Frontal Plane Moments Do Not Accurately Reflect Ankle Dynamics During Running

Kristian M. O’Connor\textsuperscript{2} and Joseph Hamill\textsuperscript{1}
\textsuperscript{1}Univ. of Massachusetts; \textsuperscript{2}Univ. of Wisconsin–Milwaukee

The ankle joint has typically been treated as a universal joint with moments calculated about orthogonal axes and the frontal plane moment generally used to represent the net muscle action about the subtalar joint. However, this joint acts about an oblique axis. The purpose of this study was to examine the differences between joint moments calculated about the orthogonal frontal plane axis and an estimated subtalar joint axis. Three-dimensional data were collected on 10 participants running at 3.6 m/s. Joint moments, power, and work were calculated about the orthogonal frontal plane axis of the foot and about an oblique axis representing the subtalar joint. Selected parameters were compared with a paired $t$-test ($\alpha = 0.05$). The results indicated that the joint moments calculated about the two axes were characteristically different. A moment calculated about an orthogonal frontal plane axis of the foot resulted in a joint moment that was invertor in nature during the first half of stance, but evertor during the second half of stance. The subtalar joint axis moment, however, was invertor during most of the stance. These two patterns may result in qualitatively different interpretations of the muscular contributions at the ankle during the stance phase of running.

Key Words: subtalar, gait, power

Accurate calculation of joint moments is critical for understanding the loading of the musculoskeletal system. Joint powers that are calculated from the net joint moment provide information about energy flow between segments. There are several limitations inherent in the calculation and interpretation of net joint moments and power. Error propagation (McCaw & DeVita, 1995), the inability to account for muscle co-contraction (Winter, 1990), and the potential contribution of passive structures (Chen, Siegler, & Schneck, 1988) are all confounding factors in interpreting net joint moments. Based on these limitations, interpretation of joint moments must be viewed with caution.

\textsuperscript{1}Biomechanics Laboratory, University of Massachusetts, Amherst, MA 01003; \textsuperscript{2}Dept. of Human Movement Sciences, University of Wisconsin–Milwaukee, PO Box 413, Milwaukee, WI 53201.
The net joint moment also may not reflect the loading of internal structures because the net joint moments are typically reported in the cardinal planes of the body even though the joint configuration may not be aligned with the cardinal planes. This is particularly true at the ankle (Inman, 1976), where joint kinetics have typically been calculated about a spherical joint located at the ankle joint center (Apkarian, Naumann, & Cairns, 1989; Eng & Winter, 1995; McClay & Manal, 1999). However, the motion of the foot occurs at several joints, with most of it occurring at the talocrural and subtalar joints (Lundberg, Svensson, Bylund, Goldie, & Selvik, 1989). Each of these joints can be approximated as single degree-of-rotational-freedom joints (Inman, 1976). The sagittal plane motion at the ankle primarily occurs at the talocrural joint, while the frontal plane motions primarily occur through rotation at the subtalar joint.

Based on the work of Inman (1976), the subtalar joint is inclined approximately 42° and oriented medially approximately 23° from the long axis of the foot, defined from the posterior aspect of the calcaneus through a point between the second and third metatarsals. While sagittal plane moments have been shown to be similar to those calculated about an anatomically oriented talocrural joint (Scott & Winter, 1991) for walking, the frontal and transverse plane moments calculated about a universal joint have not been directly compared to moments calculated about an anatomically oriented subtalar joint. Scott and Winter (1991) reported joint moments about an estimated subtalar joint that resulted in an inversion moment throughout stance. This stands in contrast to the frontal plane moment reported by Eng and Winter (1995) that was highly variable.

