Investigating the mechanical relationship between the feet and low-back

by

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Abstract

Introduction: Claims that foot orthoses can resolve low-back pain are common in the marketing of these devices. The claims are based on the notion that wearing the orthoses will limit excess pronation at the subtalar joint thus reducing excessive internal tibial and femoral rotations. Excess leg rotations increase the anterior tilt of the pelvis and subsequently the degree of lumbar lordosis. Since lumbar lordosis has been suggested as a cause of low-back pain, it is speculated that foot orthoses could be used to treat and prevent pain to the low-back by reducing the forward curvature of the spine. This mechanical link between foot function and the low-back has not been investigated by experimental studies.

Purpose: The purpose of this thesis was to investigate whether increased internal rotation of the femur induced an anterior tilt of the pelvis thus increasing the degree of lumbar lordosis and if external rotation induced a posterior pelvic tilt thus decreasing the degree of lumbar lordosis.

Methods: In order to internally and externally rotate the femur, participants placed their feet in 18 different foot positions. Seven of these positions ranged from 15 degrees of foot eversion to 15 degrees of foot inversion and 11 positions ranged from 40 degrees of external foot rotation to 40 degrees of internal foot rotation. Six cameras surrounded the motion capture area and angles of pelvic tilt and lumbar lordosis were calculated.

Results: Foot eversion and inversion did not have a statistically significant effect on pelvic tilt and lumbar lordosis. In-toeing had a statistically significant linear relationship with anterior pelvic tilt ($R^2=0.35$, $F_{1,131}=69.79$, $p=0.00$). Internally and

externally rotating the feet had no effect on lumbar lordosis ($R^2=0.001$, $F_{1,153}=0.09$, $p=0.77$).

Conclusion: Internally rotating the legs caused the pelvis to tilt anteriorly but only at extreme ranges of motion, much greater than what would normally be seen during gait. At which point, lumbar angles remained unaffected. This study does not dispute the effectiveness of foot orthoses to treat low-back pain but the results do not support the mechanical link proposed as the mechanism by which they work.

Table of Contents

List of Figures

FIGURE NUMBER **PAGE NUMBER**

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1. Introduction

Low-back pain is one of the most common musculo-skeletal problem affecting North Americans, striking over 80% of Canadians at one point in their lives. This debilitating condition causes over ten million work absence days in a year, resulting in serious economic repercussions (Hicks et al, 2002). Not only is the etiology of low-back pain misunderstood but its traditional medical management, such as the prescription of drugs or surgery, remain ambiguous and often ineffective (Manga et al, 1993; Vleeming et al, 1997). Alternative and less invasive treatment methods such as the use of foot orthoses have been suggested but never directly investigated.

The foot is the interface between the ground and the rest of the body and plays the dynamic role of shock absorber during gait. During the initial portion of the stance phase of gait, the foot rolls inwards or pronates as one of the mechanism to absorb the shock of heel strike and to allow the foot to become flexible in order to adapt to the terrain (Bates et al., 1978; Clarke et al., 1984). During the last 60% of the stance phase, the foot must supinate in order to lock the foot into a rigid segment used as a lever for propelling the body forwards. Excess foot pronation, defined as calcaneal eversion lasting beyond the initial 40% of the stance phase, of excess amplitude or of excess velocity (Powers, 2003) has been linked to overuse injuries such as patellofemoral syndrome (Clement et al, 1981), plantar fasciitis (Glickman et al, 1988) and mechanical low-back pain (Dananberg, 1999).

The mechanical link between the feet and the low-back begins at the subtalar joint. The subtalar joint is located between the calcaneus and the talus. Movement about this joint occurs in three-dimensions such that foot pronation is a combination of foot abduction, dorsiflexion and calcaneal eversion. Foot supination is a combination of foot adduction, plantarflexion and calcaneal inversion. During foot pronation, as the calcaneus everts, the talus slides medially and inferiorly. The talus is tightly located in the deep socket formed at the distal end of the tibia and femur. This medial downward movement of the talus therefore induces an internal rotation of the tibia (Tiberio, 1987; Nawoczenski et al, 1998). During supination, the movements are reversed and the tibia externally rotates (Inman, 1969).

At the knee joint, internal tibial rotation relative to the femur allows the anterior cruciate and collateral ligaments to relax thus allowing knee flexion. Both knee flexion and calcaneal eversion act as mechanisms to absorb the shock of heel strike. During foot supination the tibia externally rotates, tightening the collateral ligaments at the knee thus allowing its extension. Levens (1948) was one of the first to investigate thigh rotations during gait and concluded that as the tibia internally rotates in the initial 40% of the stance phase the femur internally rotates with lesser amplitude. Khamis (2006) suggested that by increasing the amplitude of calcaneal eversion, both the tibia and femur increased their amplitude of internal rotation. If the foot fails to supinate at 40% of the stance phase, Tiberio (1967) proposed a mechanism by which the femur may increase its internal rotation to allow the knee to extend.

Tiberio (1967) suggested that delayed subtalar supination during gait would delay external rotation of the lower leg thus delaying extension at the knee. Since knee extension is a pre-requisite for normal ambulation, the femur would increase its internal rotation to place the tibia in relative external rotation (Tiberio, 1967). This increased internal femoral rotation would permit knee extension even though the tibia remains internally rotated. Although evidence suggests that internal tibial rotation is accompanied by internal femoral rotations of lesser amplitude (Levens, 1948; Khamis, 2006), evidence that excess pronation leads to increased femoral rotation, as suggested by Tiberio (1967) is inconsistent (MacLean et al., 2006; Reischl et al., 1999; Powers et al, 2002). Nevertheless, increased femoral rotation would subsequently impact the hip joint.

At the hip joint, the head of the femur rests in the acetabulum. The hip joint is surrounded by a fibrous capsule which is reinforced by three ligaments arranged in a spiral fashion. This arrangement allows the ligaments surrounding the hip to become taut when the hip is extended thus decreasing the energy demands of quiet stance. Rothbart (2002) speculated that increased internal rotation at the femur creates a push from the head of the femur to the posterior portion of the acetabulum. This backwards push on the posterior aspect of the pelvis would cause the pelvis to tilt anteriorly. Based on the anatomical relationship between the pelvis and the lumbar spine, an anterior tilt of the pelvis would influence lumbar posture.

Since the pelvis is tightly connected to the lumbar spine at the sacro-iliac joint by an extensive fibrous connection, an anterior tilt of the pelvis would induce an increased forward curvature of the lumbar spine also known as a lordosis (Egund et al, 1978; Levine and Whittle, 1996). Low-back pain may occur as a result of excessive stress on the lumbar spine and sacroiliac joints due to this increase in the forward curvature of the spine (Denslow, JS et al 1962; Caillet, 1981). Treatments in these cases are focused on decreasing the amount of anterior pelvic tilt and concurrently reducing the depth of lumbar lordosis (Kisner et al, 1990). Although several authors have suggested the possibility of excess pronation affecting the pelvis and lumbar spine (Tiberio, 1987;

Rothbart et al, 1988; Genova and Gross, 2000), only one provided evidence of anterior pelvic tilt in response to excess calcaneal eversion (Khamis et al, 2006). In 40% of their participants, increasing calcaneal eversion by 4.8 degrees during quiet stance caused an anterior pelvic tilt of two to three degrees. The study did not address the effects on the low-back and did not investigate the effects of calcaneal inversion.

Foot orthoses are devices prescribed to support and align the foot (Wu, 1990) thus limiting excess foot pronation (Saxena and Haddad, 1998; Landorf et al, 2004). Since foot pronation has been linked to mechanical low-back pain (Dananberg, 1999), foot orthoses manufacturers advertise their product as an effective treatment modality. According to the advertisements, foot orthoses relieve low-back pain because of the proposed mechanical link between the feet and the low-back. The claims made by foot orthoses manufacturers are widely advertised but poorly supported by peer-reviewed literature. Although empirical evidence does suggest that wearing foot orthoses helps relieve low-back pain when compared to other traditional treatment methods such as physiotherapy and chiropractic manipulations (Dananberg, 1999), the mechanisms remain unclear. Since the changes made in foot posture by foot orthoses are quite small (Stacoff et al, 2000; Nigg et al, 1998) it was thought that exaggerating the effects of these orthoses might give us a clearer understanding of the consequences of excess subtalar movement at the pelvis and low-back.

Foot pronation and supination lead to internal and external leg rotations respectively. It was anticipated that in-toeing and out-toeing would magnify the effects of foot pronation and supination respectively. In-toeing would internally rotate and out-toeing would externally rotate the tibia and femur. The effects at the pelvis and low-back would then be exaggerated and more noticeable. If pelvic and lumbar postures do not change, it could be that the effects of orthoses are not due to the proposed mechanical link between the feet and the low-back.

1.1. Statement of the Problem

The purpose of this study was to determine whether bilateral internal and external rotations of the legs affect pelvic tilt and lumbar lordosis. Specifically, the following questions were addressed:

i) Does calcaneal eversion and inversion have an effect on pelvic tilt and lumbar lordosis?

ii) Do increased internal and external rotations of the femur, which naturally results from foot pronation and supination respectively, have a relationship with pelvic tilt?

iii) Do increased internal and external rotations of the legs have a relationship with lumbar lordosis?

1.2. Hypotheses

There were three hypotheses for this study:

i) Increasing the external rotation of the femur by inducing out-toeing and calcaneal inversion will increase posterior pelvic tilt.

ii) Increased internal rotation of the femur by in-toeing and calcaneal eversion will result in increased anterior pelvic tilt.

iii) With increasing internal rotations of the legs the degree of lumbar lordosis will increase. With external leg rotations the angle of lumbar lordosis will decrease.

1.3. Significance of the Study

This study was an investigation of the claim, made by foot orthoses manufacturers, that wearing their products to limit excess calcaneal eversion modifies posture of the pelvis and low-back. It is an opportunity for health care professionals to understand the effects of modifying foot function on structures above the ankle joint.

2. Procedures

To investigate the effects of femoral rotations on pelvic tilt, participants were asked to stand quietly with their feet in 18 different positions. Seven of the positions ranged from 15 degrees of foot inversion to 15 degrees of foot eversion. Foot eversion results in internal leg rotation and foot inversion results in external leg rotation. The remaining 11 positions ranged from 40 degrees of external rotation to 40 degrees of internal rotation. Internally and externally rotating the feet induced internal and external femoral rotations respectively. The effects of the feet manipulations were observed at the pelvis and low-back with six motion capture cameras. The angles of pelvic tilt and degree of lumbar lordosis at each foot position were calculated and compared to the neutral standing position. The procedures are explained in detail in the following section.

2.1. Participants

Sixteen volunteers gave their informed consent to participate in this study. Participants were 19 years of age or older. All participants were free of pain at the time of testing and had no history of low-back pain or trauma to the back and legs. Although some participants indicated that they currently wore foot orthoses, none had obvious foot deformities or foot pain according to self-report. Participants were visually assessed as lean to allow for easier identification of bony landmarks.

2.2. Research Design

The predictor variable in this model was foot position. The outcome variables were pelvic tilt and lumbar lordosis. A simple regression model allowed the investigator to assess the degree to which leg rotation predicted pelvic tilt and secondly, lumbar lordosis. The alpha level was set *a priori* to 0.05.

2.3. Testing

2.3.1. Initial Assessment

Data were collected at the Biomechanics Laboratory of the University of British Columbia in Vancouver. The testing took place over one session of approximately 90 minutes. During this period, participants were asked to wear a minimal amount of tight fitting dark clothing.

A range of motion assessment was conducted on all participants prior to testing. There was no warm-up session prior to the assessment. Passive range of motion testing included hallux dorsiflexion, ankle plantarflexion, ankle dorsiflexion, knee flexion, knee extension, hip flexion, internal hip rotation and external hip rotation. The protocol followed to test the ranges of motion is explained in Appendix C. Twenty three plastic spheres, one centimeter in diameter, were covered with reflective tape and attached to a circular piece of leather. The leather bases could then easily be taped on the participant's skin with medical tape. During the range of motion assessment, reflective markers were placed on the participant's left ankle, knee, anterior superior iliac spine, posterior superior iliac spine, greater trochanter and acromion process. Two markers were also placed on a vertical line bisecting the calcaneus and two markers were placed on a vertical line bisecting the gastrocnemius into two halves. The markers on the calcaneus were joined together to form a segment and the markers on the gastrocnemius were joined to create another segment. The angle calculated from the intersection of the two lines represented calcaneal inversion and eversion. A zero degree value represented a perfectly erect calcaneus with respect to the shank. A positive value represented calcaneal eversion and a negative value represents calcaneal inversion relative to the shank. Pictures were taken of the participants in maximal anterior pelvic tilt, posterior pelvic tilt, trunk flexion and trunk extension. The extended protocol can be found in Appendix D.

2.3.2. Data Collection

Upon completion of the range of motion assessment, reflective markers were placed on the lateral and medial malleolus, tibial condyles, femoral condyles, greater trochanter, anterior superior iliac spine (ASIS), posterior superior iliac spine (PSIS) of both legs and both shoulder joints. Markers were also placed on the spinous process of the L1, L3 and S1 vertebrae. The investigator was trained by a chiropractor to locate the spinous processes by palpation. Participants were asked to bend forward to facilitate the identification of the spinous processes.

Prior to data collection, the motion capture area had to be calibrated. Six Panasonic JHD Cameras surrounded the 2.04 m X 1.3 m X 2 m calibration area. The shutter speed of the cameras was set at 0.004 seconds to allow sufficient light on the markers. Kinematic data were collected at 60 Hertz. The center of the lens of the first camera was set at 1.74 m above ground level, camera two was at 1.79 m, camera three at 1.17 m, camera four at 1.21 m, camera five at 1.54 m and camera six was placed at 1.95 m above ground level. Camera one was located 6.33 m away from the center of the calibration area, camera two was at 5.7 m, camera three was at 5.7 m, camera four was at 5.5 m, camera five was at 5.3 m and camera six was at 5.7 m from the center of the calibration area. This particular arrangement allowed all cameras to monitor as many target points as possible at all times.

A calibration spider, consisting of 24 balls on eight branches aimed in different directions spreading across the entire area to be calibrated, was initially filmed from each camera view. These 24 balls are control points with known locations in three-dimensional space with respect to one corner. Once the images were captured from each camera view, they were digitized to produce two-dimensional coordinates of each point for each view. From the two-dimensional coordinates of the 24 control points, a set of 48 equations were developed by Peak Motus software (version 7.1.1) for each camera view. This set of equations was solved for 11 direct linear transformation (DLT) parameters relative to each camera. The DLT algorithms is a least square fit of the coordinate points therefore the more often the markers are detected, the greater precision that can be acquired. These constants characterize the relationship between object space and image space and permit the prediction of the spatial location of an object from its image recorded on film. In this way, a calibrated space was achieved. In this reference frame, the y-direction corresponds to the vertical, the x-direction was the length of the rectangle and the z-axis identified the width of the rectangle. The absolute location of the control points had been obtained with a residual error of less than 0.3 %. The calibration procedures were repeated once a week and each time the cameras were moved. During the entire three and a half week data collection period, the cameras were re-calibrated four times.

Each camera was time-synchronized by placing a light emitting diode (LED) bulb in its field of view. All LED lights were driven by a master synchronization unit. When the trigger button was pressed, all LED lights lit up indicating the start of the trial. The trial ended after 60 frames were collected.

Participants were tested in 18 different foot positions which were divided into two blocked tasks. During each condition, participants were instructed to look straight ahead and to maintain a relaxed stance. The arms of the participants were held across their chest. Data were collected when the experimenter assessed that the participant had relaxed by visual assessment of the shoulders dropping and the calcaneus everting back to a neutral position. Between each condition participants were free to walk around the lab or sit on a nearby chair. The first set of foot positions included seven foot positions that induced foot eversion and inversion. The participants placed their feet on two pieces of wood with their second toes facing straight ahead. The apparatus is displayed in Figure 1. A hinge on the inner edge of the platform pieces allowed the feet to be placed in five, 10 and 15 degrees of inversion, a neutral position and five, 10 and 15 degrees of eversion. A metal rod held the center of the platforms in

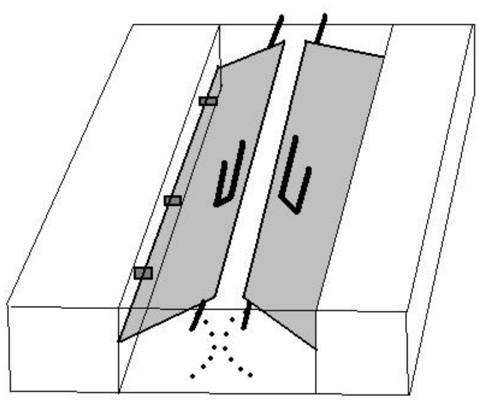

Figure 1: Participants were asked to stand on the two wooden platforms. The platforms were moved to invert and evert the feet of the participants by five, 10 or 15 degrees.

the appropriate positions. The purpose of including these foot positions was to see if foot eversion and inversion was enough of a manipulation to notice an effect on pelvic tilt and lumbar lordosis. A secondary purpose was to validate the use of internal and external leg rotations to magnify the effects of calcaneal inversion and eversion. It was anticipated that the tibia and femur would internally rotate during foot eversion and externally rotate during foot inversion thus justifying the use of leg rotation to magnify the effects of calcaneal eversion and inversion.

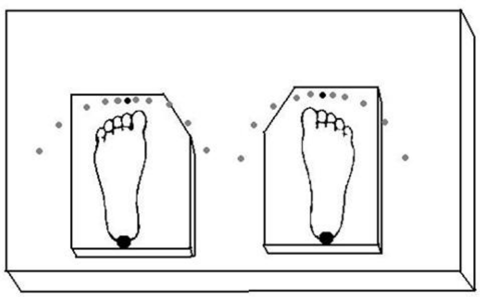

Figure 2: The wooden platforms rotated to externally and internally rotate the feet of the participants by 2.5, 5, 10, 20 and 40 degrees.

The second task, involving 11 positions, rotated the legs internally and externally by inducing in- and out-toeing. The participants placed their feet on two rotating platforms with the pivot located at the back and center of the heel. This device, illustrated in Figure 2, rotated their feet to line up the second toe with a line at the appropriate angle. The feet were maintained in the same position on the rotating platforms throughout all the trials. All positions inducing out-toeing were repeated with the feet in-toeing and they included: 40 degrees 20 degree, 10 degrees, five degrees, 2.5 degrees, zero degrees. These positions were chosen because they closely approach the average range of internal and external rotation at the hip joint. In average, maximal internal rotation at the hip is 30 degrees and maximal external rotation is 45 degrees (Watkins, 1999). Although foot rotations do not directly translate in the same amplitudes of rotation at the hip they guided the choice of foot positions.

The order of the foot positions was randomly selected for each participant but the two protocols were blocked. In each position participants were instructed to stand comfortably with their arms across their chest looking straight ahead. Each position was held comfortably for one to two minutes although only one second (yielding 60 frames) worth of data was used in the analysis. Since the positions were only held for a few minutes, the effects represented immediate changes in posture as opposed to long term adaptations. It was assumed that the immediate effects would give us some indication of the long term postural changes caused by foot function. Each position was recorded once. According to a pilot study, recording once had comparable variability to recording the same position several times. Sufficient rest was provided on the participants request in order to prevent fatigue.

