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TIBIOFEMORAL KINEMATICS AND CONDYLAR MOTION DURING THE STANCE PHASE OF GAIT

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Abstract

Accurate knowledge of the dynamic knee motion in vivo is instrumental for understanding normal and pathological function of the knee joint. However, interpreting motion of the knee joint during gait in other than the sagittal plane remains controversial. In this study, we utilized the dual fluoroscopic imaging technique to investigate the six-degree of freedom kinematics and condylar motion of the knee during the stance phase of treadmill gait in eight healthy volunteers at a speed of 0.67m/sec. We hypothesized that the 6DOF knee kinematics measured during gait will be different from those reported for non-weightbearing activities, especially with regards to the phenomenon of femoral rollback. In addition, we hypothesized that motion of the medial femoral condyle in the transverse plane is greater than that of the lateral femoral condyle during the stance phase of treadmill gait. The rotational motion and the anterior-posterior translation of the femur with respect to the tibia showed a clear relationship with the flexion-extension path of the knee during the stance phase. Additionally, we observed that the phenomenon of femoral rollback was reversed, with the femur noted to move posteriorly with extension and anteriorly with flexion. Furthermore, we noted that motion of the medial femoral condyle in the transverse plane was greater than that of the lateral femoral condyle during the stance phase of gait (17.4±2.0 mm vs. 7.4±6.1 mm, respectively; $p<0.01$). The trend was opposite to what has been observed during non-weightbearing flexion or single-leg lunge in previous studies. These data provide baseline knowledge for the understanding of normal physiology and for the analysis of pathological function of the knee joint during walking. These findings further demonstrate that knee kinematics is activity-dependent and motion patterns of one activity (non-weightbearing flexion or lunge) cannot be generalized to interpret a different one (gait).

INTRODUCTION

Accurate knowledge of six degree-of-freedom kinematics (*6DOF*) and condylar motion is critical for full comprehension of physiological knee joint motion - baseline knowledge which could be used for the analysis of various pathologies and their treatments. However, interpreting knee joint motion during gait in other than the sagittal plane remains challenging. The reported data on angular and linear motions in the transverse and coronal plane vary in

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Conflict of Interest Statement
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terms of magnitude and direction and it is unclear what constitutes the physiological motion of the knee in *6DOF*.[1–8] Several investigators raised concerns that most kinematic data on the lower extremity have been obtained from methods which include errors due to skin and soft tissue motion.[1,3,9] At the knee joint, this can particularly affect the measurement of more subtle movements such as internal-external rotation, abduction-adduction or mediolateral translation. New techniques have been introduced to measure the motion of the knee during walking.[2,9,10] These studies significantly improved the measurement accuracy of knee joint motion. However, a considerable controversy remains. Some studies reported external femoral rotation during the stance phase of gait[1,2,9] and also found the center of knee rotation in the transverse plane to be located predominantly on the lateral side of the joint.[11] These findings suggest that the medial femoral condyle should make greater excursions than the lateral femoral condyle, being further away from the center of rotation. However, this is in contrast to the current contention that the medial femoral condyle is less mobile than the lateral femoral condyle.[12–22]

Recently, we validated the dual fluoroscopic imaging system (DFIS) for the measurement of dynamic knee joint motion.[23] In this study, we utilized the DFIS technique to investigate the *6DOF* kinematics of the knee during the stance phase of gait on a treadmill. We hypothesized that the *6DOF* knee kinematics measured during gait will be different from those reported for non-weightbearing activities especially with regards to the phenomenon of femoral rollback. Furthermore, motion of the medial femoral condyle in the transverse plane is greater than that of the lateral femoral condyle during the stance phase of treadmill gait.

MATERIAL AND METHODS

Eight healthy subjects, six males and two females, aged 32 to 49 years, with average body mass index (BMI) of 23.5 kg/m^2 were recruited for this study. The subjects had no history of knee injury, surgery or systemic disease. Knee pathology was also ruled out upon physical and radiographic (MRI and X-ray) examination. The study was approved by our Institutional Review Board, and written consent was obtained from all study participants.

First, each knee (five left and three right) was scanned in a relaxed extended position using a 3-Tesla scanner (MAGNETOM Trio®, Siemens, Erlangen, Germany) and a double-echo water excitation sequence (Figure 1A). The images were then used to create 3D computer models using a solid modeling program (Rhinoceros® version 4.0, Robert McNeel & Associates, Seattle, WA). Next, dual fluoroscopic imaging system (DFIS) setup, previously validated for treadmill gait analysis,[23,24] was used to determine knee kinematics during the stance phase of gait (Figure 1B). The subject practiced the gait on the treadmill for one minute at a treadmill speed of 1.5 miles per hour (MPH) i.e. 0.67 m/s. Two thin pressure sensors (Force Sensor Resistor (FSR), Interlink Electronics Specifications, Camarillo, CA) were fixed to the bottom of each shoe, recording the heel strike and toe-off of the studied as well as the contralateral foot. Two laser-positioning devices, attached to the fluoroscopes, helped to align the target knee within the field of view of the fluoroscopes during the stance phase. During this adjustment the subject's natural gait and stride length were not altered as the subject's position was only adjusted in anteroposterior and mediolateral direction. The knee was then imaged during three consecutive strides at a frame rate of 30 Hz.

