A comparison of metatarsophalangeal joint center locations on estimated joint moments during running

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ABSTRACT

The forefoot functions as the base of support during late stance, rotating about the dual-axis of the metatarsophalangeal joints. Previous research has shown that joint axis definition affects estimated joint moments about the forefoot. However, little is known about how metatarsophalangeal joint center definition affects estimated joint kinetics. This study compared moments about the metatarsophalangeal joint using four different defined joint centers. There was a significant difference ($p < .001$) in peak moments between joint center definitions, differing by up to 0.488 N-m/kg for the slow and 0.878 N-m/kg for the fast running speeds tested. Additionally, there was a significant difference ($p < .001$) for when peak plantar flexor moment occurred during the slower running condition. The more posteriorly oriented joint centers resulted in higher moments and earlier onset of the plantar flexor moment. In addition to careful modeling of the metatarsophalangeal joint axis, it is recommended that joint center definition should be considered as well.

1. Introduction

The forefoot functions as the base of support during running after the heel lifts off the ground during stance (Miyazaki and Yamamoto, 1993; Stefanyshyn and Nigg, 1997). Rotation about the five metatarsophalangeal (MTP) joints occurs about two anatomical axes of rotation; a transverse axis across the first and second MTP joints, and an oblique axis across the second to fifth MTP joints (Bojsen-Møller, 1978). The foot has a complex anatomy with a number of muscle-tendon units crossing the MTP axes in addition to the plantar fascia (Mckeon et al., 2015). Insertion points of the muscle-tendon units vary between the second to fifth metatarsals (i.e. flexor digitorum longus, brevis) and the hallux (i.e. abductor hallucis longus, brevis) and the plantar fascia inserts onto all phalanges (Bojsen-Møller and Lamoreux, 1979). However, the MTP joint is commonly modeled as a single oblique axis for running analysis (Smith et al., 2012; Stefanyshyn and Nigg, 1997).

Definition of the MTP joint axis affects estimated moments during sprinting (Smith et al., 2012). A two-dimensional approach using a medial-lateral perpendicular axis from the fifth metatarsal marker (Stefanyshyn and Nigg, 1997, 1998, 2000) results in joint moments two to four times higher than when estimated about an oblique or dual axis (Smith et al., 2012). Further, moments about a dual axis are lower compared to an oblique axis (Smith et al., 2012). During running, most motion occurs about the transverse portion across the first and second metatarsals of the dual axis, as the center of pressure travels medial to the second metatarsal during push-off (De Cock et al., 2008; Smith et al., 2012; Willwacher et al., 2013).

There is no commonly accepted location for where to model the MTP joint center. Fixed MTP joint center locations have previously included the midpoint of the oblique axis (Hoogkamer et al., 2018; McDonald et al., 2016; Oh and Park, 2017; Oleson et al., 2005; Roy and Stefanyshyn, 2006), in plane with the long axis of the foot in the medial-lateral direction and the first metatarsal head in the anterior-posterior direction, over the second metatarsal (Miyazaki and Yamamoto, 1993; Willwacher et al., 2013), and the fifth metatarsal for two-dimensional analysis (Bezodis et al., 2012; Smith et al., 2012; Stefanyshyn and Nigg, 1997, 1998, 2000). Additionally, a non-fixed joint center method treating the MTP joint as a true hinge joint has been utilized (Rolian et al., 2009; Smith et al., 2014). Use of a non-fixed joint center accounts for inter-subject variability that can arise from toe-out angle, compared to a fixed joint center location (Chang et al., 2007; Rolian et al., 2009). A non-fixed joint center may more accurately represent the anatomy of the forefoot and toe segments, where the primary motion is in the sagittal plane with muscle-tendon units inserting on the metatarsals to modulate flexion and extension

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(Bojsen-Møller, 1978; Bojsen-Møller and Lamoreux, 1979; Mckeon et al., 2015).

The purpose of this study was to investigate how MTP joint kinetics change with differing joint center definition. We hypothesize that the more posteriorly oriented joint centers will have larger peak moments and that the external dorsiflexion moment will arise earlier in stance phase. It is also hypothesized that the use of a non-fixed joint center will result in the lowest peak moment.