2.3.3. Data Analysis

Raw kinematic data were processed with PEAK Motus (version 7.1.1) software and scaled according to calibration constants specifications. Once scaled, the data were filtered and two-dimensional segmental angles were calculated. Segment angles were calculated for the pelvis, lumbar spine, femur and tibia in relationship to three planes: x-y (frontal plane), x-z (transverse) and y-z (sagittal) planes. The angles defined in this study were the internal angles between the segment specified by two points and a reference plane. The segment defined by two points (A_1 and A_2) is projected onto a plane perpendicular to the plane of interest such that A_2 is defined at the intersection of both planes. The angle between the segment and the plane of interest was calculated between the range of 0 and 90 degrees. The angles were calculated for each segment in relationship to the three planes (frontal, transverse, sagittal). The pelvis was defined as the projection of the segment formed by the ASIS and PSIS markers onto the three planes. In the sagittal plane, a negative angle represented an anterior tilt of the pelvis and a positive angle represented a posterior tilt relative to the neutral position. The lumbar spine was defined as the addition of projection of the angle formed by the segment defined by the L1 and L3 markers and the segment formed by the L3 and S1 markers onto the three reference planes. In the sagittal plane, the neutral position of the spine is defined by a zero value. A positive value represents a decrease in the forward curvature of the spine and a negative value represents an increase in the forward curvature of the spine. The femoral angles were defined as the projection of the segment formed by the lateral femoral condyle and the medial femoral condyles onto the three reference planes. The tibial angles were defined as the projection of the segment formed by the lateral tibial condyle and the medial tibial condyle onto the three planes. In the transverse plane, a positive angle represents external rotation and a negative angle represents internal rotation.

The mean of the 60 frames for each condition was calculated for each participant. The average of all conditions across participants was then calculated to analyze the changes in the angles across the conditions.

2.3.4. Statistical Analysis

The statistical tests were performed on the two separate tasks, foot inversion/eversion and external/internal rotation. Two simple regression models were used to assess the effects of foot position on pelvic tilt and lumbar lordosis. The predictor variable was leg rotation defined by the degree of foot inversion/eversion or in-toeing/out-toeing and the outcome variables were pelvic tilt and lumbar lordosis. The p-value was set *a priori* at 0.05. An analysis of variance was used to assess whether the model resulted in a significantly good degree of prediction of the outcome variables. A power analysis was performed with GPower 3.0.8 (Erdfelder et al., 1996).

In the first set of statistical tests, each condition was compared back to the neutral position of the respective task. In a second set of analysis, these values were then normalized to the participants' range of motion. The values for femoral and tibial rotations were compared to the total range of internal and external rotation at the hip joint. The values for pelvic tilt were expressed as a percentage of the maximum anterior tilt of each participant recorded during the initial assessment. The values of lumbar lordosis were expressed as a percentage of the maximal angle of lordosis achieved by the participants during the initial assessment.

3. Results

3.1. Description of Participants

Sixteen participants, 8 men and 8 women, volunteered to take part in this study. The descriptive data of the participants can be found in appendix E. The mean age was 25.8 years (standard deviation (sd) = 3.85 years), the mean height was 1.75 m (sd =0.08 m) and the mean mass was 69.2 kg (sd=12.68 kg). Data of two male participants were lost due to equipment failure and data from two female participants could not be used because the camera settings had been changed and not re-calibrated properly therefore data of twelve participants (6 females, 6 males) were used in the analysis. The mean age was 26.2 years (sd =4.4 years), the mean height was 1.7 m (sd= 0.08 m), and the mean mass was 67.7kg (sd =12.4 kg). The mean subtalar position for the group of participants was 3 degrees everted (sd =2.89 degrees) for the left foot and 7.3 degree everted (sd=3.8 degrees) for the right foot. Four participants (Participants 2, 5, 6, 12) indicated that they wore orthotic insole to control the degree of foot pronation.

3.2. Task 1: Foot inversion/eversion

3.2.1. Leg Rotations

Foot eversion resulted in internal femoral and tibial rotation and foot inversion results in external femoral and tibial rotation (Figure 3). The linear regression between foot position and tibial rotation was statistically significant (*R=0.34*, R^2*=0.12*, $F_{1, 76}$*=9.99*, *MS=393.62*, *power=0.2*, *p<0.00*). The regression between foot position and femoral rotation was also statistically significant (*R=0.39*, R^2*=0.15*, $F_{1, 76}$*=13.59*, *MS=413.76*, *power=0.2*, *p<0.001*).

When leg rotations were normalized to the individual's range of hip rotation, there was a statistically significant correlation between tibial rotation and foot position (*R=0.24*, R^2*=0.06*, $F_{1, 76}$*=9.70*, *MS=1108.5*, *power=0.1*, *p=0.002*). The regression between foot position and femoral rotation was also statistically significant (*R=0.25*, R^2*=0.06*, $F_{1, 76}$*=10.12*, *MS=1175.8*, *power=0.1 p<0.001*). These data are presented in Figure 4.

3.2.2. Pelvic Tilt and Lumbar Lordosis

The correlation between foot inversion/eversion and pelvic tilt (*R=0.10*, R^2*=0.01*, $F_{1, 76}$*=0.78*, *MS=4.4*, *power=0.06*, *p=0.38*) and between foot inversion/eversion and lumbar lordosis (*R=0.18*, R^2*=0.03*, $F_{1, 76}$*=2.36*, *MS=296.1*, *power=0.08*, *p=0.13*) were not statistically significant. The correlation between foot position and pelvic tilt is illustrated in Figure 3.

When pelvic tilt was normalized to the individual's maximal anterior pelvic tilt angle the regression between foot inversion/eversion and pelvic tilt (Figure 4) was not statistically significant (*R=0.09*, R^2*=0.01*, $F_{1,76}$*=1.2*, *MS=226.1*, *power=0.06*, *p=0.28*). When the degree of lumbar lordosis was normalized to the individual's maximal degree of lumbar lordosis, the regression between lumbar angle and foot position was not statistically significant ($R=0.16$, $R^2=0.03$, $F_{1, 76}=3.6$, $MS=302.1$, $power=0.08$, $p=0.11$).

3.3. Task 2: Foot external/internal Rotation

3.3.1. Leg Rotations

Foot rotation manipulation resulted in rotation of the tibia and femur. The data in the transverse plane are illustrated in Figure 5. There was a statistically significant correlation between foot out-toeing and external rotation of the tibia and foot in-toeing and internal tibial rotation ($R=0.78$, $R^2=0.61$, $F_{1, 262}=406.9$, $MS=38\,557.2$, $power=0.98$, $p<0.001$). There was a statistically significant linear correlation between foot out-toeing and external rotation of the femur and foot in-toeing and internal femoral rotation ($R=0.74$, $R^2=0.55$, $F_{1, 262}=321.3$, $MS=31\,943$, $power=0.94$, $p<0.001$).

When the rotations of the tibia and femur were normalized to the total range of hip rotation, the correlations between tibial rotation ($R=0.77$, $R^2=0.59$, $F_{1, 262}=280.9$, $MS=33\,076$, $power=0.96$, $p<0.001$) and foot position and femoral rotation ($R=0.72$, $R^2=0.51$, $F_{1, 262}=207.7$, $MS=27\,771$, $power=0.90$, $p<0.001$) and foot position were both statistically significant (Figure 6).

3.3.2. Pelvic Tilt

The pelvis was shown to adopt a posteriorly tilted position when the feet were externally rotated and an anteriorly tilted position when the feet were internally rotated (Figure 5). The linear relationship is statistically significant ($R=0.47$, $R^2=0.22$, $F_{1, 262}=74.26$, $MS= 344.12$, $power=0.39$, $p<0.001$).

When pelvic tilt was normalized (Figure 6) to maximal anterior tilt angle, the correlation between pelvic tilt and foot position was statistically significant ($R=0.25$, $R^2=0.06$, $F_{1, 262}=13.35$, $MS=2686.4$, $power=0.13$, $p<0.001$).

The effects of foot position on pelvic rotation (transverse plane) ($R=0.11$, $R^2=0.013$, $F_{1, 262}=3.3$, $MS=60$, $p=0.07$) and pelvic side-to side tilt (frontal plane) ($R=0.061$, $R^2=0.004$, $F_{1, 262}=0.99$, $MS= 19.39$, $p=0.32$) were not statistically significant.

From visual inspection of the graphs, the effect of internal leg rotation seemed more obvious at the pelvis than the effects of external leg rotation. Statistical testing was therefore done on data representing the neutral foot position and internally rotated positions. It was shown that the correlation between foot position and pelvic tilt was stronger ($R=0.60$, $R^2=0.36$, $F_{1, 141}=77.94$, $MS=314.19$, $power=0.65$, $p<0.001$).

The normalized pelvic angles also adopt a stronger relationship with foot position when looking at internally rotated feet positions only ($R=0.57$, $R^2=0.32$, $F_{1, 141}=50.42$, $MS=178$, $power=0.58$, $p<0.001$).

When analyzing the correlation between external feet rotations and pelvic tilt, the regression was not statistically significant ($R=0.14$, $R^2=0.019$, $F_{1, 141}=2.737$, $MS=10.32$, *p=0.10)* implying that increasing the external rotation of the feet does not increase the posterior tilt of the pelvis.

3.3.3. Lumbar Lordosis

There was no statistically significant linear correlation between the degree of lumbar lordosis (sagittal plane) and the foot conditions ($R=0.02$, $R^2=0.001$, $F_{1, 153}=0.09$, $MS= 4.22$, $power=0.05$, $p=0.77$) suggesting that lumbar lordosis does not change throughout the range of external and internal leg rotations (Figure 7). A Pearson correlation was not significant between pelvic tilt and lumbar lordosis (*Pearson =-0.12, p=0.15*). When normalizing the data (Figure 8) to each participants maximal lumbar angle, the correlation between foot position and lumbar angles is not statistically significant ($R=0.01$, $R^2=0.00$, $F_{1, 153}=0.03$, $MS= 13.7$, $power=0.05$, $p=0.87$).

The correlation between internal foot rotation only and lumbar lordosis is not statistically significant ($R=0.01$, $R^2=0.00$, $F_{1, 83}=0.00$, $MS= 0.16$, $power= 0.05$, $p=0.95$).

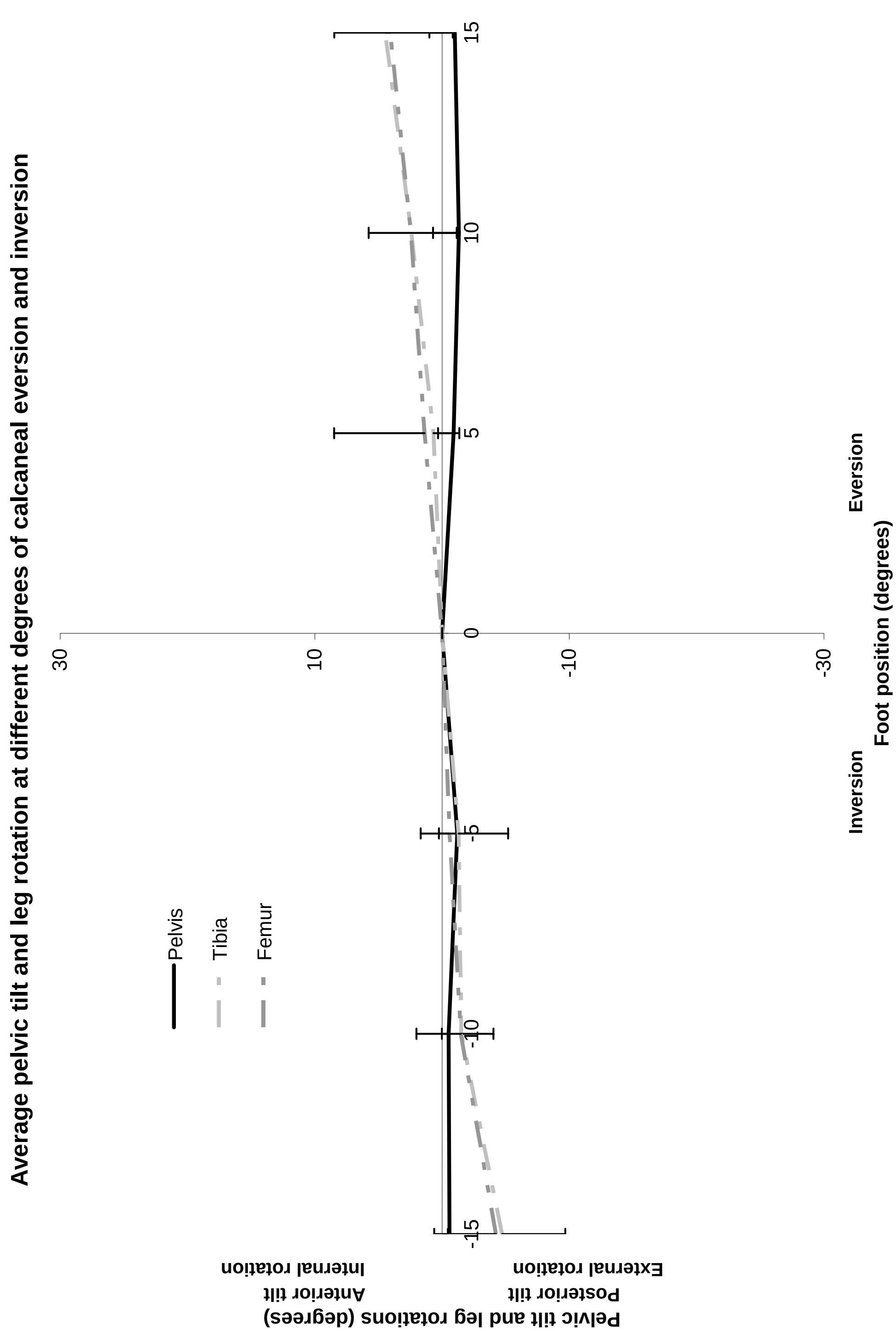

Figure 3: Average pelvic tilt and leg rotation when the feet are everted and inverted. Eversion causes the legs to internally rotate and inversion causes the legs to externally rotate. The effect at the pelvis is not statistically significant.

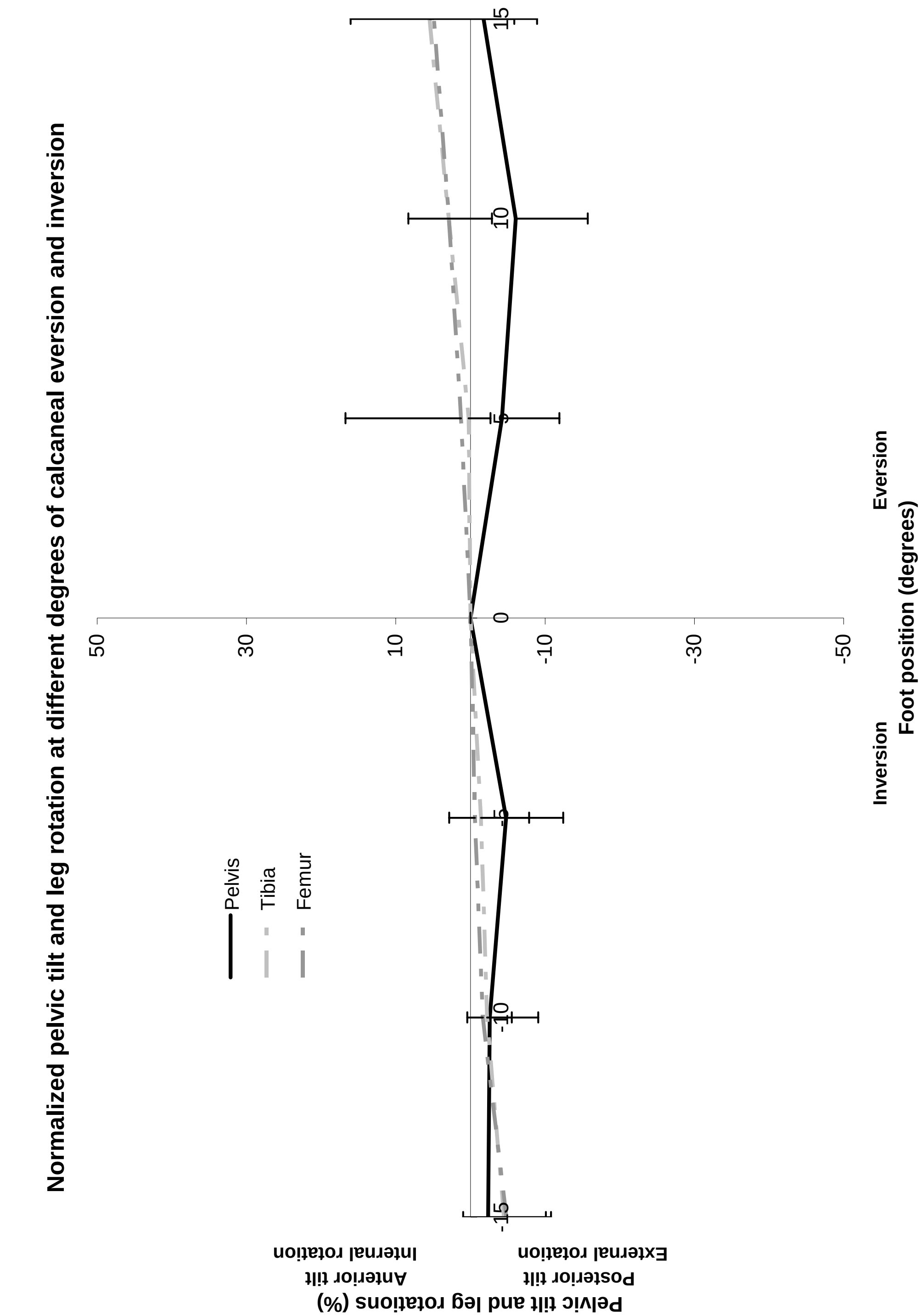

Figure 4: Average pelvic tilt and leg rotation when the feet are everted and inverted. Pelvic tilt is normalized to the maximal angle of anterior pelvic tilt of each participant. Tibial and femoral rotations are normalized to the individuals' range of hip motion.