After testing, the fluoroscopic images were imported into the modeling software and placed in calibrated planes to reproduce the geometry of the fluoroscopes during the testing. The 3D MR-based knee model was also imported into the software and manipulated in *6DOF* until the projections of the model matched the outlined silhouettes of the bones captured on the two fluoroscopic images (Figure 2). This process was repeated at each 10% of the stance phase starting from heel strike until the series of knee models reproduced the motion of the subject's knee during the entire stance phase.

The kinematics was measured using a joint coordinate system based on the transepicondylar axis of the femur (Figure 3). Next, we measured the motion of medial and lateral femoral condyle with respect to the tibia using both, the transepicondylar and the geometric center axis (Figure 3).[25] A center of each condyle was determined on the transepicondylar axis of the femur and on the geometrical center axis of the femur.[25] The geometric center axis was constructed by fitting circles to the medial and lateral condyles and by connecting the centers of these circles with a line.[25,26] Subsequently, two points were selected on each axis, representing the center of the medial and lateral condyle.[25] The condylar centers were then projected onto the transverse plane of the tibial coordinate system and the anteroposterior distance was measured as the perpendicular distance of the projected condylar center from the mediolateral tibial axis.

The *6DOF* kinematics of the knee was averaged among all subjects during the stance phase of gait. The correlation between the flexion-extension motion of the knee and motion in other degrees of freedom was analyzed using a square of the Pearson product moment correlation coefficient (r^2). A paired Student t-test was used to compare the range of motion of the medial and lateral condyles in the transverse plane. The level of significance was set at $p<0.05$.

RESULTS

Tibiofemoral kinematics

The predominant motion of the knee during the stance phase of gait occurred in the sagittal plane (Figure 4). The knee was extended at heel strike, flexed during loading response and reached the first flexion peak of about 8° during early midstance. Thereafter, the knee begun to extend until about 40% of stance phase and remained in slight hyperextension (average 3.5°) throughout midstance. Approximately halfway through the terminal stance the knee was observed to flex again and the flexion continued throughout the pre-swing and peaked at toe-off when the stance phase ended. The magnitude of this second flexion peak was on average 36°.

The axial rotation of the knee (internal-external) showed similar pattern to the flexion-extension (r^2=0.53). The motion was determined as the motion of femur with respect to the tibia. At heel strike the femur was found to be internally rotated on average 1.6°. The femur then rotated externally and reached the first peak of external rotation (average 5°) shortly after opposite toe off i.e. in early midstance. Direction of the axial rotation was then reversed and the femur was noted to rotate internally throughout midstance until early terminal extension when the rotation reversed again. During the terminal extension and pre-swing the femur rotated externally until it reached the second maximum of external rotation at toe-off (average 7.4°).

The average magnitude of knee motion (femur relative to tibia) in the coronal plane was 3.7° and the pattern was also moderately correlated with that of flexion-extension (r^2=0.56). At heel strike the knee was on average in 3.2° of valgus and rotated slightly into further valgus during the loading response (4.1°). At early midstance the direction of this rotation reversed again and the knee rotated back towards varus until about 40% of the stance phase. Thereafter, the knee remained in about 3° of valgus until 70% of the stance phase (terminal extension) when it started to rotate into valgus again. At toe-off the knee joint was in 5.7° of valgus.

The pattern of anteroposterior shift (femur relative to tibia) also followed that of flexion-extension (r^2=0.79). We noted that at heel strike the femur was 2.6 mm posterior to the tibia.

The femur then shifted anteriorly during loading response and reached the first peak of anterior shift during early midstance. At this point the femur was on average 0.1 mm posterior to the tibia. The femur then begun to shift back posteriorly during the midstance. The posterior motion peaked at 50% of stance when it was 4 mm posterior to the tibia. Thereafter its direction reversed and the femur was shifting anteriorly until toe-off when it reached the second maximum and was on average 2.5 mm anterior to the tibia. Therefore, the average excursions in the anteroposterior directions during stance phase were approximately 5 mm.

With regard to the mediolateral motion of the knee (femur relative to tibia), we noted that an initial lateral shift of the femur was followed by medial motion that peaked before toe-off. At heel strike the center of the femur was oriented 3.2 mm laterally with respect to the tibial center. Afterwards, the femur moved laterally during the loading response until early midstance and reached the maximum at 5.2 mm. The direction of the mediolateral motion was then reversed and the femur moved medially until 80% of stance phase when the center of the femoral coordinate system was 1.1 mm lateral to the tibial one. Thereafter, the femur started to shift medial again towards its position at heelstrike. The average mediolateral displacement measured was 4.1 mm.

Finally, motion of the femur with respect to tibia in the proximal-distal direction was on average 2 mm with amplitudes occurring at 20% and 80% of stance phase.