2. Methods

Nineteen (5 female) competitive runners were recruited for this study (24 ± 6 yr, 63 ± 10 kg, 52 ± 14 mi/wk, 16:43 average 5000 m best). Inclusion criteria included: 5000 m personal best under 18:00 (males) and 20:00 (females), no lower extremity injury in the previous six months, and currently running over 30 miles/week. Participants provided informed consent prior to data collection. This study was approved by the Institutional Review board at the University of Oregon.

Retro-reflective markers were placed on the foot in accordance with Goldmann et al. (2013). The forefoot was defined by markers on the superior distal aspect of the hallux and heads of the first and fifth metatarsals (medial and lateral aspects, respectively). The rearfoot was defined by markers on the medial, lateral, and posterior aspects of the calcaneus. Windows were cut in the shoes to place markers directly on the foot (Bishop et al., 2014). Participants all wore the same standard neutral cushioned footwear (Brooks Launch 3) to eliminate the effects of longitudinal bending stiffness (Stefanyshyn and Nigg, 2000; Willwacher et al., 2013, 2014).

Running trials were conducted on a force instrumented treadmill (Bertec, Inc., Columbus, OH). Kinematic data were collected at 200 Hz and kinetic data were collected at 2000 Hz. Participants ran at five speeds, 3.89, 4.44, 5.00, 5.56, and 6.11 m/s. For the current analysis of MTP endpoint effect, the slowest and fastest speeds, 3.89 and 6.11 m/s, were analyzed.

A custom MATLAB (version R2016b; MathWorks, Natick, MA) program was used to estimate joint kinematics and kinetics for stance phase only, defined as when the vertical ground reaction force exceed 5% body weight. Marker coordinate data were filtered using a zero-lag, fourth-order low pass Butterworth filter with at 20 Hz cutoff frequency (Willwacher et al., 2013). Center of pressure was visually assessed and assured by low-pass filtering force data (cutoff = 20 Hz) to eliminate treadmill vibration noise (Willems and Gosseye, 2013).

The five MTP joints were modeled as a single hinge axis defined by the vector from the first to fifth metatarsal markers (Smith et al., 2012). Three separate methods using fixed joint center locations were defined according to previous studies (Fig. 1). These methods included joint center locations at the head of the fifth metatarsal (Bezodis et al., 2012; Stefanyshyn and Nigg, 2000, 1998, 1997), the midpoint between the first and fifth metatarsals (Hoogkamer et al., 2018; McDonald et al., 2016; Oh and Park, 2017; Oleson et al., 2005; Roy and Stefanyshyn, 2006; Willems and Gosseye, 2013), and at a point that was in the plane of the head of the first metatarsal in the anterior-posterior direction and the long axis of the foot in the medial-lateral direction (Miyazaki and Yamamoto, 1993; Willwacher et al., 2013), referred to henceforth as the second metatarsal head joint center. Kinetic estimations for the fifth metatarsal location were solved in a two-dimensional model.

In addition to the fixed joint center approaches, we tested a non-fixed joint center method utilizing the perpendicular moment arm from the center of pressure (COP) to the MTP oblique axis. This approach is similar to (1) Rolian et al. (2009) who transferred the COP into the forefoot coordinate system and estimated resultant moments using ground reaction forces and respective moment
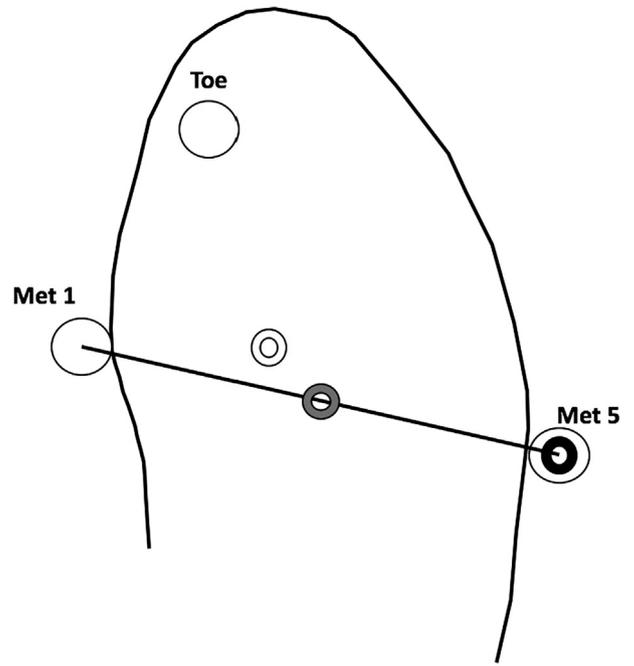