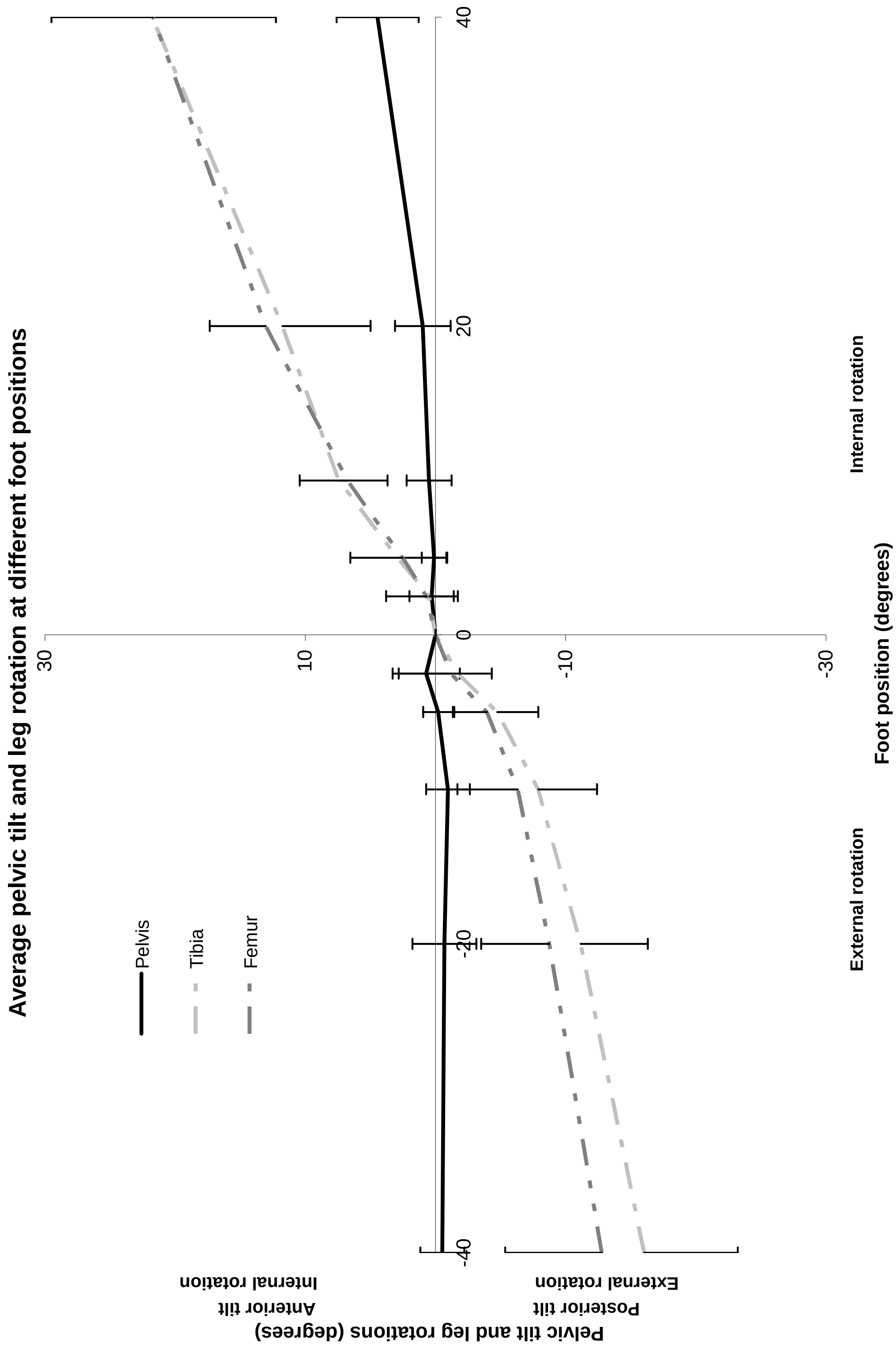

Figure 5: Average pelvic tilt and degree of tibial and femoral rotation at different foot positions. The error bars represent standard deviations. With external leg rotation the tibia and femur externally rotate and the pelvis remains posteriorly tilted. With internal leg rotation the tibia and femur internally rotate and the pelvis tilts anteriorly.

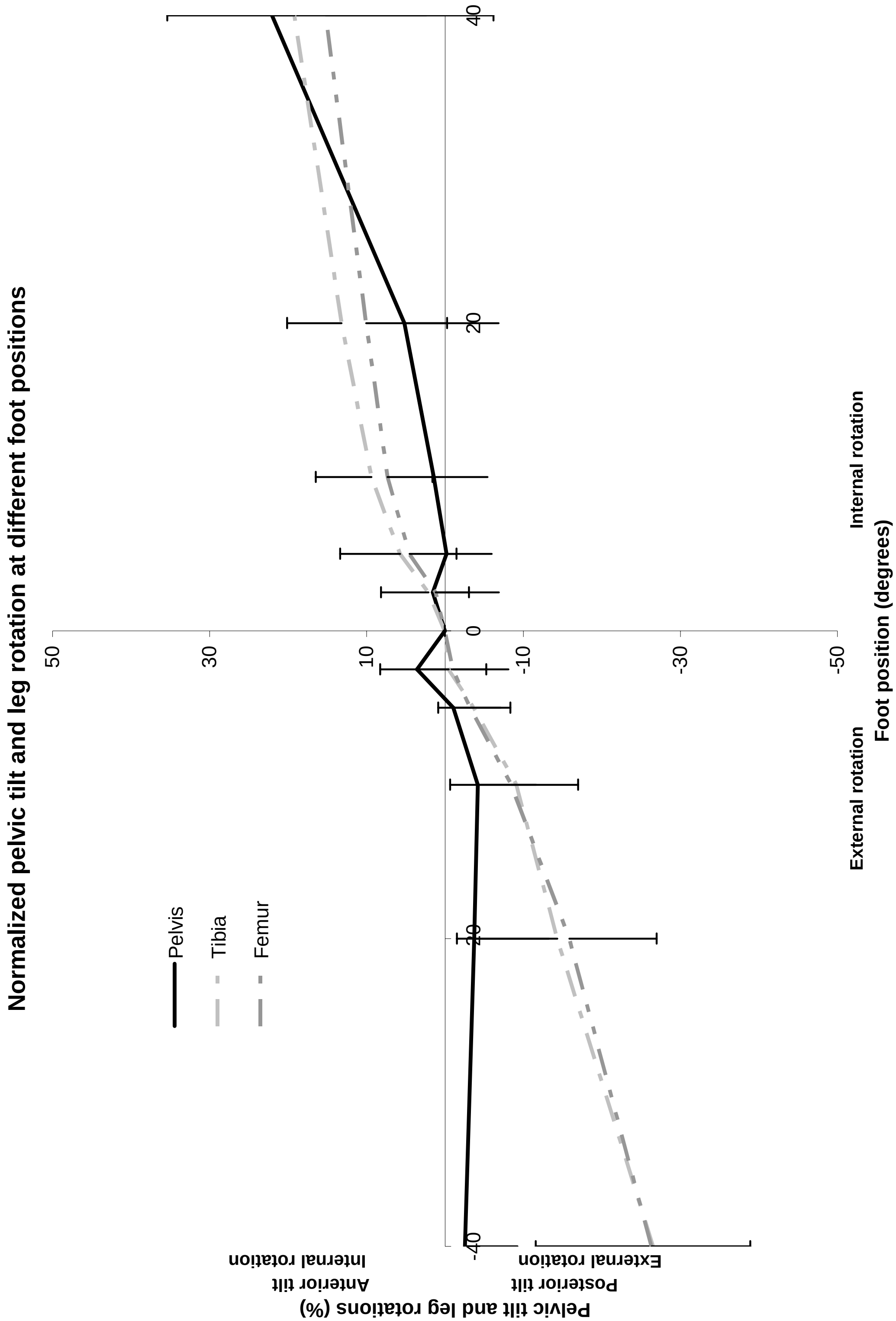

Figure 6: Average pelvic tilt and degree of tibial and femoral rotation at different foot positions. The error bars represent standard deviations. Pelvic tilt was normalized to the maximal angle of anterior pelvic tilt of each participant. Tibial and femoral rotations are normalized to the individuals' range of hip motion.

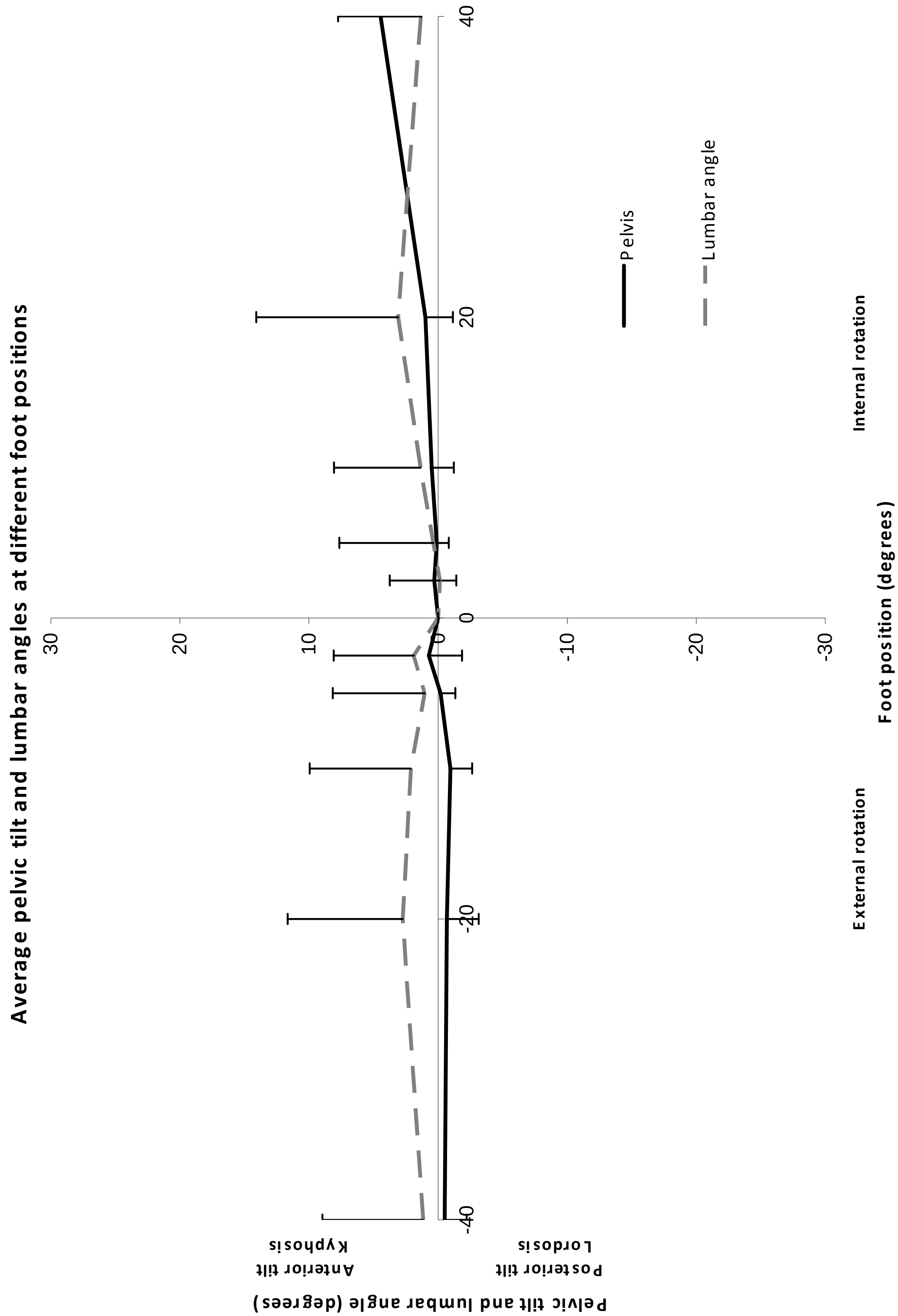

Figure 7: Average pelvic tilt and lumbar angle at different foot positions. The error bars represent the standard deviations. With internal leg rotation the pelvis tilts anteriorly but the degree of lumbar lordosis does not change.

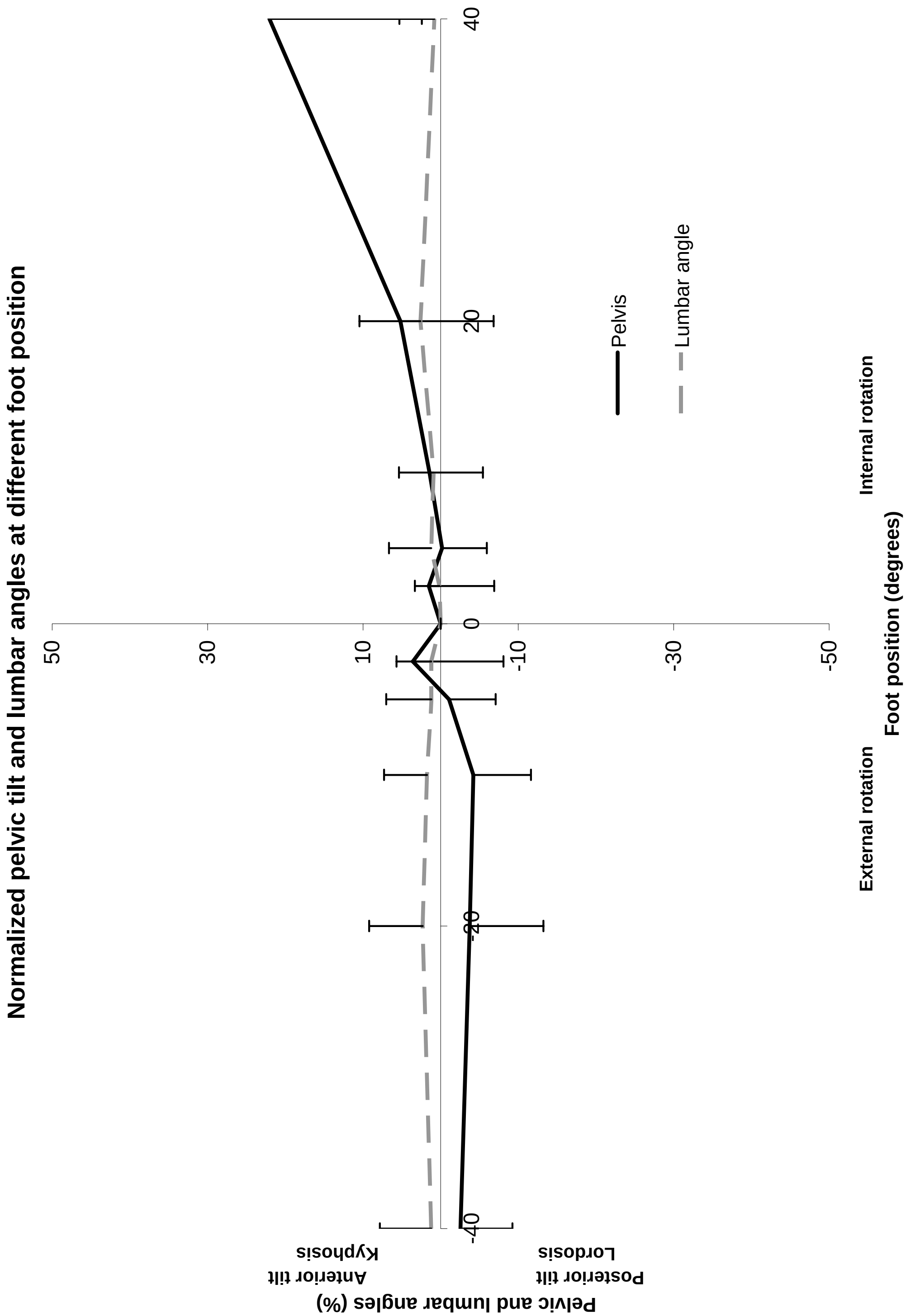

Figure 8: Average pelvic tilt and lumbar angle at different foot positions. The error bars represent the standard deviations. Pelvic tilt was normalized to the maximal angle of anterior pelvic tilt of each participant. Lordosis was normalized to the maximal angle of lordosis of each participant.

4. Discussion

4.1. Overview

Low-back pain is a common musculoskeletal problem with high economic repercussions. A link between the mechanics of the feet and the pelvis during gait has been suggested (Tiberio, 1987) but never directly investigated. This study was designed to investigate the effects of inducing excess leg rotation on pelvic tilt and lumbar lordosis. Unlike previous studies focused on the effects of foot position on proximal segments this study proposed to induce excess rotation of the leg through out-toeing and in-toeing in addition to foot eversion and inversion in order to simulate and magnify the effects of excess calcaneal movement.

It has previously been shown that foot pronation, or calcaneal eversion is accompanied by internal rotation of the tibia and femur. A greater degree of calcaneal eversion translates into greater amplitude of tibial and femoral rotation (Khamis et al 2006; Coplan, 1989). Similarly, foot supination or calcaneal inversion is coupled with external tibial and femoral rotation (Inman, 1969). In order to justify the use of internal and external leg rotation to magnify the effects of calcaneal eversion and inversion, data were collected with participant's feet everted and inverted. Although the changes at the pelvis were too small to be statistically significant, the rotations that occurred at the tibia and femur were as predicted. Everting the feet lead to an internally rotated tibia and femur. Inverting the feet lead to an externally rotated tibia and femur. The linear relationships for both the tibia and femur were statistically significant. These data suggest that inverting and everting the calcaneus resulted in external and internal tibial and femoral rotations respectively thus justifying the use of out- and in-toeing to magnify the effects of pronation and supination of the subtalar joint. Everting and inverting the feet was not a large enough manipulation to infer an effect at the pelvis and low-back.

Rotating the feet exteriorly and interiorly magnified the effects of foot inversion and eversion. From 40 degrees of external rotation to 40 degrees of internal rotation, it was clear that out-toeing externally rotated the tibia and femur and in-toeing internally rotated the tibia and the femur. As expected, the pelvis tilted anteriorly with internally rotated legs and adopted a posteriorly tilted position with externally rotated legs. Increasing or decreasing the magnitude of external rotation of the legs does not change the position of the pelvis. Pelvic position only change when internally rotating the legs particularly at the extreme ranges of motion.

A study by Khamis et al. (2006) found similar yet stronger findings. Thirty-five participants stood on wedged platforms of five, 10 and 15 degrees that forced their calcaneus into eversion. The pelvis anteriorly tilted with increased amplitude of calcaneal eversion. These results suggest an effect of calcaneal eversion on pelvic tilt although the changes seen at the pelvis were within one degree. This difference would have been too small to be detectable with the statistical power of the present study. In order to detect the very small effect of the calcaneus on the pelvis, the current study should have recruited 10 to 15 more participants.

When the feet are in contact with the ground, the femur can be described as a fixed structure upon which the pelvis rotates. The head of the femur is rounded and moves in the semi-spherical acetabulum. When both heads of the femur are rotated to the extreme of the normal range of motion, as is the case in the 40 degrees of internal rotation of the feet, they both push backwards in the acetabulum. Since the femur is fixed to the ground, the pelvis responds to this backwards push by tilting forwards. It could further be speculated that individual differences in the response could be attributed to differences in the angle of the femoral neck. An individual with a greater femoral neck angle may have a less noticeable anterior pelvic tilt than an individual with a smaller femoral neck angle. A smaller femoral neck angle would have better congruency between the wall of the acetabulum and the head of the femur thus allowing a stronger backwards push than a larger femoral neck angle. The limits of external femoral rotation were not reached in this study.

Based on the anatomical relationship between the pelvis and lumbar spine, it is generally accepted that changes in the inclination of the pelvis will affect the degree of lumbar lordosis (Levine and Whittle, 1996; Day et al, 1984). During the initial range of motion assessment, the data suggested that the pelvis of the participants has an average range of motion of 26 degrees which changed the forward curvature of the spine by an average of 20 degrees. During the range of motion assessment, extreme ranges of motion at the pelvis were used to detect changes at the spine. Authors who studied pelvic tilt and lumbar curvature during relaxed stance failed to find a correlation between the two variables (Walker et al, 1987; Youdas et al, 1996; Beninato et al, 1993). The smaller ranges of motion at the pelvis obtained by rotating the femur internally and externally may not have been sufficient to trigger a detectable change in spinal curvature. It is speculated that the small changes seen at the pelvis in the study by Khamis (2006) were not enough to affect lumbar angles.