Condylar motion

When measured with the transepicondylar axis of the femur, the range of motion of the medial condyle in the anteroposterior direction (9.7±0.7 mm) was significantly greater than that of the lateral condyle (4.0±1.7 mm, $p<0.01$) and both followed the pattern of anteroposterior motion of the tibiofemoral joint. At heel strike, the medial and lateral condyles were located 3.3±1.1 mm and 1.9±1.0 mm posterior to the mediolateral axis of the tibia, respectively. The anterior motion of the medial condyle during the first half of stance phase peaked at about 20% of stance phase, and the medial condyle then moved posteriorly. The anterior motion of the lateral condyle reversed its direction earlier in the stance phase than the medial condyle (at about 10% of stance). After reaching the first anterior peak, both the medial and the lateral condyles shifted slightly posteriorly to 3.3±0.5 and 2.9±0.8 mm at 50% of stance, respectively. Thereafter, the condylar shift was minimal until 75% of stance when both condyles moved anteriorly again until toe-off when the medial condyle was 5.3 anterior and the lateral condyle 0.7 mm posterior to tibia (Figure 5).

Condylar motion demonstrated similar trends when measured with the geometrical center axis. Again, in the anteroposterior direction, the excursions of medial condyle (17.4±2.0 mm) were greater than those of lateral condyle (7.4±6.1 mm, $p<0.01$). At heel strike the position of the medial and lateral condyle was 9.3±2.9 and 6.6±3.2 posterior to the mediolateral axis of the tibia. Thereafter, the lateral condyle shifted anteriorly: the lateral condyle to 5.8±3.4 posterior at 10% of the stance phase and the medial condyle to 2.6±2.3 posterior at 20% of the stance phase. Both condyles then translated posteriorly to about 40% of stance phase and minimally thereafter until 75% of stance when anterior shift was initiated again, peaking at toe-off (Figure 6).

DISCUSSION

Accurate knowledge of *6DOF* knee kinematics is important in the context of providing new information on the function of the knee which can be further utilized to improve current treatments of knee pathology. In this study we applied an innovative technique utilizing MR imaging, dual fluoroscopy and advanced computer modeling to investigate the kinematics of knee joint during the stance phase of treadmill gait. The results confirmed our hypotheses that the patterns of motion were different from those reported in non-weightbearing activities. We found that the knee showed consistent patterns in all rotations and translations. The internal-external rotation, varus-valgus rotation, as well as anterior-posterior translation showed a clear relationship with the pattern of flexion-extension. Furthermore, we noted that excursions of the medial femoral condyle in the anteroposterior direction were greater than those of the lateral femoral condyle.

Although human gait is the most commonly studied activity in musculoskeletal research, little data is available on the *6DOF* tibiofemoral kinematics during gait. In the literature, the flexion-extension pattern is consistent across the reported studies showing two flexion and two extension peaks during the stance phase.[1–8] The first flexion peak occurs in early midstance and the second at toe-off. However the data in the literature vary when describing knee motion in the other degrees of freedom.[1–8]

In our study, the patterns of rotations as well as anteroposterior translation closely followed that of flexion-extension. We observed the femur to rotate externally after heel strike and further externally towards toe-off. Similar trend has been noted by Lafortune et al.[2] who studied the tibiofemoral kinematics during gait by means of intracortical traction pins placed in the femur and tibia in five healthy volunteers. Later, Andriacchi et al.[9] corroborated those findings using the point cluster technique. Both studies reported external rotation of the femur during the stance phase and offered an explanation that it is caused by forces generated by muscle contraction as well as the inertia of the upper body rotating the femur externally while the foot is planted on the ground. There was a slight difference from our data in that we observed internal rotation following the first peak of external rotation corresponding to the first flexion during midstance. This internal rotation, reported also in several other studies,[27–31] can be caused by the action of quadriceps, especially vastus medialis, extending the knee during this part midstance after it has reached the first peak of flexion.[28,32–35]

The literature is also inconsistent with respect to the abduction-adduction motion. Some studies report the knee to rotate into varus[9,27–30] during the stance phase while others found valgus rotataion[2,7,8]. We noted two abduction peaks following the pattern of flexion-extension. The abduction of the knee seems paradoxical since the ground reaction force exerts adduction moment on the knee during the stance phase.[36–38] Therefore, muscle forces must drive this motion, otherwise the knee would move into adduction under the external varus moment. Electromyographic studies have shown that the peak of quadriceps activity corresponds to the contralateral toe off (the end of loading response) and precedes the first flexion and abduction peak.[28,32–35] The maximum of gastrocnemius activity, on the other hand, corresponds to contralateral heel strike (beginning of pre-swing) which is followed by the second flexion and abduction peak at ipsilateral toe off.[32,35,39] Shelburne et al.[32] investigated the contribution of muscles and ligaments to the stability of the knee during gait and demonstrated that muscles that contribute most to forward propulsion (quadriceps and gastrocnemius) also have the greatest contribution to the stability in the coronal plane by resisting the adduction moment. Therefore, the muscles that are active most during the two peaks of knee flexion can at the same time abduct the knee.[40–43]

Motion of the knee in the anteroposterior direction was most closely correlated with the flexion-extension during the stance phase. This coupling of motion has been previously reported by Lafortune et al.[2] and also by Dyrby et al.[1] They observed that the femur moves anteriorly twice during the stance phase along with knee flexion and explained that at heel strike the more posterior position of the femur corresponds to the extensor mechanism pulling on the tibia. During loading response the breaking action of the tibia causes the femur to slide forward as the knee flexes. Later during midstance, as the knee extends back, the contraction of quadriceps causes the femur to shift posteriorly. During terminal extension and pre-swing the center of gravity moves forward, the gastrocnemius fires, and the femur slides anteriorly on the tibia, again. Additionally, we observed that the phenomenon of femoral rollback, described during non-weightbearing activities and weight-bearing single leg lunge, was reversed since with flexion of the knee the femur moved anteriorly and vice versa.