A complication in interpreting 3-D joint moments is that moments can be reported in one of several reference frames. Lower extremity net joint moments have been reported in the global reference frame (Eng & Winter, 1995), the reference frame of the segment proximal to the joint (Holden & Stanhope, 1998), and the reference frame of the segment distal to the joint (O’Connor & Hamill, 2004). An added difficulty is that many studies do not report the chosen reference frame, which can make it difficult to compare results (McClay & Manal, 1999; Mündermann, Nigg, Humble, & Stefanyshyn, 2003). It should also be noted that O’Connor and Hamill (2004) did not report their choice of the distal reference frame. This convention was adopted in the thought that it would be more functionally appropriate to examine the effect of ankle moments on the foot by reporting moments relative to the cardinal planes of the foot. If the intent is to infer information about muscular control of the foot, however, it seems logical that the moments calculated about an anatomically oriented axis would provide a more complete picture of the neuromuscular demands.

While subtalar joint motion is difficult to measure directly, quantifying the differences between an anatomically oriented axis and a frontal plane representation could be important in determining the benefit of calculating kinetics about the subtalar joint. While it would be preferable to calculate joint moments about anatomically oriented axes, it is not established whether the additional effort in doing so is warranted. Therefore, the purpose of this study was to compare net joint moments calculated in the frontal plane of the foot reference system (foot-FP\textsubscript{AXIS}) with those calculated about an estimate of the subtalar joint axis (STJ\textsubscript{AXIS}) during running. It was hypothesized that the joint moment calculated about the STJ\textsubscript{AXIS} would be greater in magnitude than that calculated about the foot-FP\textsubscript{AXIS}. Furthermore, energy absorption will also be greater for the subtalar orientation. While the
primary purpose of this study was to compare moments calculated about the foot- 
FP\textsubscript{AXIS} and those calculated about the STJ\textsubscript{AXIS}, the ankle moment reported in the 
frontal plane of the leg (leg-FP\textsubscript{AXIS}) was also included in order to relate these 
results to McClay and Manal (1999) and Mündermann et al. (2003), since it could 
ot be determined whether a proximal or distal reference frame was used in these 

\textbf{Methods}

Ten young men classified as rearfoot strikers were recruited for this study. Data 
from these same participants also appear in a separate study (O’Connor & Hamill, 
2004). Their height, mass, and age were $1.72 \pm 0.07$ m, $72.6 \pm 5.3$ kg, and $27 \pm 5$ 
years, respectively. All were active recreationally and injury-free at the time of the 
study, and none wore orthotics. They all signed an informed consent in accordance 
with university regulations.

The shoes, custom built for this study, had a midsole constructed of ethyl 
vinyl acetate (EVA) with a durometer of 45 (Shore A). The upper portion of the 
shoes was modified such that there was no heel counter. This design was em-
ployed in order to directly track movement of the calcaneus. In a pilot study, it was 
found that all participants were able to run at least 5 minutes on a treadmill com-
fortably in these shoes based on subjective assessments.

Three-dimensional kinematic data were collected on the right limb of all 
participants using a 7-camera Qualisys Pro-Reflex motion capture system (Qualisys 
Medical AB, Gothenburg, Sweden). Ground reaction force data were collected 
with a force platform (model BP6001200, AMTI, Inc., Watertown, MA) mounted 
flush with the floor. Speed was monitored by recording the time between two 
photoelectric cells placed at each end of the testing zone. Kinematic data were 
sampled at 240 Hz and ground reaction force data were sampled synchronously at 
1,920 Hz.

Four reflective markers, mounted on a rigid plate, were attached to the lat-
eral aspect of the shank and three markers mounted on a rigid triad were attached 
to the posterior aspect of the calcaneus in order to record ankle joint kinematic 
data. Prior to data collection, a standing calibration trial was collected with the 
participant barefoot. For the standing calibration, additional reflective markers were 
placed on the participant in order to define segment geometries and the segment 
coordinate systems. Markers were placed over the medial and lateral epicondyles, 
the medial and lateral malleoli, and the heads of the first and fifth metatarsals. The 
calibration was performed barefoot in order to more accurately locate the markers 
over the metatarsal heads. These markers were removed prior to the collection of 
running data.