A limitation of this study was that data were recorded with the participants in a static stance. Although excess pronation is usually attributed as a risk factor during gait, using a static position reduced the variability of marker movement due to skin movement and to differences in participants gait styles. The static postures adopted during testing were positions that were part of the dynamic movement that occurs during walking. Before applying the results of this study to a clinical setting, it is important to remind ourselves that walking is an activity that involves single-leg support and pelvic rotations in the transverse plane. Since data were collected with participants in quiet stance, it is not possible, from the results of this study, to predict pelvic tilt and changes in lumbar lordosis during gait. In order to further understand the link between the feet and the low back during gait, data should be gathered in single stance and during gait. Taking this into consideration it is possible to make a few clinical recommendations. The use of foot orthoses to treat low-back pain was addressed. Their effectiveness, regardless of the mechanism by which they work, should be sufficient evidence that they could still be prescribed as a mechanism to treat pain. Since we did not see changes in pelvic and lumbar posture within ranges of calcaneal eversion typically seen in excess pronators, the mechanism by which foot orthoses work to treat pain may not be mechanical. It may be that foot orthoses play some sort of a placebo effect or that those patients willing to purchase foot orthoses may also be willing to subconsciously change their behaviors in favor of pain relief.

4.2. Support for Hypothesis

The three hypotheses presented in the introduction have been addressed:

i) Increasing the external rotation of the femur by inducing out-toeing had no statistically significant effect on pelvic tilt. This hypothesis was rejected.

ii) The correlation between internal femoral rotation and anterior pelvic tilt was statistically significant. The results of the regression analysis suggested that by increasing the amplitude of internal rotation of the femur, the pelvis tilted anteriorly. This hypothesis was accepted.

iii) The correlation between leg rotation and lumbar lordosis was not statistically significant. According to the methods used in this study this hypothesis was rejected.

4.3. Methodological Considerations

Variability occurs naturally during data collection. The average standard deviation for pelvic tilt in the sagittal plane for one second was 0.37 degrees. The variability was consistent across participants and across conditions. The inter-participant variability can be attributed to differences in the anatomy of the participants such as the range of motion at the hip joint and the angle of the femoral neck.

There are certain limitations to consider when interpreting the data from this study. Reflective markers were placed on the participants in order to identify bony landmarks. It was assumed for the purpose of this study that skin movement was not a factor in the error of measurement. Since the movements were minimal, slow and involved no impact, it was assumed that the error would be consistent if it was in fact a factor.

This research operated under the literature guided assumption that internally and externally rotating the legs of the participants represented the magnified effects that would normally occur due to calcaneal eversion and inversion respectively.

5. Conclusion

The use of foot orthoses to treat low-back pain has been the subject of many controversies. This project provided evidence that reducing internal rotation of the legs may reduce the degree of anterior pelvic tilt at extreme ranges of leg rotation. Evidence suggesting that foot orthoses have an effect on the pelvis, on the other hand, is still lacking. In fact, the data from this study suggest that foot pronation does not affect the pelvis unless extremely exaggerated, to values above what would normally be seen during gait. Since the effects of pelvic tilt on the lumbar spine are only noticeable when pelvic tilt is exaggerated beyond values seen this study it seems far-fetched to assume a link between everyday foot pronation and an increase in lumbar lordosis. Although the results from this study offer valuable insight into the mechanical link between the feet and the low-back, it does not support the use of foot orthoses to decrease the degree of lumbar lordosis. More research is needed to determine how foot orthoses help relieve low-back pain.

5.1. Recommendations

This study was merely a first step in the investigation of biomechanical changes that occur at the pelvis and low-back because of manipulations at the feet. Although we now have a better understanding of the link between the feet and the low-back at extreme ranges of motion, it would be ideal to further investigate postural changes that occur with changes in foot position in ranges that simulate normal gait patterns. If the pelvis is affected with foot pronation and supination of normal amplitudes, it may be more helpful to infer an effect of excess pronation on the low-back. Until it can be shown, effects of excess pronation, within a normal range of motion, on the pelvis remain speculations. It would be interesting to follow the changes that occur during foot eversion and inversion with an x-ray machine in order to detect the subtle changes.

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Appendix A

Review of the Literature

i. The Foot

Of the 206 bones in the human body, 26 are located in the foot. They are supported by over 100 ligaments and 30 muscles. Of these 26 bones the talus connects the shank to the foot; the calcaneus, also known as the heel bone, sits under and supports the talus; the navicular, cuboid and three cuneiforms form the mid-foot; the five metatarsals project out to the toes and the 14 phalanges form the toes. These bones form three functional arches: the medial longitudinal arch, the lateral longitudinal arch and the transverse arch. The medial longitudinal arch is formed by the calcaneus, talus, navicular, medial and center cuneiforms and the first three metatarsals. The lateral longitudinal arch is formed by the calcaneus, cuboid and fourth and fifth metatarsals. The transverse arch is formed by the five metatarsal bones from the lateral to the medial side of the foot. Much like the structures of buildings, the arches of the foot are the foundation of the body and are designed to withhold the mass of the body. During locomotion, the structures of the foot play a dynamic role in shock absorption and propulsion. The shock of heel strike during gait creates peak forces just above body weight and during running these forces represent two to three times the body weight. These shockwaves propagate upwards notably to the pelvis, spine and skull. Repetitive forces of this magnitude need to be dissipated in order to prevent injury to the bones and joints. The shock-absorbing mechanisms of the foot include the heel pad and foot pronation. The heel pad has an average thickness of 18mm and is located under the calcaneal bone. It is the weight-bearing portion of the heel. The deformation of the heel pad at heel strike contributes to the shock absorption (Sarrafian, 1993). Foot pronation occurs at the subtalar joint and is a combination of foot dorsiflexion, abduction, and eversion. It is described in further details in the following section.

ii. The Subtalar joint

The talus has a rounded head which projects forwards and medially at the end of a short neck which connects posteriorly to its body. The superior aspect of the body of the talus is tightly wedged in the deep socket formed by the distal end of the tibia and fibula. The fibula is firmly anchored to the tibia with a tough fibrous sheet of connective tissue, the interosseous membrane. At the distal end of the shank, the interosseous membrane is reinforced by the anterior and posterior tibiofibular ligaments. The talus, fibula and tibia form the ankle joint. Its main function is to allow hinge-like dorsiflexion and plantarflexion of the foot on the leg.

The subtalar joint is located between the talus and the calcaneus. The talus is located superiorly and anteriorly on the calcaneus therefore movement occurs around an oblique axis of approximately 42 degrees from a sagittal view. Movements at the subtalar joint include foot pronation and supination. Because of the joint's oblique axis, movement about this joint can be described in three reference planes such as pronation which is a combination of abduction, dorsiflexion and eversion and supination which is a combination of adduction, plantarflexion and inversion. Foot pronation is a normal mechanism by which the foot flattens or rolls inward for the first 37.5% of the stance phase to absorb the shock of heel strike. The foot then supinates to lock the foot into one rigid segment. This segment is used as a lever to propel the body forwards during the push-off phase of gait. A certain degree of foot pronation is crucial to properly absorb the shock of heel strike. Excess pronation is defined as calcaneal eversion beyond 37.5% of the stance phase during gait or pronation of excessive amplitude.

Movement at the calcaneus is transferred up to the tibia and fibula because of the tight articulation between the talus and shank bones. As the calcaneus everts as it would during foot pronation, the talus slides medially and inferiorly. Since the tibia and fibula form a tight connection with the talus, this medial and downward movement of the talus induces an internal rotation of the tibia (Tiberio, 1987, Nawoczenski et al, 1998). During supination, the movements are reversed and the tibia externally rotates (Inman, 1969).

This transfer of movement during weight bearing has been shown in previous studies. During static standing on ten degree laterally wedged platforms, Khamis et al, (2006) showed that inducing calcaneal eversion by 2.6 degrees increased internal rotation of the tibia by 2.33 degrees. Coplan (1989) compared healthy participants to excess pronators and noticed that excess pronators demonstrated greater internal tibial rotation than the healthy group. Excess pronators are defined as a population who remain in calcaneal eversion after 37.5% of the stance phase during a gait cycle. Typically the calcaneus of a healthy population pronates from 0 to 37.5% of the stance phase and then supinates until the push-off phase. Excess amplitude and velocity of pronation has been linked to overuse injuries. Lafortune et al, (1994) induced excess pronation in their participants with laterally wedged shoes and noticed an increase in internal tibial rotation with increased foot eversion. Other studies have controlled excess pronation with the use of foot orthoses and have noticed a decrease in internal tibial rotation amplitude (Cornwall et al, 1995; Mundermann et al, 2003; Nawoczenski et al, 1999; Nester et al, 2003; Stacoff et al, 2000; Donatelli .1990; Powers et al, 2002). The data from these studies suggest that during gait, pronation is coupled with internal tibial rotation and that increased calcaneal eversion increases this rotation.

iii. The Knee joint

The knee joint consists of the articulation between the femur and the tibia and between the patella and the femur. The fibula is not involved in the knee joint but articulates with the proximal lateral side of the tibia. Above this articular facet, the tibia expands in the transverse plane to form the tibial plateau. The medial and lateral tibial condyles are flattened surfaces at the proximal end of the tibia and they articulate with the femoral condyles at the femur's distal end. The convex femoral condyles articulate with the slight concave articular surfaces of the tibial plateau. The medial condyle is longer in the antero-posterior direction than its lateral counterpart. The radius of curvature of the lateral condyle decreases more rapidly from front to back that the medial condyle. Between the two articular surfaces, the intercondylar eminence resembles a raised inverted cone. The eminence is the pivot around which the femur rotates. It is straight medially and convex laterally; suggesting that as the femoral condyles move around the eminence the larger medial femoral condyle translates in a straight line, while the lateral femoral condyle has a curved excursion.

Although the movement at the knee is mainly one of flexion and extension, referring to it as a hinge joint is a common oversimplification. During knee extension, the articular surfaces between the tibia and femur are broad and flat assuring stability. In flexion, the articular surfaces move to the rounded areas of the posterior aspects of the femoral condyles. Two fibrocartilaginous menisci, one on each side of the tibial plateau, accommodate to changes in the shape of the articular surfaces of the femur during joint movement. The menisici are held in position by the coronary ligaments located on the edges of the tibial condyles. Their thickness increases radially providing a closer fit to the femoral condyles. As the flexed knee initiates extension, both the rounded femoral condyles are able to roll on the tibial plateau. Since the lateral condyle is smaller, its flattened posterior part comes into contact with the tibia sooner than the medial condyle. For the knee to continue extension the tibia must laterally rotate to allow the medial condyle of the femur to continue rolling until the flattened surface comes into contact with the tibial plateau. At this point the anterior cruciate ligament and the collateral ligaments are tightened and the knee joint is locked into position with the flat femoral condyles tightly pulled onto the tibia. This locked position during knee extension is important to minimize muscular activity and thus the energy demands of quiet stance. The anterior cruciate ligament attaches to the medial anterior part of the intercondylar eminence on the tibia and on the posterior internal portion of the lateral condyle of the femur. The posterior cruciate ligament joins the posterior lateral intercondylar eminence to the anterior internal portion of the medial femoral condyle. It is also attached to the posterior end of the lateral meniscus. These passive structures, along with the collateral ligaments and the fibrous capsule which surrounds the entire knee by grouping muscle tendons, aponeurosis and ligaments maintain contact between the articular surfaces along with the collateral.

The popliteus is a small fan-shaped muscle that originates on the lateral side of the femoral condyle and inserts on the medial side of the posterior tibia. This muscle unlocks the knee to permit flexion by initiating lateral rotation of the femur on the tibia.

Tiberio (1987) has hypothesized a mechanism by which femoral rotations may compensate for excess internal rotation of the tibia caused by excess pronation. As mentioned earlier, the tibia must be internally rotated relative to the femur to relax the ligaments and allow knee flexion. Internal rotation of the tibia serves to ‘unlock’ the knee allowing shock absorption during gait for example. The tibia must then externally rotate relative to the femur to allow for knee extension during midstance. During gait, excessive subtalar pronation would delay external rotation of the lower leg thus limiting the extension at the knee which is a requirement for ambulation during midstance. Tiberio (1987) suggested a mechanism by which the femur may increase its internal rotation to place the tibia in relative external rotation thus permitting knee extension. This excess femoral rotation is speculated to lead to overuse injuries (Tiberio, 1987).

The transfer of tibial rotation to the femur is not well understood. During quiet stance, Khamis et al, (2006) have shown that increasing calcaneal eversion by 5.94 degrees, increased internal rotation of the tibia by 4.75 degrees and increased the internal rotation of the thigh by 4.21 degrees suggesting that internal rotation of the tibia is accompanied by internal rotation of the femur during quiet stance. Levens et al (1948) were amongst the first to investigate thigh rotations during gait and concluded that during normal locomotion, the femur rotates in the same direction as the tibia but with less magnitude. During the initial portion of the stance phase when the foot is known to evert, the tibia and the femur internally rotate. During the later portion of the stance phase when the foot is known to supinate, the tibia and femur externally rotate.

Studies addressed whether or not excess pronation lead to excess femoral rotations in support of Tiberio's (1987) theoretical mechanism discussed previously. During a running study MacLean et al (2006) found no differences in femoral and tibia rotations between a healthy and an excess pronators group. The authors of this study only corrected excess pronation with a 5 degree post on the orthotic which may have been too small of a difference to be detected. Reischl et al (1999) found small and unsystematic changes in femoral rotation when correcting excess pronation which may have been due to the small calcaneal eversion excursion. Buchbinder et al (1979) supported Tiberio's (1981) theoretical mechanism by stating that an increased femoral rotation occurs when the lower leg is excessively internally rotated.

iv. The hip joint

The hip consists of a large ball and socket joint between the head of the femur and the acetabulum. This multiaxial ball and socket joint is designed for stability and weight bearing. Movements at this joint include flexion, extension, abduction, adduction, medial rotation, lateral rotation and circumduction. The large cup shaped acetabulum consists of both articular and non-articular parts. The non-articular part is rough and forms a shallow circular depression in central and inferior parts of the acetabular floor. The articular surface is broad and surrounds the anterior, superior and posterior margins of the acetabular fossa. The smooth crescent-shaped articular surface is broadest superiorly where most of the body's weight is transmitted through the pelvis to the femur. The acetabular fossa provides attachment for the ligament of the head of the femur.

The axis of the femoral neck runs obliquely, superiorly, anteriorly and medially while the axis of the acetabulum runs obliquely inferiorly, anteriorly and laterally. The head of the femur is not completely covered by the acetabulum as the antero-superior surface is exposed. The position of the femur in the acetabulum can be explained from an evolutionary viewpoint. It has been shown that the spherical head of the femur rests completely in the acetabulum of a hip that is flexed by 90 degrees, slightly abducted and slightly laterally rotated. This position describes a quadrupedal position. This represent the true position of the hip but the evolutionary transition from quadrupeds to biped gait has caused a loss of the coincidence of the articular surfaces of the hip joint. During bipedal stance, the head of the femur rests anteriorly 10-30 degrees in the acetabulum. This angle is known as the angle of anteversion and is defined as the angle between an imaginary transverse line that runs medially to laterally through the knee joint and an imaginary transverse line passing through the center of the femoral head and neck (Crane, 1959).

The fibrous membrane that encloses the hip joint is thick and strong. Ligaments reinforce the external surface of the fibrous membrane and stabilize the joint. These ligaments are the iliofemoral (anterior to the hip joint), pubofemoral (anteroinferior to the hip joint) and ischiofemoral (reinforces the posterior aspect of the fibrous membrane) ligaments. The fibers of all three ligaments are oriented in a spiral fashion around the hip joint so that they become taut when the joint is extended and slightly internally rotated. This stabilizes the joint and reduces the amount of muscle energy required to maintain a standing posture. The iliofemoral ligament, the strongest of the hip ligaments, provides passive restraint to hip hyperextension and external rotation. The pubofemoral ligament resists hyper-abduction and extension and the ischiofemoral ligament tightens with extension and internal rotation (Watkins, 1999).

If the ligaments reach their limit in stability demands, forces are transferred to the sacroiliac joints and subsequently to the lumbar joints (Porterfield and deRosa, 1991). Motion of the hip can therefore influence pelvic and subsequently lumbar mechanics (Rothbart, 2002).

v. The Pelvis and Lumbar Spine

Each pelvic bone is formed of three bones: the ilium, ischium and the pubis which fuse together during childhood. The ilium is superior and the pubis and ischium are anteroinferior and posteroinferior respectively. The sacroiliac joints are the joints between the sacrum, an inverted triangle formed by the fusion of the five sacral vertebrae, and left and right iliac bones, which are part of the posterior pelvis. Besides muscular connections, extensive fibrous connections exist between the sacrum and pelvis and the sacrum and the lumbar spine notably the sacrotuberous ligament which is continuous with the biceps femoris muscle. As a consequence of the tightness of the fibrous connections and of the undulated articular surfaces between the sacrum and ilium, mobility of the sacroiliac joint is very limited (Egund et al, 1978, Mooney, 1997). When the pelvis tilts anteriorly, the sacrum is induced into a forward tilt causing an exaggerated forward curvature of the lumbar spine also known as a lordosis (Egund et al, 1978; Levine and Whittle, 1996). When the pelvis tilts backwards, the lumbar spine is forced into a kyphosis which is defined as a backwards curvature of the lumbar spine (Levine and Whittle, 1996).

The effects of increase internal femoral rotation on pelvic tilt are not well documented. Although several researchers have suggested the possibility of excess pronation affecting the pelvis and lumbar spine (Tiberio, 1987; Rothbart et al, 1988; Genova and Gross, 2000), only one provides evidence of an effect of excess foot eversion on pelvic tilt. Khamis et al (2006) noted that everting the calcaneus by 4.8 degrees induced an anterior pelvic tilt of 0.81 degrees during quiet stance which was statistically significant at a p-value of less than 0.05. In 40% of the participants, increasing calcaneal eversion by 4.8 degrees caused an anterior tilt of two to three degrees. This study did not investigate the physical characteristics that may have been similar in the participants that were more prone to respond to orthotics when compared to other. This study also did not address the effects of calcaneal eversion on the spine and neglects to address the effects of foot inversion.

The mechanical effects of calcaneal eversion and inversion on the lumbar spine are unknown. Several authors have previously suggested that low-back pain may occur as a result of excessive stress on the lumbar spine and sacroiliac joints due to an exaggerated anterior pelvic tilt (Denslow, JS et al, 1962; Caillet, 1981). Treatments in these cases are focused on decreasing the amount of anterior pelvic tilt and concurrently reducing the depth of lumbar lordosis (Kisner et al, 1990). Some foot orthoses manufacturers have speculated that by reducing excess pronation at the subtalar joint, foot orthoses reduce internal tibial and femoral rotations which in turn reduce the anterior pelvic tilt and lumbar lordosis. Reducing the degree of lumbar lordosis would then enable the symptoms of low-back pain to dissipate.

When studying the effects of foot orthoses to limit the effects of excess pronation, many authors agree that the effects are minimal and unsystematic across participants (Stacoff et al (2000); Nigg et al (1998)). In fact, the effects of excess pronation are very small above the ankle joint therefore the potential injuries resulting from excess pronation would result from repeated micro-traumas over an extended period of time. It is speculated that the changes that occur simply from calcaneal eversion and inversion may be too small to be statistically relevant in a laboratory setting.