The mediolateral motion did not follow the trend of flexion-extension. The femur was found to shift laterally during the first half of the stance phase and medially in the later half. This observation is in agreement with the study of Lafortune et al.[2] who found similar pattern of mediolateral motion during the stance phase. The initial lateral shift of the femur can be attributed to the center of gravity moving laterally as the weight is transferred from double to single leg support with the tibia planted on the ground. In the second half of the stance phase the body weight is transferred back to double leg support and towards the contralateral leg causing the femur to move medially.

An interesting finding of this study is that motion of the lateral femoral condyle in the transverse plane is less than the motion of its medial counterpart as measured using both, the transepicondylar and the geometric center axes. In contemporary orthopedic literature the medial femoral condyle is described as less mobile and more conforming.[12–22] This contention is based on numerous studies which investigated the condylar motion and tibiofemoral contact mechanics during weightbearing lunge[12–14,19,22,44] or non-weightbearing[20,21] flexion and all found the motion of the medial condyle in the transverse plane to be of smaller magnitudes.[3] However, there are very few data on the condylar motion during gait. Komistek et al.[10] studied condylar motion during gait using single plane fluoroscopy and reported the excursions of the lateral femoral condyle in the transverse plane to be greater than those of the medial condyle, confirming the findings observed during single leg lunge and non-weightbearing flexion. More recent gait studies, however, are suggesting the contrary. Koo and Andriacchi observed that the center of rotation of the knee is on the lateral side of the joint for the most part of the stance phase.[11] This suggests that the medial condyle is located further away form the center of rotation and therefore its motion in the transverse plane is greater. Our study corroborated the findings of Koo and Andriacchi[11] by showing that the medial condyle makes greater excursions in the transverse plane than the lateral femoral condyle. These findings demonstrate that knee kinematics is activity dependant and motion patterns of one activity (non-weightbearing flexion or lunge) cannot be generalized to interpret a different one (e.g. gait).

Several limitations of this study should be noted. The knee kinematics was studied during treadmill gait, not during overground walking. It has been shown in the literature that treadmill gait can differ from overground gait in several biomechanical parameters.[34,45–47] However, recently it has been demonstrated that in healthy individuals the differences in kinematics are minimal and the overall patterns of these two behaviors are similar.[48] Another limitation is the relatively slow walking speed (0.67 m/sec) which might have had an effect on the amplitude of the kinematic parameters. However, the measured kinematic patterns compare favorably with those reported in other studies which utilized video gait analysis and frame rates >60 Hz. Further, we only investigated the kinematics during the stance phase. The swing phase was not studied because due to the limitation of our DFIS it is difficult to capture the entire motion path of the knee within the common field of view of the two fluoroscopes during the entire stride. In addition, we did not investigate the kinematics of both knees of each subject since this would double the radiation exposure to the study participants. However, despite the abovementioned limitations, this technique has several advantages. It is accurate, non-invasive and does not require placement of external devices or markers on the knee that could potentially interfere with its natural motion. Furthermore, the system can be assembled using any two commercially available fluoroscopes. In the future, this technique could provide information on the in-vivo motion of the knee, valuable for understanding various types of knee pathology and evaluate effectiveness of reconstructive procedures for ligamentous injuries.

In conclusion, this study investigated the *6DOF* tibiofemoral kinematics and condylar motion of the normal knee during the stance phase of treadmill gait using MR imaging, DFIS and advanced computer modeling. The data showed consistent patterns in rotations and translations. The rotational motion and the anterior-posterior translation of the femur with respect to the tibia showed clear relationship with the flexion-extension path of the knee during the stance phase. Additionally, we observed that the phenomenon of femoral rollback was reversed and the femur was noted to move posteriorly with extension and anteriorly with flexion. Furthermore, we noted that motion of the medial femoral condyle in the transverse plane was greater than that of the lateral femoral condyle during the stance phase of gait. The trend was opposite of what has been observed during non-weightbearing flexion or single-leg lunge. These data provide baseline knowledge for understanding of normal physiology and for analysis of pathological function of the knee joint during walking. These findings further demonstrate that knee kinematics is activity-dependant and motion patterns of one activity (non-weightbearing flexion or lunge) cannot be generalized to interpret a different one (e.g. gait).

