion, the results of the present study indicated that biomechanical changes in the transverse plane occur concomitantly with changes in knee malalignment in the frontal plane independent from the presence of knee OA. A mechanical consequence of varus knee malalignment is obviously an internal foot placement and an internal knee rotation in conjunction with an increase of the internal knee rotation moment and external knee adduction moment during the stance phase of gait. Therefore, varus malalignment of the knee should not be viewed as an isolated problem in the frontal plane.

Conflict of interest statement

The authors disclose any financial and personal relationships with other people or organizations that could inappropriately influence their work.

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