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Appendix B

Definitions of Terms

1. **Three-dimensional angles:** The angles defined in this study are the internal angles between the segment specified by two points and a reference plane. The y-axis represents the vertical, the x-axis defines the width of the motion capture area and the z-axis defines the depth. The segment defined by two points (A_1 and A_2) is projected onto a plane perpendicular to the plane of interest such that A_2 is defined at the intersection of both planes. The angle between the segment and the plane of interest is calculated between the range of 0 and 90 degrees. The angles were calculated for each segment in relationship to the three planes (xy, xz, yz).

2. **Tibial Rotation:** Tibial movement is defined in the three planes. The segment is defined by the lateral and medial tibial condyles. The medial condyle is the point defined at the intersection of the two planes. Tibial rotation is defined in the transverse plane. A positive angle represents external rotation and a negative angle represents internal rotation when compared to the neutral position.

3. **Femoral Rotation:** Femoral movement is defined in the three planes. The segment is defined by the lateral and medial femoral condyles. The medial condyle is the point defined at the intersection of the two planes. Femoral rotation is defined in the transverse plane. A positive angle represents external rotation and a negative angle represents internal rotation when compared to the neutral position.

4. **Pelvic tilt:** Pelvis movement is defined in the three planes. The segment is defined by the anterior superior iliac spine and the posterior superior iliac spine. The posterior superior iliac spine is the point defined at the intersection of the two planes. Pelvic tilt is defined in the sagittal plane. A positive angle represents an anterior tilt of the pelvis and a negative angle represents a posterior tilt of the pelvis when compared to the neutral position.

5. **Lumbar lordosis:** Lumbar lordosis and kyphosis are defined in the sagittal plane. The first segment is defined between the first lumbar vertebrae and the third lumbar vertebrae. The first angle is the interior angle between the segment and the xz plane with the third lumbar vertebrae as the anchor point. The second segment is defined between the third lumbar and first sacral vertebrae. This second angle is the interior angle between the segment and the xz plane with the first sacral vertebrae as the anchor point. Adding the two angles provides the absolute angle between the two segments. A positive angle represents a decrease in the forward curvature of the spine and a negative angle represents an increase in the forward curvature of the spine.

Appendix C

Procedures for the Determination of Ranges of Motion

1. **Hallux dorsiflexion:** The participants sat on a table with their legs hanging over the edge. The investigator held the leg lower than the height of the table and placed the pivot of the goniometer on the based of the first proximal metatarsal with one branch following the long axis of the hallux and the other following the long axis of the foot. The hallux was then dorsiflexed to the point of resistance. The protocol was repeated for both feet and the maximum angle of dorsiflexion was recorded.

2. **Ankle dorsiflexion:** The participants sat on a table with their legs hanging over the edge. The investigator held the leg lower than the height of the table and placed the pivot of the goniometer on the lateral malleolus of the ankle being tested. One branch of the goniometer followed the long axis of the foot while the other ran up the tibia. The investigator placed the palm of her hand on the ball of the foot and asked the participant to relax while she dorsiflexed the foot as far as possible. The protocol was repeated for both feet and the maximum angle of dorsiflexion was recorded.

3. **Ankle plantarflexion:** The participants sat on a table with their legs hanging over the edge. The investigator held the leg lower than the height of the table and placed the pivot of the goniometer on the lateral malleolus of the ankle being tested. One branch of the goniometer followed the long axis of the foot while the

other ran up the tibia. The investigator placed the palm of her hand on the top of the foot and asked the participant to relax while she plantarflexed the foot as far as possible. The protocol was repeated for the both feet and the maximum angle of plantarflexion was recorded.

4. **Knee flexion:** To measure knee flexion, the participants were asked to lie down with their abdomen in contact with the table, their legs extended and their feet hanging over the edge of the table for comfort. The investigator placed the pivot of the goniometer on the center of rotation of the knee. A branch of the goniometer aimed along the tibia while the other was lined up with the femur. The investigator flexed the knee as far as possible while holding on to the ankle with one hand and holding the thigh down to the table with the other. The protocol was repeated for both legs and the maximum angle of flexion was recorded.

5. **Knee extension:** The participants sat on a table with their legs hanging over the edge. The investigator placed the pivot of the goniometer on the center of rotation of the knee. A branch of the goniometer aimed along the tibia while the other was lined up with the femur. The investigator held the thigh down with one hand and elevated the shank with the other to extend the knee. The protocol was repeated for both legs and the maximum angle of extension was recorded.

6. **Hip flexion:** The participants were lying on their back with both legs extended and resting on the table. The pivot of the goniometer was placed on the greater

trochanter with one branch aimed along the trunk and the other down the femur. The investigator stabilized the pelvis by pressing it firmly against the table with one hand and held onto the proximal shank with the other. Both legs remained straight and the leg that was not held by the investigator remained in contact with the table throughout the measurement. The investigator flexed the hip of the participant pushing the leg as far as it would go before the leg bent, the other leg lifted off the table or the participant felt pain. The protocol was repeated for the both legs.

7. **Internal hip rotation:** The participants were lying on their back with both legs extended and resting on the table. The investigator flexed the knee of one leg to 90 degrees and the hip to 90 degrees. Holding onto to distal end of the shank, the investigator rotated the hip internally. The pivot of the goniometer was placed on the knee with one branch pointing towards a vertical line on the table and the other down the tibia. The investigator stabilized the pelvis by holding it firmly against the table. The protocol was repeated for the both legs and the maximum angle of internal hip rotation was recorded.

8. **External hip rotation:** The participants were lying on their back with both legs extended and resting on the table. The investigator flexed the knee of one leg to 90 degrees and the hip to 90 degrees. Holding onto to distal end of the shank, the investigator rotated the hip externally. The pivot of the goniometer was placed on the knee with one branch pointing towards a vertical line on the table and the

other down the tibia. The investigator stabilized the pelvis by holding it firmly against the table. The protocol was repeated for the both legs and the maximum angle of external hip rotation was recorded.

9. **Pelvic range of motion:** In a standing position, participants were instructed to maximally tilt their pelvis anteriorly and posteriorly while keeping their legs extended. Static photos were taken from the sagittal plane and the range of motion was calculated by measuring the difference in pelvic tilt between the anteriorly tilted pelvis and the posteriorly tilted pelvis.

10. **Lumbar range of motion:** In a standing position, participants were instructed to maximally tilt their pelvis anteriorly and posteriorly while keeping their legs extended. This created a lumbar lordosis and kyphosis respectively. Static photos were taken in the sagittal plane and the range of motion was calculated by measuring the difference between the maximum value of lumbar lordosis and the maximum value of lumbar kyphosis. Lordosis and Kyphosis are defined as the angle between the segment created by the L1 and L3 markers and the segment created by the L3 and S1 markers. An angle above 180 degree represents a kyphosis and an angle below 180 degrees indicates a lordosis.

11. **Spine range of motion:** Participants were instructed to bend forward at the waist as far as possible and backwards as far as they could while keeping their legs extended. Static photographs were taken in the sagittal plane at maximal flexion

and extension. The difference between the two measurements gave the investigator an indication of the range of motion of the spine.

12. **Calcaneal position:** Participants had two reflective markers placed along a line bisecting the calcaneus into a right and left half. These markers created a line. Two reflective markers were then placed along a line bisecting the shank into two halves. These markers also created a line. The angle created at the intersection of these two lines represents the degree of calcaneal inversion/eversion. A zero degree value represents a perfectly erect calcaneus with respect to the shank. A positive value represents calcaneal eversion and a negative value represents calcaneal inversion. Data were collected with participants in a relaxed stance.

Appendix D

Participant Consent form

SUBJECT INFORMATION AND CONSENT FORM

Investigating the mechanical relationship between the feet and low-back

Principal Investigator:
Dr David J. Sanderson, Professor, School of Human Kinetics, University of British Columbia, phone: (604) 822-4361

Co-Investigators:
Karine Duval, Graduate Student, School of Human Kinetics, U.B.C. phone (604) 822-0941

Your participation is voluntary.

You are being invited to take part in this research study but keep in mind that your participation is entirely voluntary, so it is up to you to decide whether or not to take part in this study. Before you decide, it is important for you to understand what the research involves. This consent form will tell you about the study, why the research is being done, what will happen to you during the study and the possible benefits, risks and discomforts.

If you wish to participate, you will be asked to sign this form. If you do decide to take part in this study, you are still free to withdraw at any time and without giving any reasons for your decision.

If you do not wish to participate, you do not have to provide any reason for your decision not to participate nor will you lose the benefit of any medical care to which you are entitled or are presently receiving.

Please take time to read the following information carefully and to discuss it with your family, friends, and doctor before you decide.

You do not waive any of your legal rights to compensation by signing this consent form.

Purpose:

Background: The goal of this study is to investigate the effects of induced excess internal and external leg rotations on pelvic tilt and lumbar lordosis. A secondary purpose is to investigate the effects of obesity on the effects of excess leg rotations.

Procedures:
Participants will visit the lab once for approximately two hours. Participants will be asked to stand quietly for 5 seconds in eighteen different foot position for two different weight bearing conditions. Sufficient time will be allowed between conditions to prevent fatigue.

The independent variable will be the position of the feet (40, 20, 10, 5, 2.5 externally and internally rotated position and a neutral position) and the weight the participant must bear in the standing position (normal body weight and weight increased to match a body mass index of 30). The dependent variables will be pelvic tilt and lumbar lordosis.

Exclusion:
If you meet any of the following criteria, you will be excluded from this study:

- If you have any known neuromuscular and/or balance disorder
- If you excessively pronate at the subtalar joint
- If you have experienced a musculoskeletal injury to either lower limbs within the past 18 months.
- If you have a leg length discrepancy greater than 5 mm.
- If you are under 19 years of age
- If you have a body mass index above 25
- If you are not comfortable maintaining a standing position with the second toe internally and externally rotated 40 degrees.

Risks:
The duration of quiet stance required for this experiment is short and it is unlikely that you will feel any discomfort from the weight you will be required to bear. In addition, between each trial there will be sufficient time to relax and recover. In the unlikely event that there is any discomfort we will stop the session. You may stop at any time.

Remuneration/Compensation:
You will not receive any reimbursement for expenses, gifts-in-kind and/or payment by participating in this study.

Confidentiality:
Any information regarding subject identification resulting from this study will be kept strictly confidential. All documents will be identified only by code number and kept in a locked and secured filing cabinet. Data will be kept up to a maximum of ten years and will only be accessible to Dr. Sanderson. Data files stored on computer will be labeled using code numbers on a computer in the Biomechanics Laboratory. You will not be identified by name in any reports of the completed study.

Contact for information about the study:
If you have any questions or require further information with respect to this study, you may contact the Dr David Sanderson at (604) 822-4361.

Contact for information about the rights of research subjects:
If you have any concerns about your treatment or rights as a research subject, you may contact the Director of Research Services at the University of British Columbia, at (604) 822 8598.

Consent:
Your participation in this study is entirely voluntary and you may refuse to participate or withdraw from the study at any time without any consequence to your class standing. Your signature below indicates that you have received a copy of this consent form for your own records.

Your signature indicates that you consent to participate in this study.

____

Participants signature Date

____

Investigator signature Date

Certificate of Ethics Approval

The University of British Columbia
Office of Research Services
Behavioral Research Ethics Board
Suite 102, 6190 Agronomy Road,
Vancouver, B.C. V6T 1Z3

CERTIFICATE OF APPROVAL - MINIMAL RISK

PRINCIPAL INVESTIGATOR:	INSTITUTION / DEPARTMENT:	UBC BREB NUMBER:
David J. Sanderson	UBC/Education/Human Kinetics	H07-00568

INSTITUTION(S) WHERE RESEARCH WILL BE CARRIED OUT:

Institution	Site
UBC	Point Grey Site

Other locations where the research will be conducted:
N/A

CO-INVESTIGATOR(S):
N/A

SPONSORING AGENCIES:
N/A

PROJECT TITLE:
Investigating the mechanical relationship between the feet and low back

CERTIFICATE EXPIRY DATE: June 28, 2008

DOCUMENTS INCLUDED IN THIS APPROVAL:

DATE APPROVED:
June 28, 2007

Document Name	Version	Date
Consent Forms:		
Consent form	N/A	January 6, 2007
Advertisements:		
Recruitment poster	N/A	January 6, 2007

The application for ethical review and the document(s) listed above have been reviewed and the procedures were found to be acceptable on ethical grounds for research involving human subjects.

Approval is issued on behalf of the Behavioural Research Ethics Board and signed electronically by one of the following:

Dr. Peter Suedfeld, Chair
Dr. Jim Rupert, Associate Chair
Dr. Arminee Kazanjian, Associate Chair
Dr. M. Judith Lynam, Associate Chair
Dr. Laurie Ford, Associate Chair

Appendix E

General Descriptive Data for all Participants

		1	2	3	4	5	6	7	8	9	10	11	12
Age		25.0	25.0	22.0	26.0	24.0	23.0	28.0	23.0	23.0	35.0	35.0	25.0
Mass (kg)		76.0	64.0	62.0	57.0	54.0	61.0	82.0	77.0	52.0	93.0	72.0	62.0
Height (m)		1.7	1.8	1.7	1.7	1.7	1.7	1.7	1.8	1.6	2.0	1.7	1.7
Sex		M	M	F	F	F	F	M	F	F	M	M	M
Stance		18"	18"	15"	15"	15"	15"	18"	18"	15"	18"	18"	18"
Longitudinal arch (cm)	Left	1.0	2.1	2.0	2.5	2.5	1.8	2.2	2.1	2.0	1.4	2.0	1.3
	Right	1.0	2.1	2.5	2.4	2.5	1.9	2.3	1.8	2.2	1.5	1.9	1.5
Navicular (cm)	Left	4.2	5.6	4.5	5.0	5.2	4.6	5.4	5.0	4.5	4.7	5.0	4.4
	Right	4.0	5.0	5.0	5.0	5.3	4.6	5.4	5.0	4.5	5.1	5.0	4.4
Subtalar eversion (º)	Left	8.0	3.0	7.0	4.0	9.0	3.0	10.0	9.0	8.0	9.0	7.0	10.0
	Right	4.0	1.0	4.0	2.0	5.0	5.0	10.0	7.0	6.0	8.0	7.0	7.0
Hallux dorsiflexion (º)	Left	67.0	65.0	84.0	70.0	53.0	70.0	60.0	70.0	86.0	60.0	71.0	57.0
	Right	68.0	68.0	85.0	70.0	60.0	70.0	65.0	70.0	80.0	59.0	76.0	57.0
Ankle dorsiflexion (º)	Left	70.0	70.0	74.0	70.0	64.0	70.0	68.0	60.0	66.0	71.0	67.0	70.0
	Right	78.0	78.0	64.0	70.0	65.0	70.0	62.0	66.0	69.0	61.0	68.0	73.0
Ankle plantarflexion (º)	Left	180.0	175.0	180.0	180.0	170.0	175.0	175.0	178.0	176.0	175.0	175.0	176.0
	Right	180.0	180.0	180.0	180.0	170.0	176.0	177.0	175.0	175.0	171.0	174.0	176.0
Knee extension (º)	Left	175.0	178.0	176.0	175.0	176.0	181.0	178.0	178.0	181.0	178.0	185.0	177.0
	Right	175.0	179.0	176.0	179.0	178.0	181.0	176.0	179.0	181.0	178.0	183.0	177.0
Knee flexion (º)	Left	55.0	44.0	38.0	35.0	40.0	42.0	46.0	49.0	32.0	43.0	42.0	55.0
	Right	60.0	42.0	40.0	35.0	40.0	40.0	44.0	49.0	34.0	42.0	45.0	45.0
Hip flexion (º)	Left	76.0	120.0	105.0	115.0	103.0	88.0	107.0	111.0	110.0	103.0	104.0	104.0
	Right	89.0	114.0	105.0	97.0	110.0	72.0	106.0	100.0	107.0	115.0	96.0	107.0
Hip internal rotation (º)	Left	32.0	40.0	47.0	50.0	52.0	40.0	41.0	39.0	32.0	51.0	51.0	47.0
	Right	35.0	40.0	40.0	53.0	57.0	40.0	45.0	35.0	35.0	55.0	45.0	47.0
Hip external rotation (º)	Left	35.0	28.0	57.0	41.0	37.0	45.0	32.0	47.0	40.0	27.0	30.0	36.0
	Right	40.0	25.0	48.0	50.0	36.0	55.0	33.0	50.0	47.0	32.0	38.0	40.0

	1	2	3	4	5	6	7	8	9	10	11	12
Pelvic Tilt (º)												
Anterior tilt	-19.5	-14.5	-22.9	-40.0	-15.8	-26.0	-37.0	-22.0	-26.0	-30.0	-18.0	-16.0
Posterior Tilt	-2.9	-6.0	5.7	5.2	5.5	-7.2	-5.7	0.0	-3.0	-2.6	0.0	-3.2
Neutral position		-11.0	-8.6	-17.0	-2.6	-14.0	-14.0	-9.6	-13.0	-5.0	-9.1	-7.2
Spine angle (º)												
Lordosis	153.0	150.0	94.0	125.0	141.0	150.0	163.0	150.0	152.0	162.0	156.0	169.0
Kyphosis	166.0	156.0	183.0	160.0	163.0	170.0	188.0	154.0	171.0	174.0	170.0	180.0
Max Flexion	95.0	77.0	99.0	120.0	109.0	116.0	88.0	93.0	103.0	115.0	123.0	107.0
Max Extension	-38.0	-34.0	-36.0	-32.0	-20.0	-55.0	-32.0	-42.0	-29.0	-9.5	-46.0	-47.0
Subtalar angle (º)												
Left	-5.0	0.0	-2.0	0.0	-4.0	0.0	-3.0	-9.0	-5.0	-2.0	-6.0	0.0
Right	-8.0	-2.0	-7.0	-2.0	-2.0	-5.5	-12.0	-8.5	-10.0	-13.0	-8.0	-10.0
Wearing orthoses?	yes	no	yes	yes	no	no	no	no	no	yes	no	yes
History of LBP?	no	no	no	no	no	sciatica	no	no	no	no	no	no

*Stance: This represents the stance adopted during the measurements, since the apparatus used to rotate the legs only offered the choice of two stance width.