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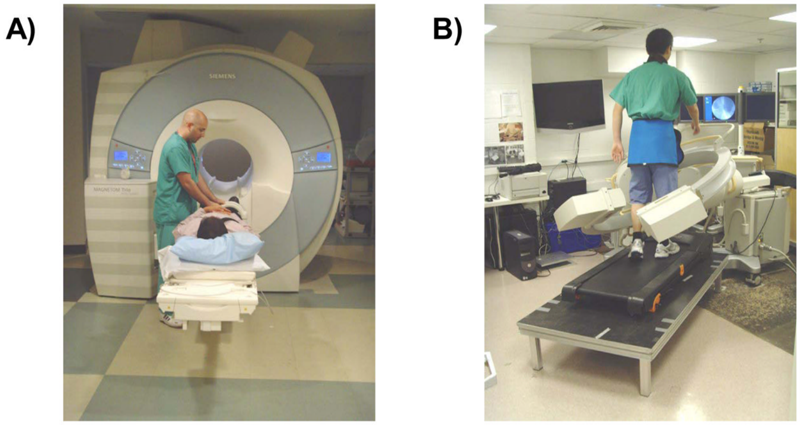

Figure 1.
A) Subjects were first MR-scanned to construct a 3D knee model. **B)** Following this, each subject performed gait on a treadmill at 1.5 MPH while the knee was scanned by the DFIS.

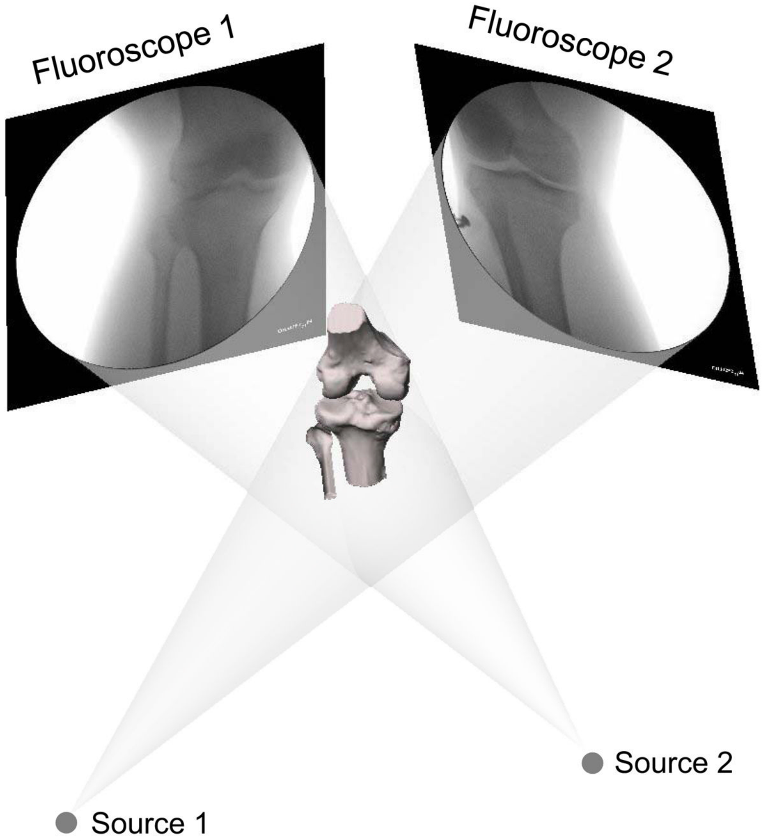

Figure 2.

Virtual reproduction of the fluoroscopic setup and tibiofemoral kinematics. The 3D MR-based models of the femur and tibia were matched to their projections on the fluoroscopic images.