Anatomical coordinate systems for the leg and foot were derived from the 
marker locations collected in the standing calibration. The origin of the foot coor-
dinate system was defined as midway between the malleoli. The +Y axis of the 
foot was oriented in the horizontal plane in the standing position and passed above 
the midpoint between the first and fifth metatarsal heads. The +Z axis was oriented 
vertically upward. The +X axis was determined by the cross-product of the foot 
+Y and +Z axes and was oriented laterally. The leg coordinate system origin was 
placed at the midpoint of the medial and lateral epicondyles. The +Z axis was 
oriented upward along a line that joins the midpoint of the malleoli and the
epicondyles. The frontal plane of the leg was defined by the four markers placed over the epicondyles and malleoli. The +Y axis was perpendicular to this plane and was oriented forward. The +X axis of the leg was determined by the cross-product of the leg +Y and +Z axes and was oriented laterally.

Participants performed five acceptable running trials at 3.6 m/s ± 5% along a 30-m runway across the force platform. They were required to land on the force plate with their right foot while kinematic and ground reaction force data were recorded. The 3-D coordinate data were filtered with a low-pass, 4th-order zero lag Butterworth filter with a 12-Hz cutoff frequency. The 3-D angular data were calculated using an XYZ Cardan rotation sequence (Cole, Nigg, Ronsky, & Yeadon, 1993). The net ankle joint moment was calculated using an inverse dynamics procedure, and foot inertial parameters were derived from Dempster (1955). The ankle moments about the foot-FP AXIS and leg-FP AXIS were calculated using Visual3D (C-Motion Inc., Rockville, MD). The leg-FP AXIS moment data were not included in the statistical analysis.

In order to calculate the kinematics and kinetics about an estimate of the subtalar joint, we transformed the foot coordinate system with +Y lying along the subtalar axis. The transformation of the Y-axis from the long axis of the foot to an orientation along the subtalar axis was performed with two rotations. The foot reference frame was first rotated about the X-axis, followed by rotation about the Z-axis. As a result of these rotations, the Y’’-axis was coincident with the average subtalar axis orientation reported by Inman (1976) (Figure 1).

This transformation is expressed in Equation 1. The angles $\theta_X$ and $\theta_Z$ are the rotations about the X- and Z-axes. The average values from Inman (1976) were used as the estimated subtalar joint axis and were oriented upward 42° and medi-
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ally deviated 23° relative to the long axis of the foot, which represent projected angles. The required rotations were 44° ($\theta_x$) and 17° ($\theta_z$) in order to obtain the orientation defined by Inman (1976).

\[
\text{Subtalar } A_{\text{Frontal}} = \begin{bmatrix}
\cos \theta_z & -\sin \theta_z & 0 & 0 \\
\cos \theta_x \cdot \sin \theta_z & \cos \theta_x \cdot \cos \theta_z & -\sin \theta_x & 0 \\
\sin \theta_x \cdot \sin \theta_z & \sin \theta_x \cdot \cos \theta_z & \cos \theta_x & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

(1)

For the moment calculation about the STJAXIS, inertial characteristics were assumed to be negligible (Morlock & Nigg, 1988). Therefore the net joint moment was calculated as the reaction to the moment applied by the ground reaction force using a custom computer program. Parameters were extracted from the frontal plane and subtalar joint kinematics and kinetics for statistical analysis. Frontal plane parameters were referred to as eversion or inversion in polarity, and data for the subtalar joint were correspondingly referred to as pronation or supination. Maximum and minimum joint moments and rotational powers and the times to the peak moments were reported for each axis. Work was computed from the time integral of the power time series. Negative and positive work were reported as well as the total work defined as the sum of the absolute values of the positive and negative work (Eng & Winter, 1995). All data profiles were time normalized to 100% of stance. A paired t-test ($\alpha = 0.05$) was performed on each parameter in order to detect differences between coordinate systems.