Appendix F

Individual Data for tibial rotation in degrees, femoral rotation in degrees and pelvic tilt in degrees

1. Tibial Rotation (TR) in degrees.

Left

TR	**2**	**3**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**Average**	**SD**
-40	11.8	10.0	11.4	34.8	33.7	20.4	31.2	27.4	27.6	19.8	26.9	10.1	22.1	9.4
-20	5.6	7.9	19.0	19.3	15.3	12.6	28.7	12.3	14.4	19.7	23.1	8.7	15.5	6.7
-10	7.8	2.2	18.7	11.5	6.7	7.3	18.5	7.1	9.4	8.8	7.1	3.7	9.1	5.1
-5	4.1	2.4	3.8	8.8	4.5	5.4	3.6	4.8	3.6	5.3	4.3	1.3	4.3	1.8
-2.5	4.5	1.9	2.8	9.5	6.4	2.3	2.9	0.0	5.9	4.8	3.3	-2.8	3.5	3.2
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2.5	0.8	-2.7	-1.0	3.9	-1.1	-2.5	-3.7	-0.7	-1.7	0.9	0.0	-4.0	-1.0	2.2
5	-7.3	-1.8	-2.7	1.5	-3.4	-2.4	-1.9	-3.3		0.7	-2.0	-3.6	-2.4	2.3
10	-9.4	-3.1	-8.9	-1.1	-2.9	-5.8	-4.7	-8.7	-2.1	-13.8	-4.1	-7.5	-6.0	3.7
20	-10.7	-4.7	-14.2	-5.2	-7.6	-2.0	-11.2	-16.6	-13.9	-16.5	-10.3	-12.4	-10.4	4.7
40	-32.7	-31.3	-30.0	-13.6	-19.5	-9.1	-15.5	-25.1	-22.8	-19.3	-13.8	-29.6	-21.9	7.9

Right

TR	**2**	**3**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**Average**	**SD**
-40	36.5	36.4	14.4	28.5	25.0	5.8	41.7	14.2	28.8	28.4	9.7	16.0	23.8	11.6
-20	15.1	14.2	8.7	10.0	9.9	13.4	15.6	13.5	13.6	24.4	10.1	4.6	12.7	4.9
-10	9.7	8.9	2.0	3.9	6.7	6.0	6.9	3.4	9.5	11.1	5.9	-3.3	5.9	4.0
-5	5.1	6.3	-4.5	-0.2	2.4	1.3	4.1	3.2	8.8	2.5	-5.5	-5.6	1.5	4.7
-2.5	1.8	5.9	-6.8	0.3	-3.3	1.6	0.7	0.5	1.5	5.4	-2.5	1.2	0.5	3.5
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2.5	-5.0	0.6	-0.2	-5.9	-5.6	-1.3	0.4	-1.5	2.1	2.6	-2.0	5.1	-0.9	3.4
5	-3.7	3.7	-4.0	-17.0	-2.4	-4.1	-7.1	-1.5		-8.8	-12.0	-1.8	-5.3	5.7
10	-7.1	-0.9	-10.0	-17.6	-5.9	-6.1	-9.5	-6.2	-9.8	-7.4	-15.2	-2.9	-8.2	4.7
20	-7.4	-0.2	-19.8	-22.3	-14.1	-15.0	-11.8	-17.2	-5.5	-4.6	-11.2	-10.5	-11.6	6.5
40	-14.3	-4.2	-27.2	-28.2	-15.0	-28.1	-17.0	-20.6	-16.0	-5.2	-21.4	-22.3	-18.3	8.0

2. Femoral Rotation (FR) in degrees.

Left

FR	**2**	**3**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**Average**	**SD**
-40	24.4	4.0	14.4	21.0	35.7	21.4	27.8	25.6	30.6	17.8	22.5	4.5	20.8	9.6
-20	12.7	5.9	23.6	9.4	14.2	13.4	26.3	10.6	20.7	16.4	17.6	8.3	14.9	6.3
-10	6.7	3.1	17.9	1.2	6.2	8.6	18.6	5.6	5.5	8.4	7.3	2.7	7.6	5.4
-5	2.9	2.5	2.6	-2.0	3.8	5.5	3.3	4.2	2.6	4.8	3.6	1.4	3.0	1.9
-2.5	2.8	0.4	1.0	-2.1	5.3	3.5	3.1	-1.0	4.4	-5.5	3.8	-3.4	1.0	3.4
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2.5	0.1	-1.8	-4.8	-6.6	-1.2	-1.8	-4.5	-0.7	-1.5	0.2	-1.3	-3.6	-2.3	2.1
5	0.6	-1.1	-1.4	-8.6	-3.7	-1.8	-1.8	-3.6		-0.7	-2.1	-3.0	-2.5	2.4
10	-0.5	-2.5	-7.2	-10.6	-3.5	-5.0	-4.7	-8.8	-13.9	-4.1	-3.3	-6.6	-5.9	3.8
20	-10.2	-3.7	-14.7	-14.8	-8.4	-8.4	-11.8	-14.7	-13.2	-17.0	-4.4	-11.1	-11.0	4.2
40	-39.0	-23.7	-31.1	-21.4	-28.5	-4.1	-15.2	-23.0	-20.8	-23.6	-12.1	-26.2	-22.4	9.1

Right

FR	**2**	**3**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**Average**	**SD**
-40	22.6	38.6	28.7	33.8	26.0	5.8	20.6	33.6	27.3	26.4	12.6	9.2	23.8	10.2
-20	15.9	14.3	10.0	22.0	10.6	12.6	14.8	12.7	13.9	24.1	12.2	-0.2	13.6	6.1
-10	10.1	13.3	-1.3	7.2	5.5	4.0	6.4	3.2	8.3	3.4	9.2	-9.5	5.0	5.9
-5	1.5	7.0	-4.3	2.9	1.2	1.4	3.7	2.7	6.8	2.1	11.3	-11.4	2.1	5.7
-2.5	0.4	7.7	-4.1	4.6	-3.5	1.3	0.6	-0.1	1.8	-0.7	1.7	-5.4	0.4	3.7
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2.5	5.0	4.4	-3.3	-1.2	-5.4	-1.5	-3.1	-0.4	-0.2	-3.5	-1.1	-2.8	-1.1	3.1
5	-2.7	1.0	-10.1	-20.1	-2.9	-3.6	-6.4	-1.0		-9.1	-3.2	-1.7	-5.4	5.9
10	-4.6	-1.0	-10.4	-21.2	-6.4	-6.9	-7.4	-5.8	-5.5	-9.6	-3.6	-10.0	-7.7	5.1
20	-4.7	4.7	-17.2	-17.2	-6.3	-14.1	-6.6	-15.7	-12.7	-9.3	-6.3	-15.6	-10.1	6.6
40	3.9	-1.4	-7.0	-20.9	8.3	-24.1	-14.7	-8.2	-25.2	-2.1	-17.0	-25.5	-11.2	11.8

3. Pelvic tilt (PT) in degrees.

Left

PT	**2**	**3**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**Average**	**SD**
-40	-1.2	-1.3	0.4	2.3	0.7	-1.9	-0.6	-1.7	-1.7	-3.3	-1.7	1.3	-0.7	1.6
-20	-0.3	-0.5	0.8	3.9	-0.6	-1.0	-1.8	-0.8	-0.8	-3.3	-4.4	-0.3	-0.8	2.0
-10	-1.8	0.6	0.0	1.9	-0.5	-4.4	-1.8	-1.7	-1.1	-2.7	-2.2	1.9	-1.0	1.9
-5	-1.5	-0.2	-0.3	1.9	0.6	-2.1	-1.6	-0.8	0.2	-1.0	-1.2	1.0	-0.4	1.2
-2.5	-0.1	-0.3	0.8	7.1	4.0	-2.5	-1.2	-0.8	1.0	-0.9	-0.4	5.2	1.0	2.9
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2.5	-0.3	0.5	0.6	2.5	0.7	-0.8	-0.3	-1.1	-1.7	-1.8	0.7	4.5	0.3	1.8
5	0.5	-1.6	0.3	-0.5	1.1	-1.0	-0.5	0.0		-0.2	0.3	1.5	0.0	0.9
10	0.5	-0.4	0.4	4.6	-1.1	-1.5	0.8	0.7	-1.6	0.8	0.9	2.6	0.5	1.7
20	-1.1	0.5	0.8	1.7	1.9	-1.7	1.2	0.7	-1.8	-0.1	3.6	7.2	1.1	2.5
40	4.0	7.2	2.7	7.0	3.9	-1.4	0.7	4.2	0.7	7.5	9.2	11.1	4.7	3.8

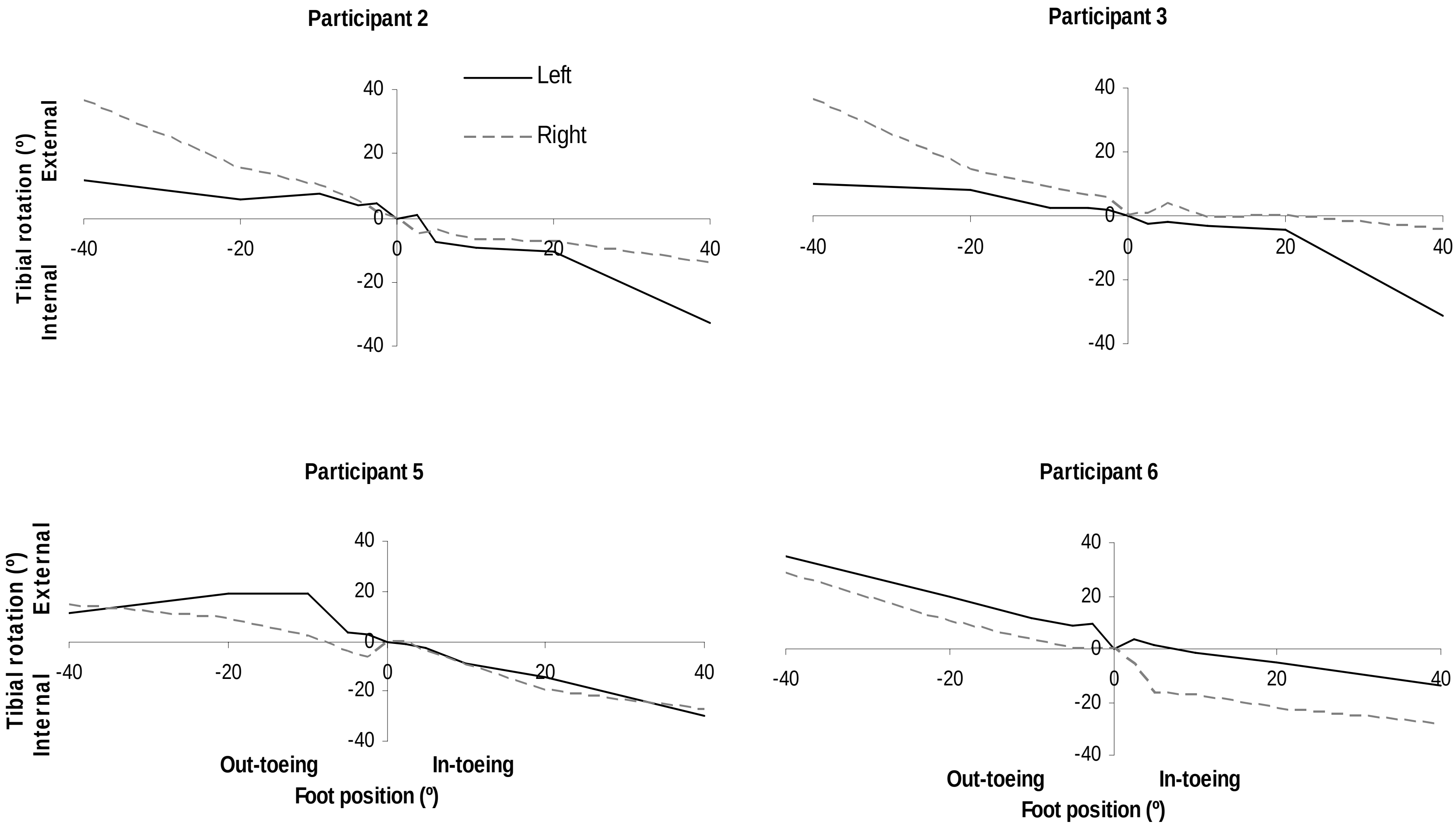
Right

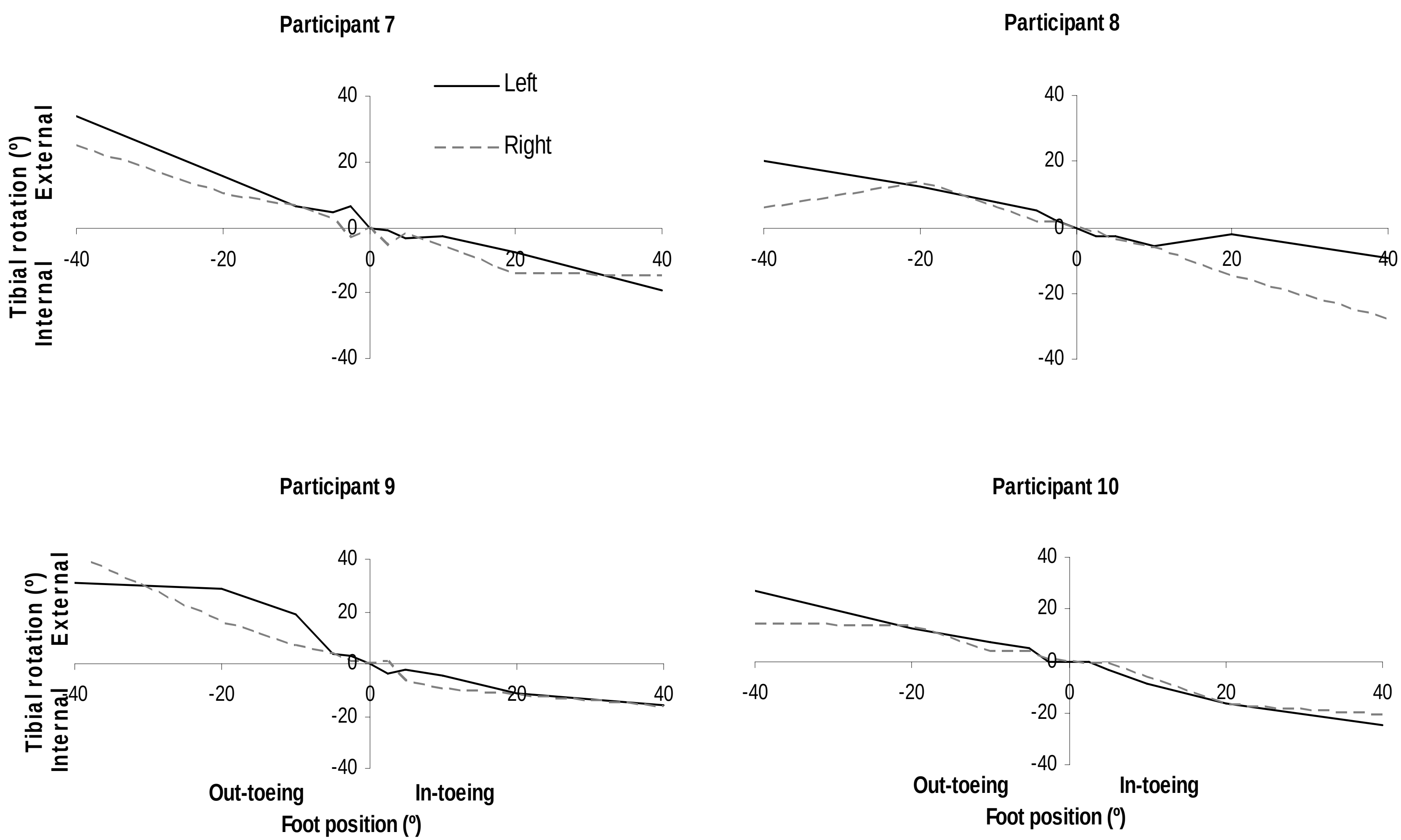
PT	**2**	**3**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**Average**	**SD**
-40	0.3	-0.1	1.3	2.3	-0.4	-1.6	3.5	-1.6	-3.4	-3.2	-1.4	0.4	-0.3	2.1
-20	1.0	-0.2	1.0	5.2	-1.5	-1.4	2.0	-1.7	-1.0	-7.3	-4.0	0.5	-0.6	3.1
-10	-0.3	0.5	-0.2	1.2	-1.8	-3.9	2.0	-2.7	-0.9	-3.1	-2.1	0.0	-0.9	1.8
-5	0.1	-0.5	0.5	3.0	-1.2	-1.8	1.3	-1.9	-0.2	-1.6	3.0	-0.4	0.0	1.7
-2.5	1.5	-0.4	1.3	5.0	3.1	-2.1	-0.7	-1.6	0.2	-2.1	-2.0	3.0	0.4	2.4
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2.5	1.2	-0.7	1.2	4.0	0.2	-1.2	1.1	-2.3	-1.3	-0.6	-1.0	2.8	0.3	1.8
5	1.9	-1.3	1.7	-0.3	0.9	-0.7	3.3	-1.1		-0.6	-1.1	-0.2	0.2	1.5
10	2.0	-0.1	1.1	4.1	-1.5	-1.1	3.7	-0.2	-1.8	-0.8	-0.8	1.0	0.5	2.0
20	0.1	0.9	0.5	3.0	-0.4	-1.0	3.1	-0.1	-2.0	-0.5	2.2	4.7	0.9	2.0
40	5.9	7.5	2.1	7.6	1.3	-0.2	3.2	4.0	0.8	3.9	5.4	8.4	4.2	2.8

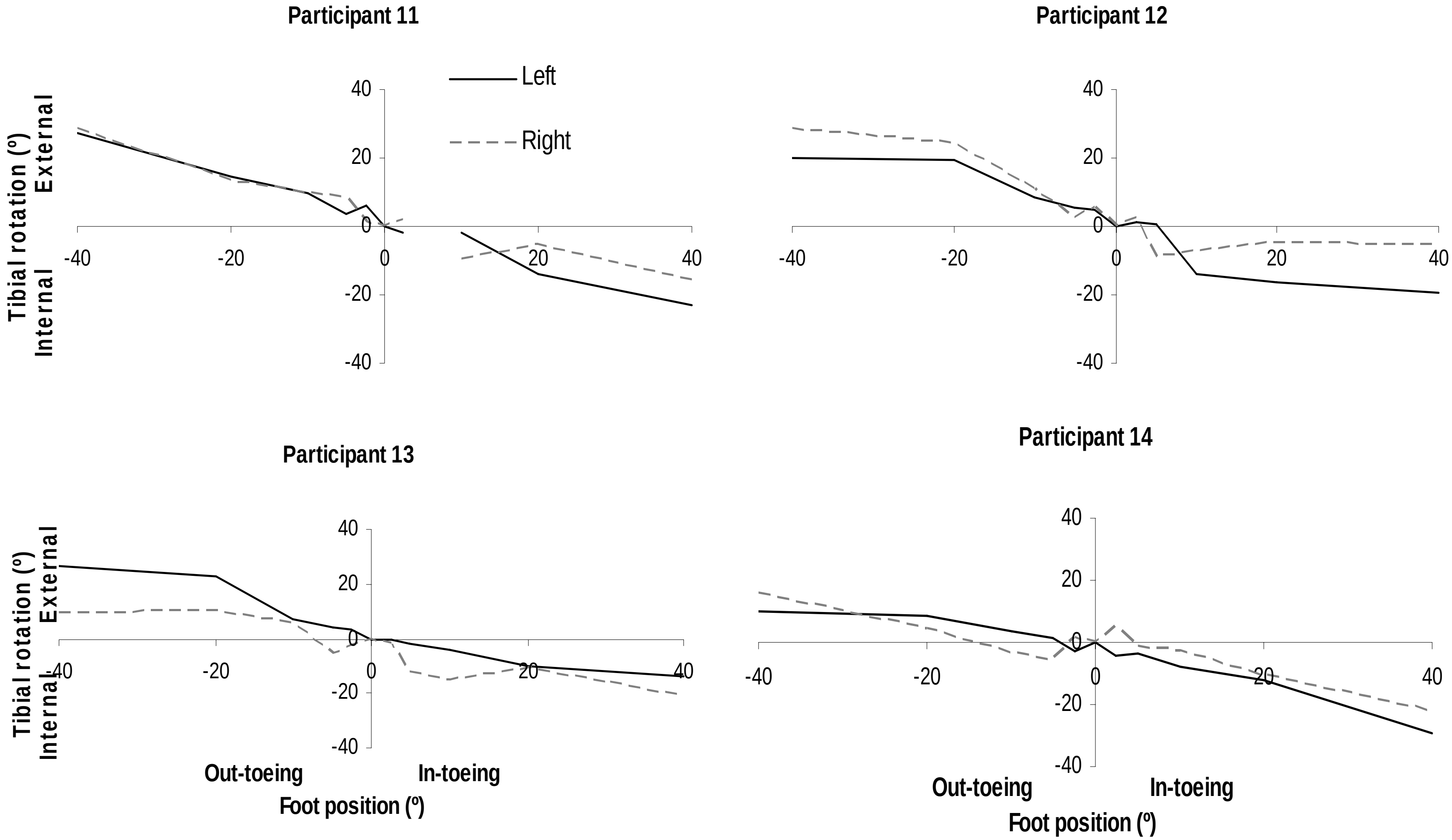
4. Lumbar angle (LA) in degrees.