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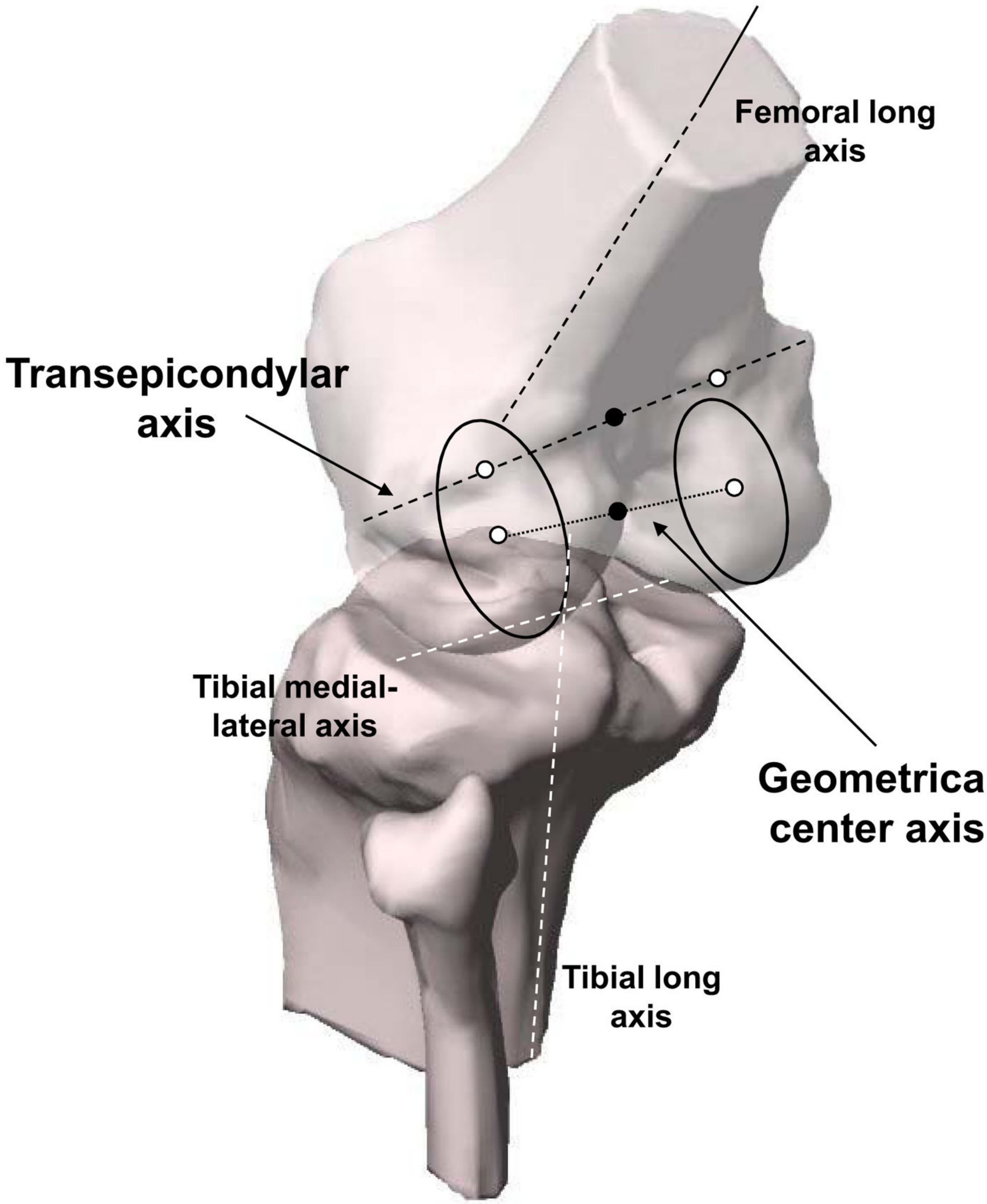

Figure 3.
Two axes were constructed to measure the motion of the femoral condyles during the stance phase of gait. The transepicondylar axis (TEA) connecting the epicondyles and the geometrical center axis (GCA) constructed by fitting circles to the posterior femoral condyles. The white dots represent the centers of femoral condyles on the TEA and GCA. The black dots represent the centers of TEA and GCA.