Results

There were significant differences between the coordinate systems for several parameters (Table 1). The touchdown angle and maximum eversion/pronation were significantly different ($p < 0.05$) between the two methods, but the ranges of motion did not differ (Figure 2a). The joint moment profiles were substantially different between the frontal plane and subtalar joint (Figure 2b). Also, it should be noted that the moment presented in the leg reference frame was similar to that of the subtalar joint. There was a significantly greater peak supination moment and virtually no period of a net pronation moment for the subtalar axis.

The joint power calculations resulted in contradictory energy flows (Figure 2c). The subtalar joint moment resulted in energy absorption during the first portion of stance, and energy generation during the second portion of stance. The frontal plane powers oscillated about zero. The negative work values were similar, but as can be seen in the power profiles, the manner in which each method arrived at these values was functionally different. There was a significantly greater amount of positive and total work done about the subtalar joint.

Discussion

The purpose of this study was to compare the kinetic information that is derived from anatomically oriented and segment-based joint axes. The kinematic data revealed that the joint excursion measured about foot-FPAXIS is similar to that estimated about the STJAXIS. This finding agrees with the results of Engsberg (1987),
Table 1  Group Mean (± SD) Kinematic and Kinetic Parameters

<table>
<thead>
<tr>
<th>Variable</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>STJ\textsubscript{AXIS}</td>
</tr>
<tr>
<td>Touchdown angle (°)*</td>
<td>-2.1 ±12.7</td>
</tr>
<tr>
<td>Range of motion (°)</td>
<td>12.5 ±4.6</td>
</tr>
<tr>
<td>Maximum angle (°)*</td>
<td>-14.5 ±9.2</td>
</tr>
<tr>
<td>Minimum moment (Nm)*</td>
<td>-5.7 ±5.3</td>
</tr>
<tr>
<td>Time to minimum moment (% stance)*</td>
<td>23.2 ±30.1</td>
</tr>
<tr>
<td>Maximum moment (Nm)*</td>
<td>55.0 ±17.7</td>
</tr>
<tr>
<td>Time to maximum moment (% stance)*</td>
<td>52.6 ±6.6</td>
</tr>
<tr>
<td>Minimum power (W)*</td>
<td>-100.1 ±27.4</td>
</tr>
<tr>
<td>Maximum power (W)*</td>
<td>136.5 ±49.7</td>
</tr>
<tr>
<td>Negative work (J)</td>
<td>-3.7 ±2.1</td>
</tr>
<tr>
<td>Positive work (J)*</td>
<td>7.4 ±2.6</td>
</tr>
<tr>
<td>Total work (J)*</td>
<td>11.1 ±3.5</td>
</tr>
</tbody>
</table>

Note: Positive kinematic and moment variables represent supination for the STJ\textsubscript{AXIS} and inversion for the foot-FP\textsubscript{AXIS}.

*Significant difference, $p < 0.05$

who concluded that frontal plane motion of the foot approximates angular motion at the subtalar joint reasonably well. There were substantial differences, however, in the kinetic information reported between these two reference systems. The STJ\textsubscript{AXIS} moment was almost entirely supination in nature while the foot-FP\textsubscript{AXIS} moments were, on average, invertor during the first half of stance and evertor during the second half of stance.

The joint moments calculated about leg-FP\textsubscript{AXIS} were quite different from those calculated about foot-FP\textsubscript{AXIS}. In the current study, the average magnitude of the peak inversion moment appears relatively small about foot-FP\textsubscript{AXIS} (~15 Nm), with a pattern that switches from an invertor to evertor moment at approximately midstance. The moment presented about the leg-FP\textsubscript{AXIS} was entirely invertor with a peak of 49 Nm. Interestingly, the moment profile reported about the leg-FP\textsubscript{AXIS} nearly matched that about the subtalar joint axis. Reporting ankle moments about the leg-FP\textsubscript{AXIS} would mean that the moment would be reported about the anterior-posterior axis of the leg. Since the leg generally internally rotates during the stance phase of running, this axis would likely point medially relative to the long axis of the foot. In that case, the reported moments could coincidently resemble the STJ\textsubscript{AXIS} moments in the current study.