LA	**2**	**3**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**Average**	**SD**
-40	-0.4	0.7	14.9	-9.8	8.0	-7.5	3.9	-3.7	12.5	-5.8	0.8	-0.8	1.1	7.7
-20	-7.7	0.2	14.1	-2.1	11.9	-10.6	3.8	2.0	10.1	0.0	0.6	-0.5	1.8	7.4
-10	-6.9	8.2	7.9	-0.8	13.0	-5.7	-8.7	2.6	10.5	-0.4	-0.9	0.5	1.6	7.0
-5	-0.6	-2.1	13.2	-4.0	12.1	-1.7	-4.2	1.1	-0.5	3.0	-6.9	-1.8	0.6	6.2
-2.5	0.9	3.0	3.2	-12.0	4.6	3.9	2.4	-0.1	12.3	3.9	0.8	-3.3	1.6	5.7
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2.5	-3.2	3.3	7.4	-3.0	1.6	1.3	-0.6	-0.9	-6.5	2.4	1.7	-5.0	-0.1	3.9
5	-12.3	8.4	6.2	-2.8	4.2	-1.3	2.0	1.0		4.2	-2.9	-8.4	-0.2	6.3
10	-11.4	10.7	0.0	4.3	-1.9	-4.7	3.6	-3.7	13.8	2.9	2.5	0.0	1.4	6.7
20	-3.1	9.2	14.1	-1.6	1.2	-6.8	4.1	-2.0	12.8	2.7	4.0	-12.3	1.9	7.8
40	5.3	11.5	2.2	-10.1	5.3	-5.6	0.5	-7.9	6.6	2.3	-0.3	6.1	1.3	6.4

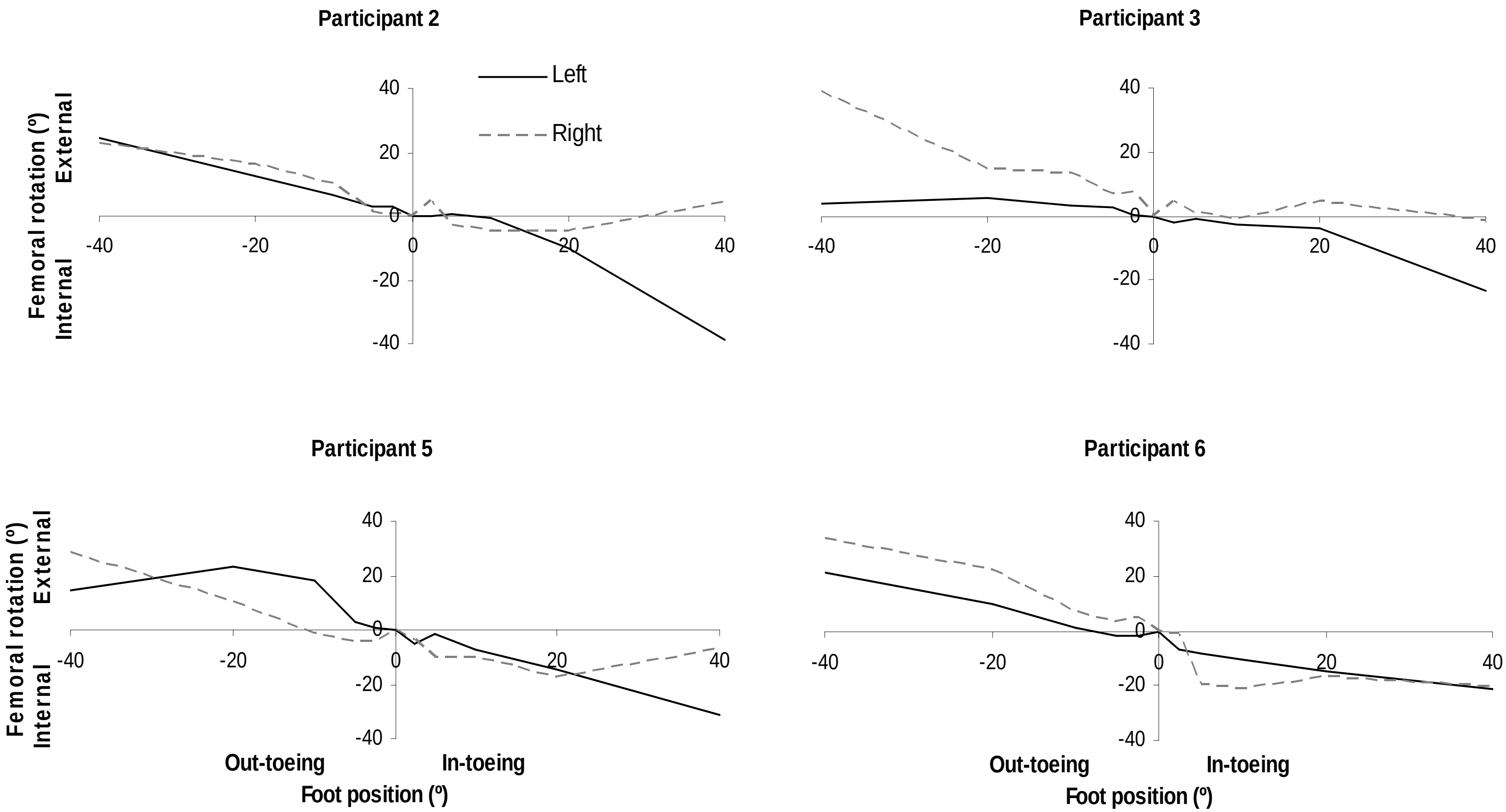
5. Individual graphs for tibial rotation

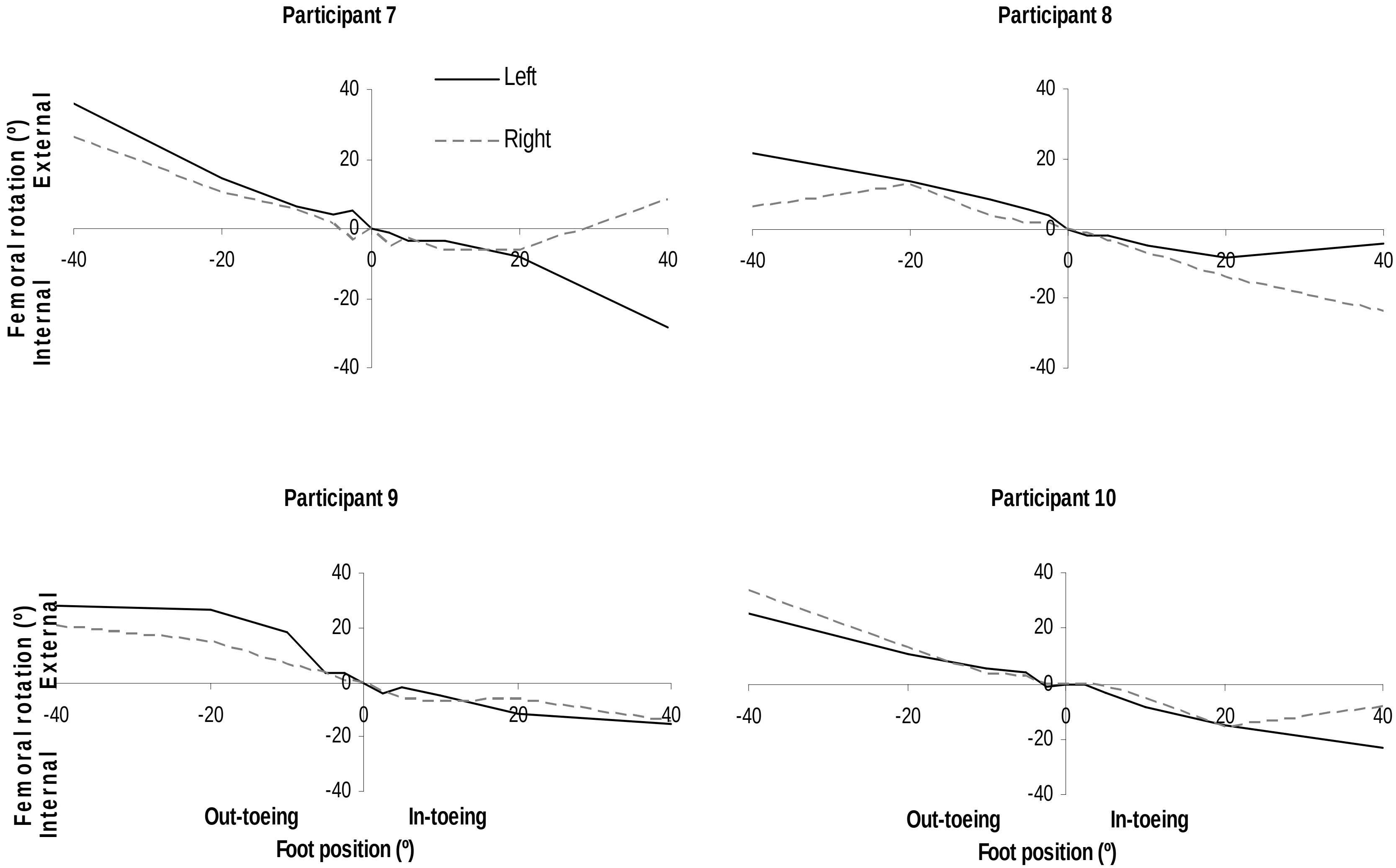


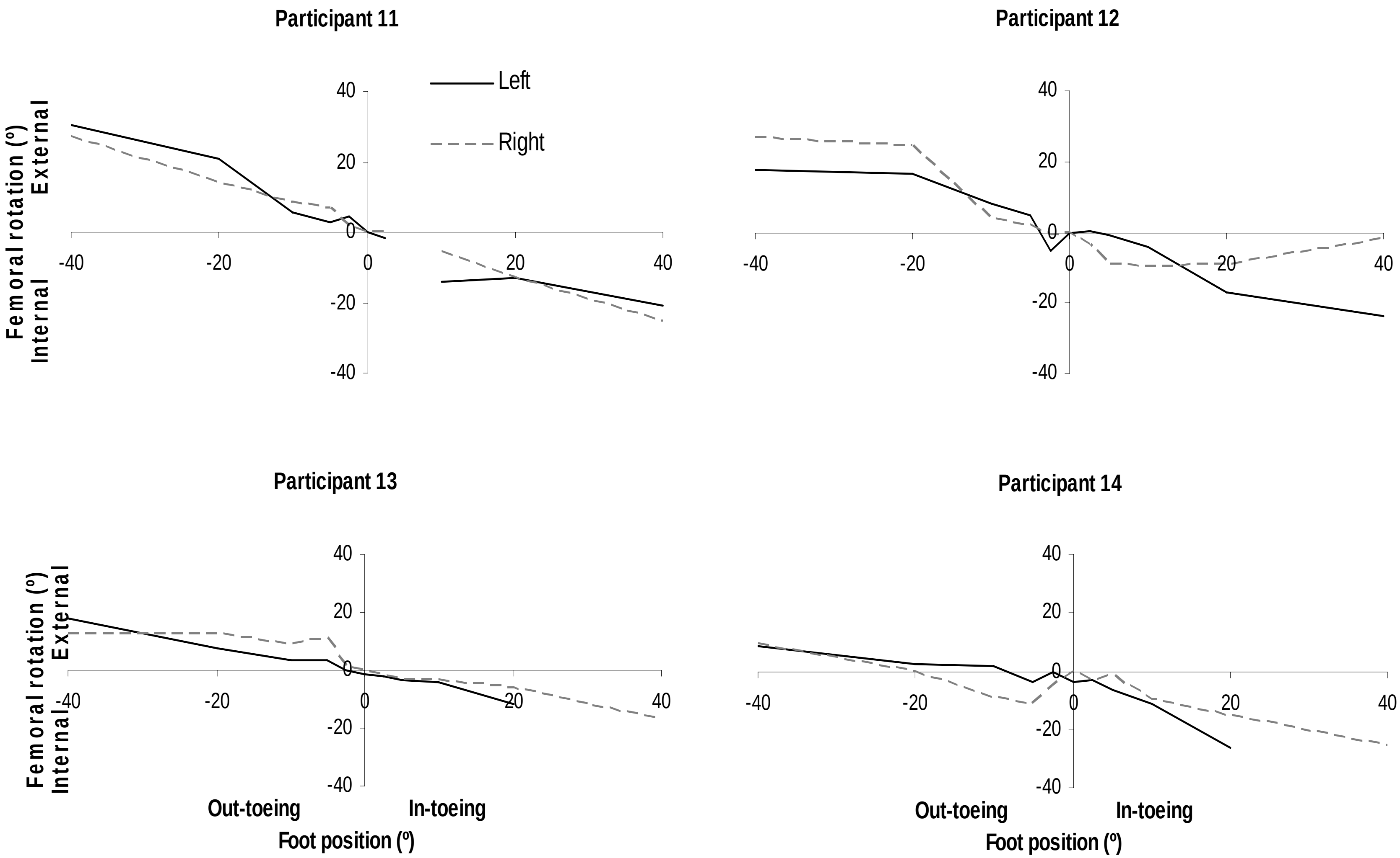

Participant 7
Left
Right
Participant 8
Participant 9
Participant 10
Tibial rotation (º)
External
Internal
Out-toeing
In-toeing
Foot position (º)
40
20
0
-20
-40


Participant 11
Left
Right
Participant 12
Participant 13
Participant 14
Tibial rotation (º)
External
Internal
Out-toeing
In-toeing
Foot position (º)
40
20
0
-20
-40

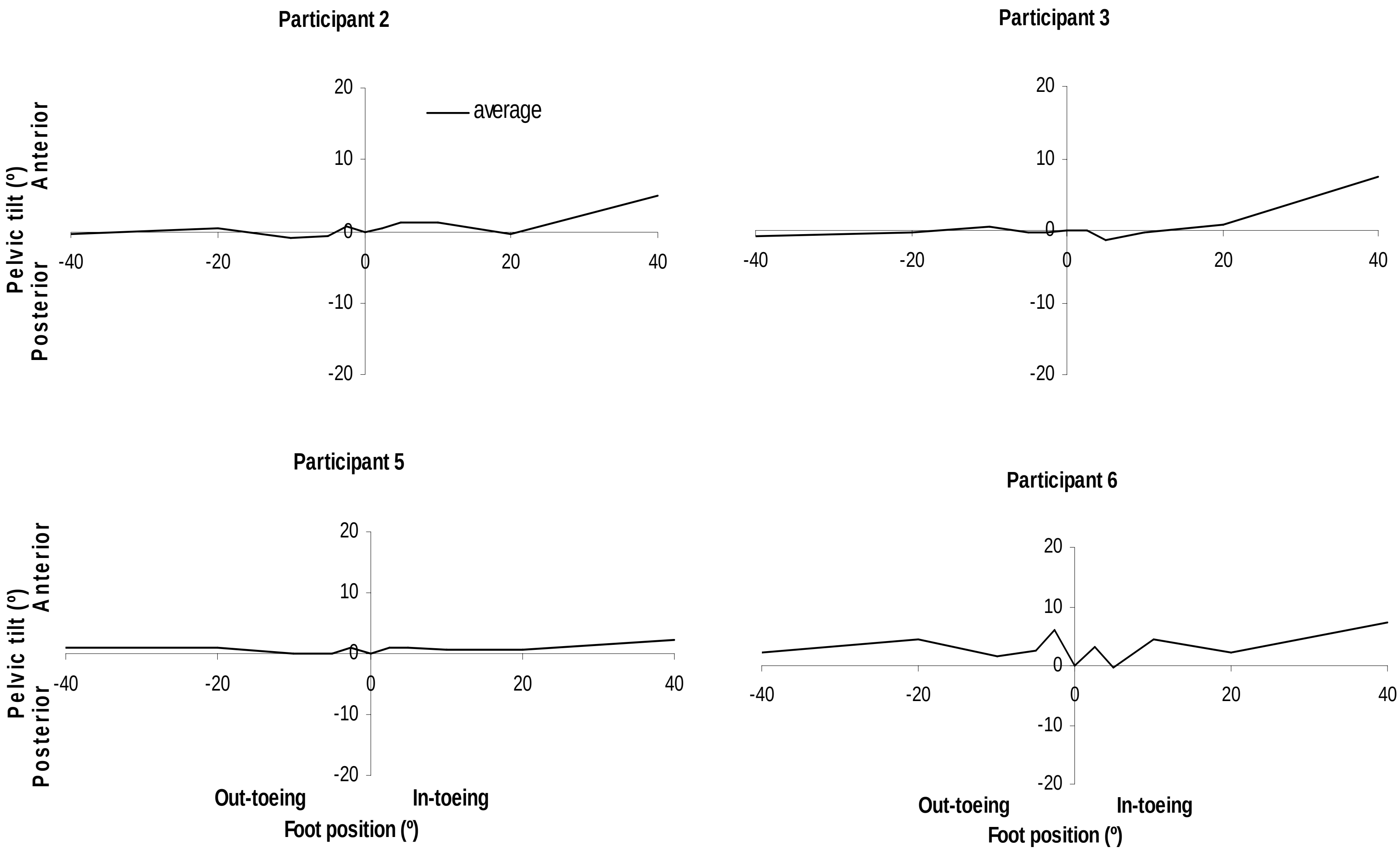
6. Individual graphs for femoral rotation