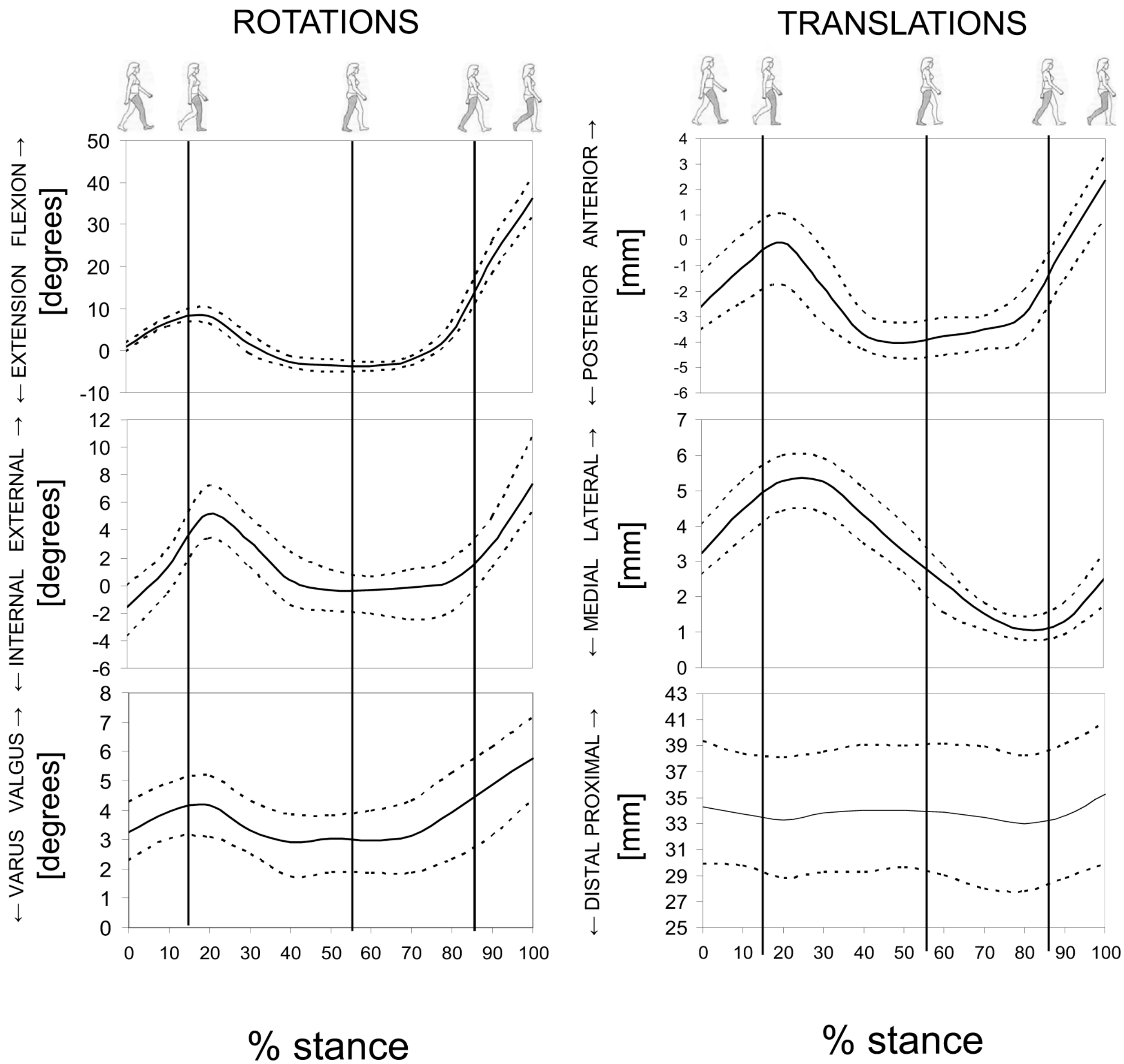

Figure 4.
showing the *6DOF* tibiofemoral kinematics of the knee joint measured during the stance phase of treadmill gait. The kinematics reported here represent the motion of femur relative to tibia. Solid lines represent contralateral toe-off, ipsilateral heel-rise and contralateral heel-strike, respectively. The dashed lines denote the kinematic range: maximal and minimal displacement. The intervals between the solid lines represent loading response, midstance, terminal extension and pre-swing, respectively.