There was also some variation when compared to frontal plane running moments in other studies. McClay and Manal (1999) reported an average peak inversion moment of ~23 Nm, with an inversion moment throughout stance. Mündermann et al. (2003) reported an average peak inversion moment of ~30 Nm, although the representative curve demonstrated both an inversion and eversion...
Figure 2 — Comparison of (a) joint kinematics, (b) net joint moments, and (c) power for all participants. Thin line represents subtalar joint data (STJ\textsubscript{AXIS}) and the shaded area represents ± 1 SD (between participants). Thick line represents foot frontal plane data (foot-FP\textsubscript{AXIS}). Dashed line in (b) represents the frontal plane joint moment in the leg reference frame (leg-FP\textsubscript{AXIS}). Positive kinematic and moment data represent supination for the STJ\textsubscript{AXIS} and inversion for the foot-FP\textsubscript{AXIS}. 
phase to the moment profile. Neither of these studies reported the reference frame in which moments were calculated, and it is difficult to match their results exclusively with either of the frontal plane profiles represented in the study. It certainly appears, however, that the choice of reference frame can greatly affect the joint moment patterns that were observed.

While it is unclear whether the differences in moment profiles between studies were due to the choice of reference frame, it is critical to understand the nature of differences between these studies. The foot-based frontal plane (foot-FP\textsubscript{AXIS}) moment in the current study yielded moment and power profiles that did not match the patterns for the subtalar joint (STJ\textsubscript{AXIS}). The patterns of McClay and Manal (1999), however, did appear to reflect the “correct” joint kinetic patterns. Unfortunately, it cannot be determined whether this was coincidental because moments were reported in the leg reference frame or if other factors were involved. The definitions of coordinate systems in the current study were based on the methods of McClay and Manal (1999), but perhaps there were subtle differences leading to large differences in joint kinetics. A sensitivity analysis is beyond the scope of this study, but this appears to be an important next step if indeed these results and those of McClay and Manal were presented in the same reference frame. While there is currently no accepted standard for reporting 3-D joint moments, based on the differences between reference frames in this study and variation in other studies, it is recommended that the choice of reference frame be expressly stated in order to allow for comparison between studies.

The large standard deviations in the average profiles represent the variability between participants. The variability in moments about foot-FP\textsubscript{AXIS} is likely due to the proximity of the center of pressure to the long axis of the foot. This can be illustrated by comparing the path of the center of pressure (the point at which the ground reaction force is applied to the foot) to possible joint axis orientations (Figure 3). An axis oriented along the long axis of the foot (foot-FP\textsubscript{AXIS}) resulted, on average, in a moment generated by the ground reaction force that changes from

Figure 3 — Mean center-of-pressure path relative to anteroposterior and subtalar axes. Solid line with arrow represents the long axis of the foot, and the dashed line approximates the subtalar joint axis as viewed from above. Foot contact occurs at the bottom left on the lateral aspect of the heel, and toe-off occurs in the upper right under the first toe. Black circle represents the ankle joint center. The subtalar joint was simplified in this graphic to also pass through this point, while in reality this is not the case.
evertor to invertor at about midstance. Given the individual variations in running style and potential sources of error in relating foot position to the center of pressure, this moment can differ dramatically between individuals. Eng and Winter (1995) also made this observation in the variability of their frontal plane moments during walking.

In contrast, a medially oriented axis like the subtalar joint will result in greater pronation moment arms for the ground reaction force for most of stance. The peak supination moment about the subtal joint was substantially greater than the inversion moments reported in previous studies (McClay & Manal, 1999; Mündermann et al., 2003). The peak moment of ~55 Nm occurred at approximately midstance at a time when the ground reaction force was greatest. Given the orientation of the subtal axis, the moment arm about that axis was relatively large at midstance. At the same time, the moment arm relative to the long axis of the foot was near zero.