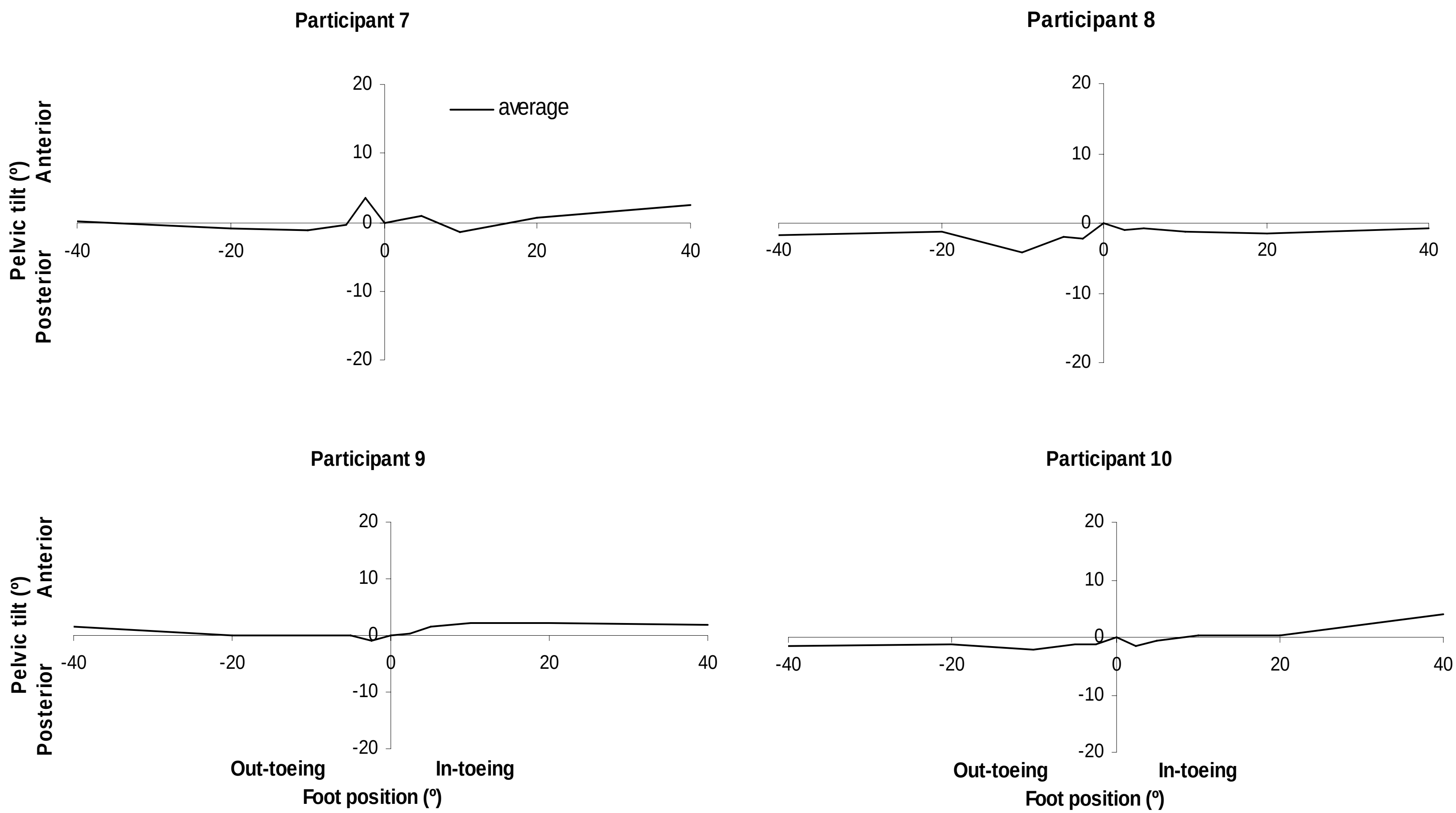


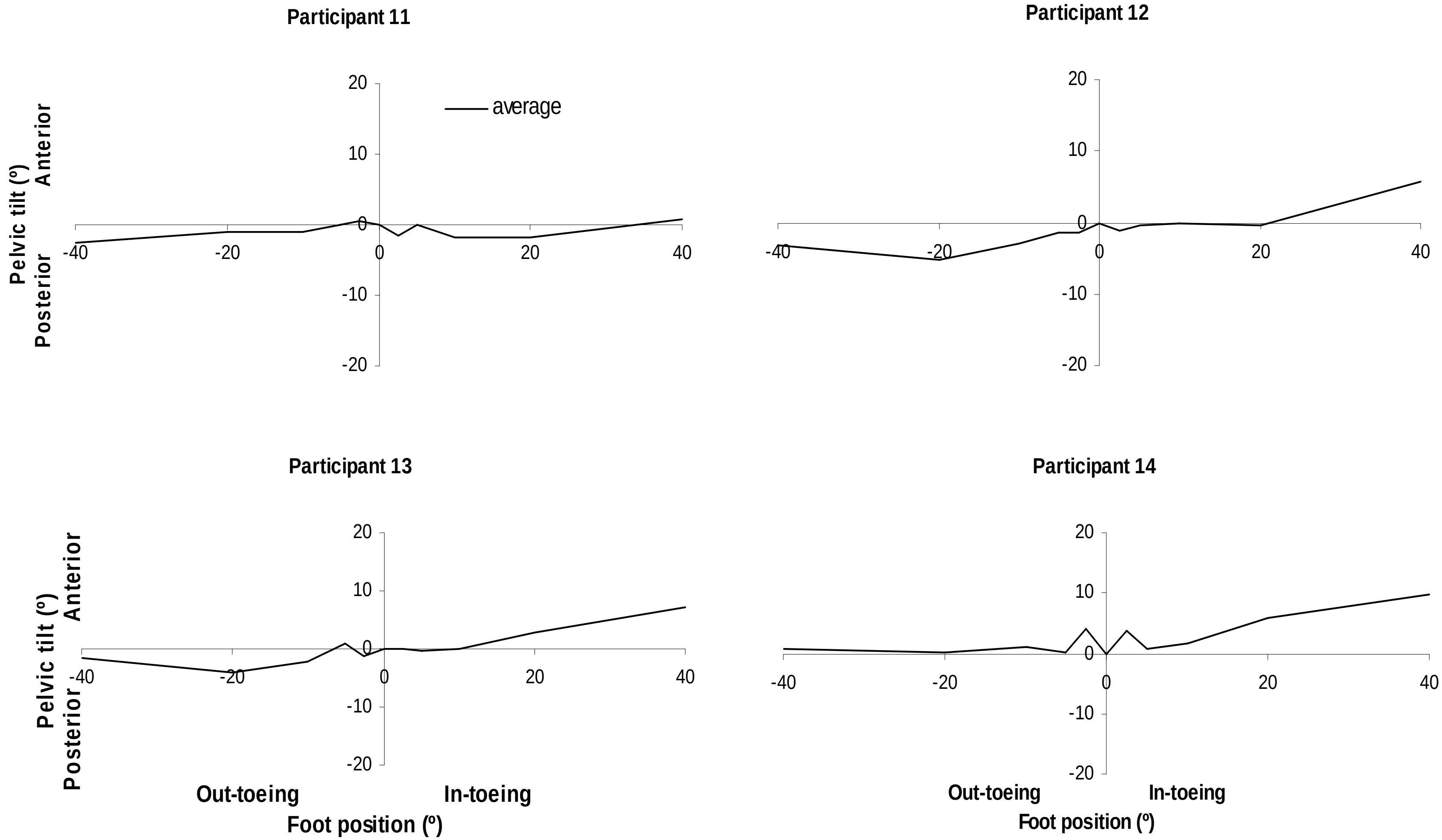

Participant 7
Participant 8
Participant 9
Participant 10
Left
Right
40
20
0
-20
-40
Femoral rotation (º)
External
Internal
Out-toeing
In-toeing
Foot position (º)


Participant 11
Participant 12
Participant 13
Participant 14
Left
Right
Femoral rotation (º)
External
Internal
Out-toeing
In-toeing
Foot position (º)
40
20
0
-20
-40

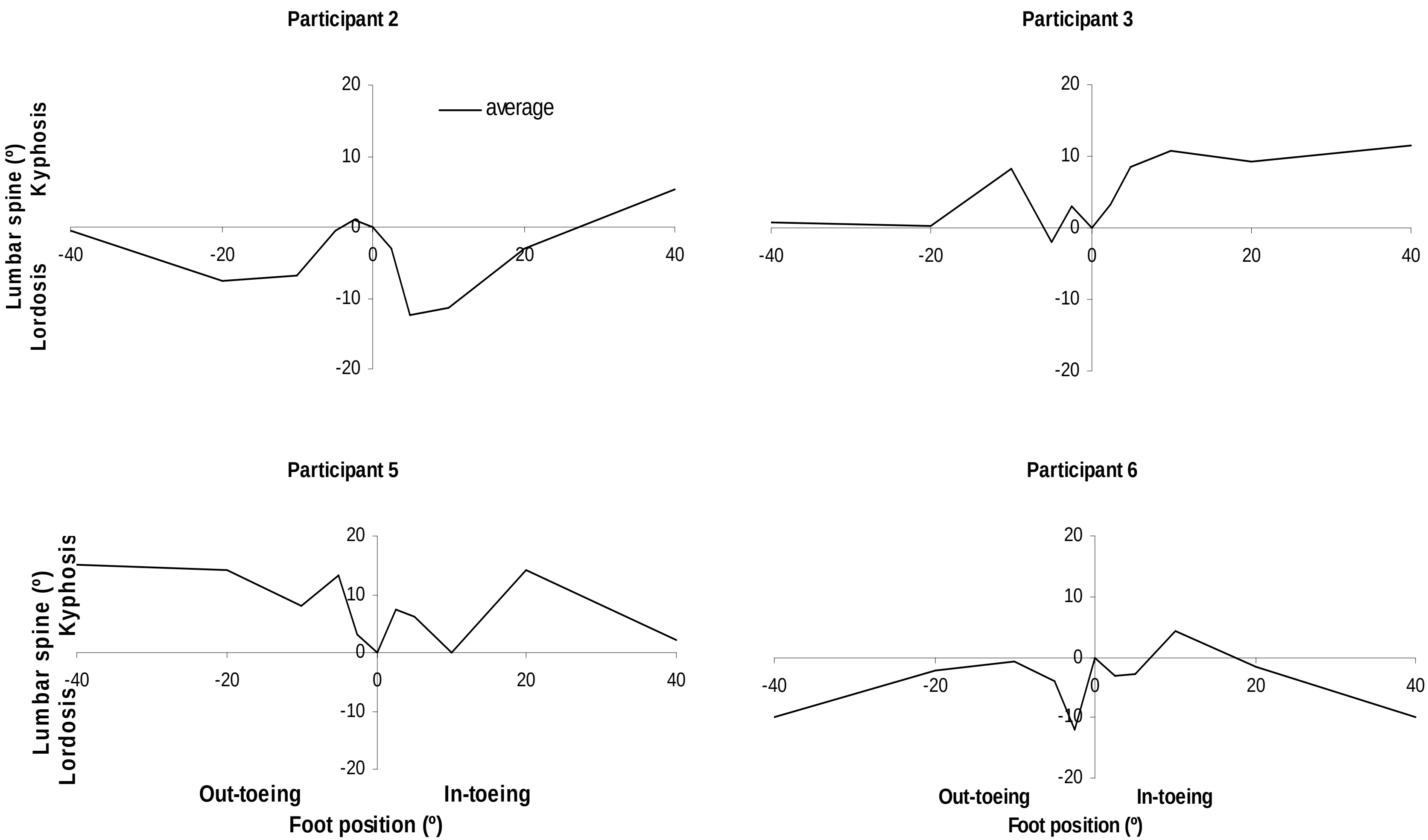
7. Individual graphs for pelvic tilt

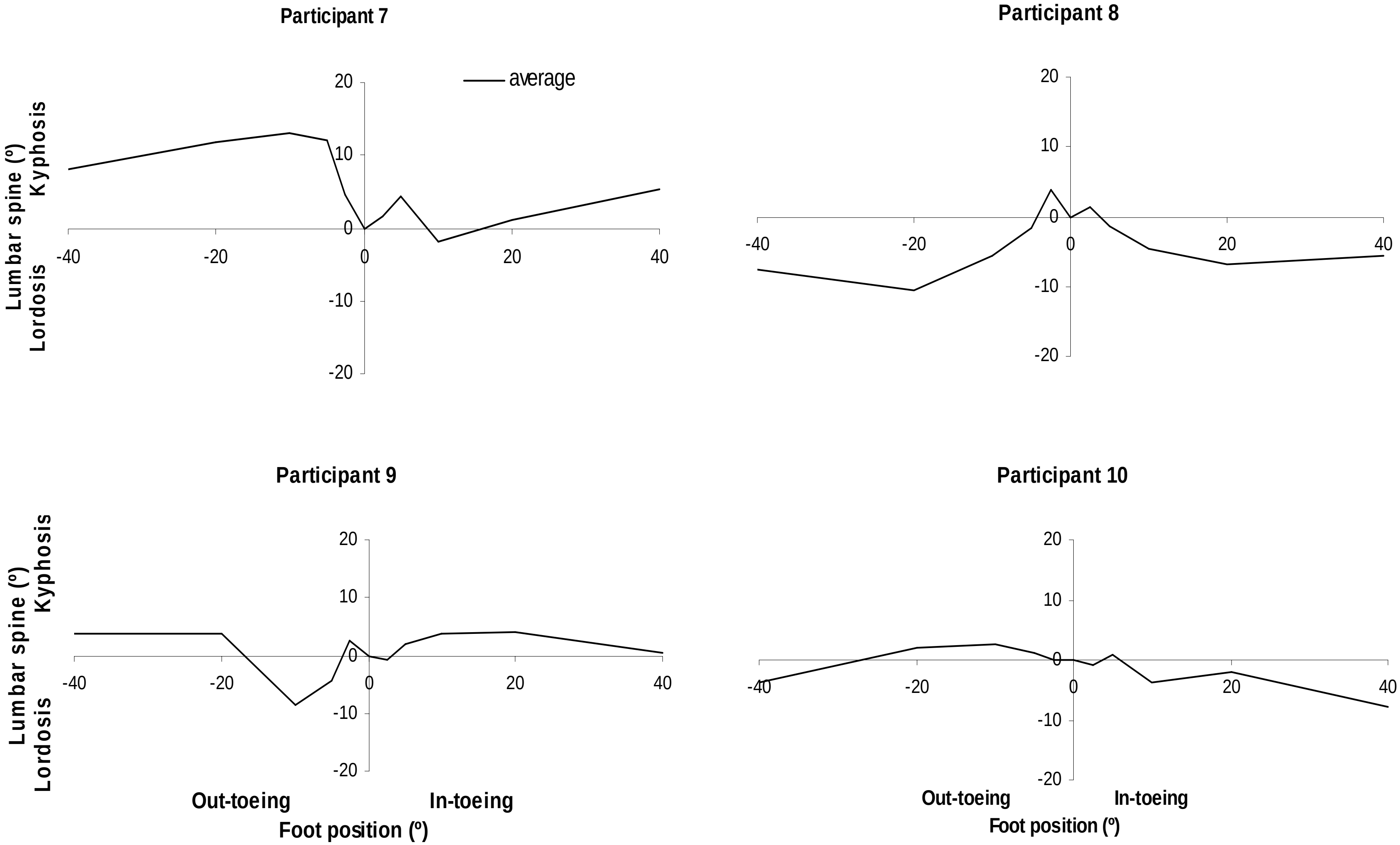


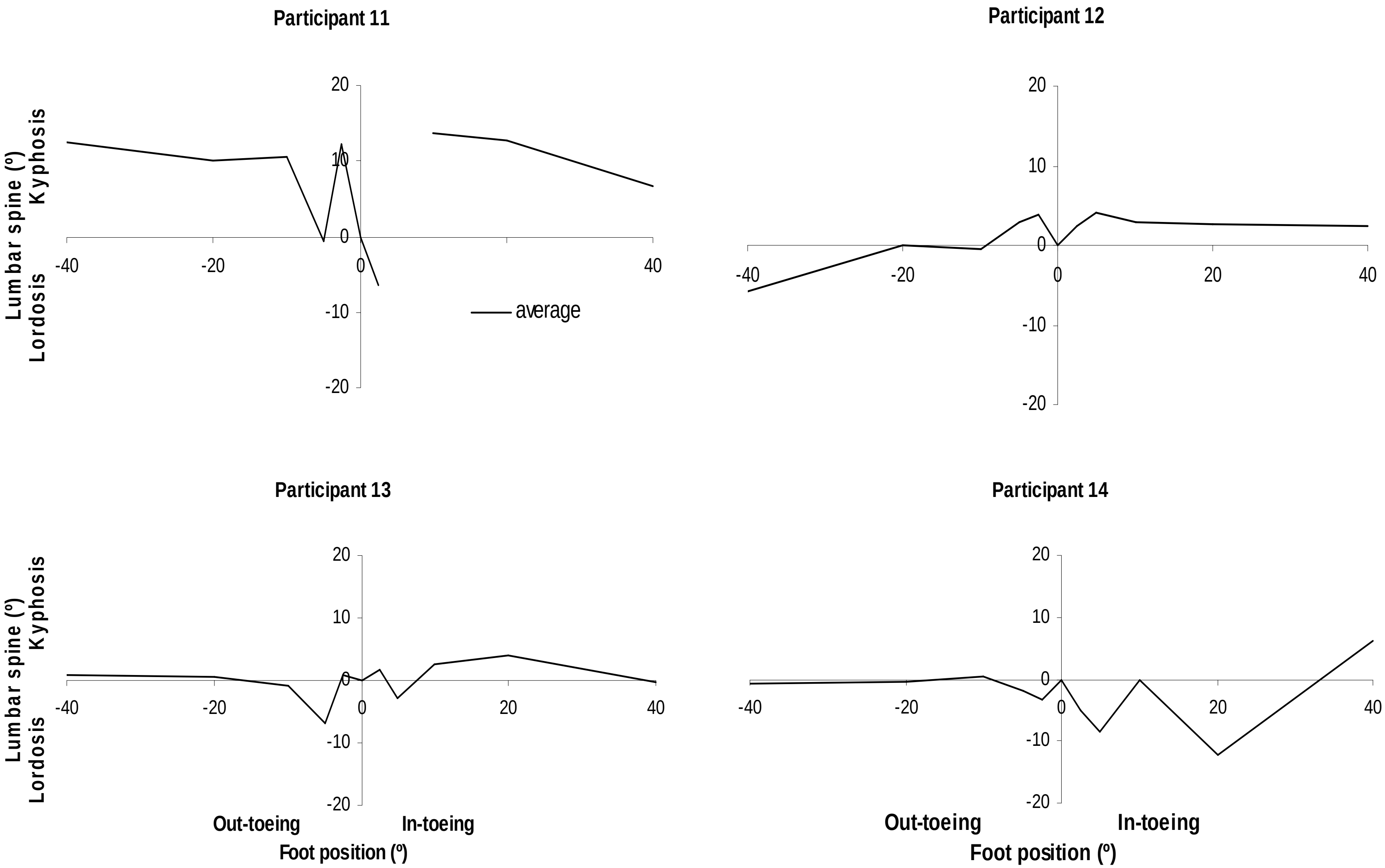

Participant 7
average
Participant 8
Participant 9
Participant 10
Pelvic tilt (º)
Anterior
Posterior
20
10
0
-10
-20
-40
-20
0
20
40
Out-toeing
In-toeing
Foot position (º)


Participant 11
average
Participant 12
Participant 13
Participant 14
Pelvic tilt (º)
Anterior
Posterior
Out-toeing
In-toeing
Foot position (º)
20
10
0
-10
-20
-40
-20
0
20
40

8. Individual graphs for lumbar angle




Participant 7
average
Participant 8
Participant 9
Participant 10
Lumbar spine (º)
Kyphosis
Lordosis
Out-toeing
In-toeing
Foot position (º)
20
10
0
-10
-20
-40
-20
0
20
40


Participant 11
Lumbar spine (º)
Kyphosis
Lordosis
20
10
0
-10
-20
-40
-20
0
40
average
Participant 12
20
10
0
-10
-20
-40
-20
0
20
40
Participant 13
Lumbar spine (º)
Kyphosis
Lordosis
20
10
0
-10
-20
-40
-20
0
20
40
Out-toeing
In-toeing
Foot position (º)
Participant 14
20
10
0
-10
-20
-40
-20
0
20
40
Out-toeing
In-toeing
Foot position (º)