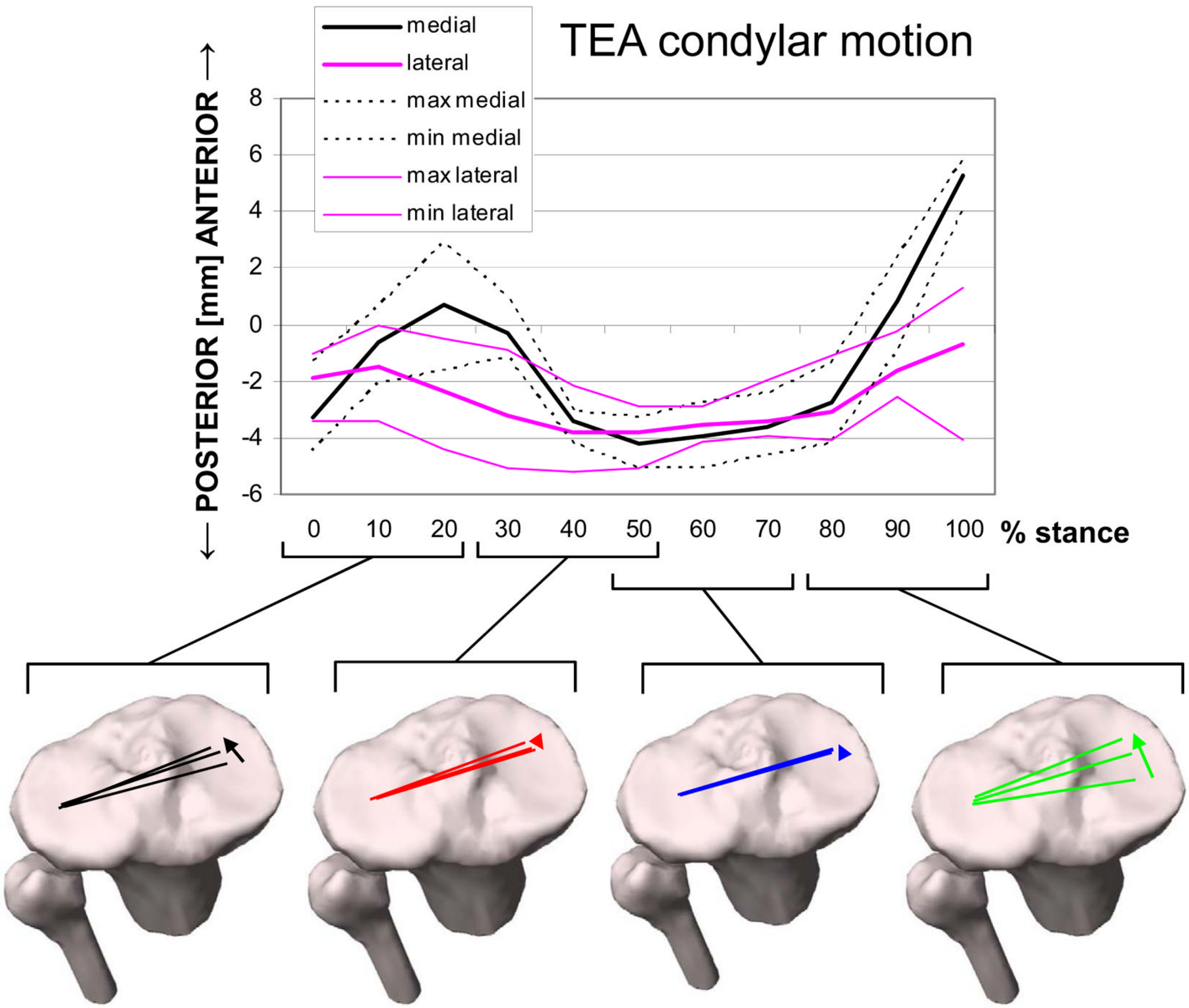

Figure 5.
Motion of the medial and lateral femoral condyle in the anteroposterior direction measured by tracking the center of each condyle on the transepicondylar axis (TEA) of the femur and projected onto the transverse plane. The medial femoral condyle made greater excursions than lateral femoral condyle.

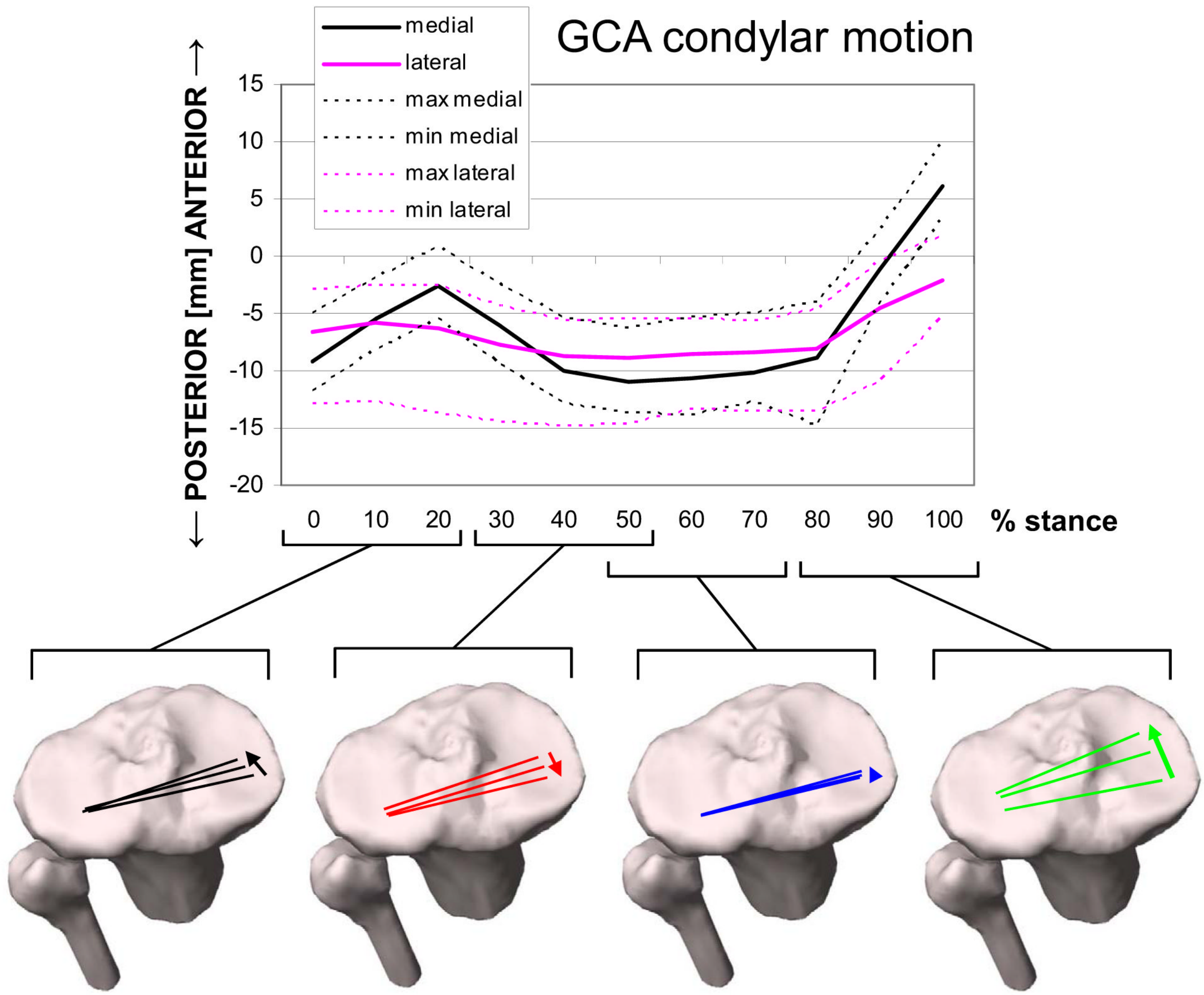

Figure 6.

Excursions of the medial and lateral condyles of the femur during stance phase determined in the anteroposterior direction. Geometrical center axis (GCA) of the femur was constructed for this measurement and the condylar centers were followed throughout the stance phase. Again, the medial femoral condyle was more mobile than the lateral.