Although work and power measures revealed significantly greater energy generation in the calculations about the STJ AXIS, energy absorption was statistically the same for each method. The line of action of the Achilles tendon produces a supination moment arm about the subtal joint axis (Perry, 1983). Given that the foot generally re-supinates in the second half of stance, it is logical that the extrinsic foot musculature acts concentrically about the subtal joint (positive power). This is consistent with the energy flows represented by the power profile for the STJ AXIS (Figure 2c). As was discussed previously, although the frontal plane powers reported by McClay and Manal (1999) appear to reflect the correct energy flow, the difference between studies may be due to a difference in the reference frame that defines the frontal plane.

As hypothesized, kinetic data calculated about the foot-FP AXIS resulted in qualitatively different joint moments than those calculated about an estimate of the STJ AXIS. If the net joint moments were used to infer net muscle activity at the ankle, these results would lead to divergent interpretations of kinetics of the ankle as it relates to foot function. For example, the moment about the foot-FP AXIS would lead to the conclusion that the evertors provide the dominant moment during the second half of stance. The moment about the STJ AXIS, which better reflects the anatomical constraints imposed on the foot, was almost entirely invertor. Therefore, examination of the joint moments calculated about the foot-FP AXIS would lead to an incorrect assessment of how muscles and passive structures contribute to energy flow between the leg and foot.

Variation of the subtal joint axis itself may also lead to incorrect interpretation of joint moments. The magnitude of the moment about the subtal joint can also be viewed in relation to the 3-D nature of the net joint moment at a joint. The ankle is generally represented by a spherical joint, and the joint moment is represented by three orthogonal components. By reporting the moment about the subtal joint, a combination of the sagittal, frontal, and transverse planes is represented. As the medial deviation of this axis increases, a greater proportion of the sagittal plane component will be reflected in the subtal moment. Also, the subtal moment will reflect the transverse plane component, with a greater inclination yielding a greater portion of this component. Given that the transverse component is relatively small when compared to the sagittal component (McClay & Manal, 1999), the moment about the subtal axis should be more susceptible to changes in the medial deviation than the inclination of the axis.
Inman (1976) reported that the mean deviation of the subtalar axis was 23°; however, the axes in their specimens ranged from 4° to 47°. Certainly the assumption of the average value (23°) for a person with a 4° medial deviation could result in exactly the opposite phenomenon than was presented in this paper. The person with a subtalar axis that is oriented closer to the long axis of the foot will experience loading similar to the frontal plane example given in this paper. Therefore, participant-specific joint axis information may be necessary in order to make individual assessments.

Another inherent difficulty in an anatomically based approach is the variability in axis orientation during the gait cycle. While many early studies approximated the subtalar joint as a stationary hinge or screw axis (Inman, 1976), recent studies indicate that this axis changes orientation when the foot is loaded (Leardini, Stagni, & O’Connor, 2001). Thus a truly accurate assessment of the joint kinetics may require instantaneous estimates of the subtalar axis during a given activity. Given the sources of variability, accurate estimates of joint kinetics about the subtalar joint will be challenging. The significant differences between the two measures suggest that calculation of joint moments about a static approximation may be preferable to calculating joint moments about a spherical ankle joint.

In summary, accurate representation of loading in the foot and ankle is essential in relating gait dynamics to the potential for injury. At the ankle, a simplified, orthogonal based reference system may be inadequate for evaluating loading of the joint and its associated musculature. Based on the results of this study, application of an anatomically based reference system could yield kinetic data that better elucidates the relationship between gait mechanics and lower extremity injury. This approach does present several challenges, particularly if the goal is to also account for between- and within-participant variation. Until such methods are more fully developed, we propose as a first step that an approximation of the subtalar axis as utilized in this study would provide more functionally relevant data than the spherical joint approach.

References


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