Fig. 1. Fixed metatarsophalangeal joint center locations at the second metatarsal head (white), midpoint (gray), and fifth metatarsal (black). Black line defines the oblique hinge axis.

arms; and (2) Smith et al. (2014) who calculated the horizontal moment arm as the perpendicular distance from the COP to the MTP joint axis.

A novel approach was developed to estimate MTP joint moments using a non-fixed joint center method. A triangle formed by the first and fifth metatarsal markers and COP coordinates and a law of cosines approach was used to calculate the perpendicular moment arm of the COP to the MTP axis (Fig. 2). The vertical
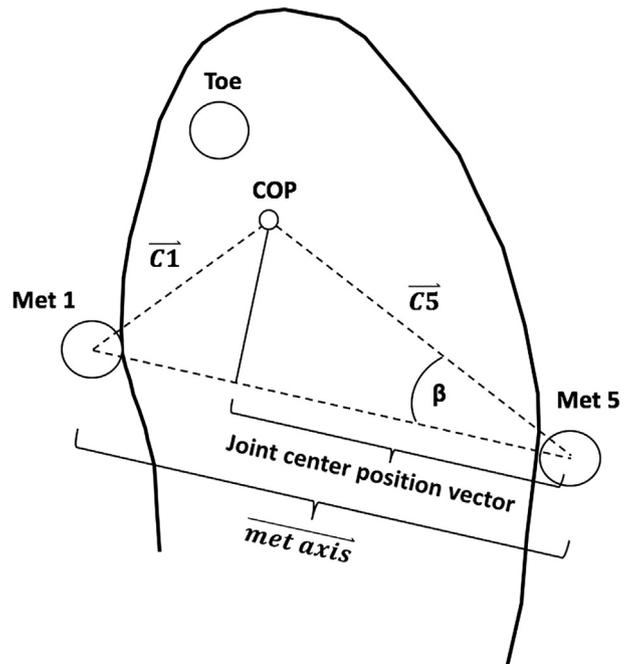

Fig. 2. Depiction of the methodology for utilizing the law of cosines to define the sliding joint center. Sliding joint center location is the intersection of the moment arm from the center of pressure to the metatarsal joint axis.

coordinate of the first and fifth metatarsal markers was set to zero to be in plane with the COP and not alter the magnitude of the resultant angle, β. The following equations were utilized to calculate the non-fixed joint center location along the MTP axis at the intersection of the perpendicular moment arm from the COP, referred to as the sliding MTP joint center.

$$\beta = \frac{\overrightarrow{C5}^2 + \overrightarrow{met\ axis}^2 - \overrightarrow{C1}^2}{2 * \overrightarrow{C5} * \overrightarrow{met\ axis}}$$

$$joint\ center\ position\ vector = \overrightarrow{C5} * \beta$$

where β is the angle near the fifth metatarsal marker, $\overrightarrow{C1}$ is the magnitude of the vector from the COP to the first metatarsal, $\overrightarrow{C5}$ is the magnitude of the vector from the COP to the fifth metatarsal, and $\overrightarrow{met\ axis}$ is the magnitude of the vector from the first to fifth metatarsal. The value for β was multiplied by $\overrightarrow{C5}$ to determine the magnitude of the distance from the fifth metatarsal to the location on the MTP oblique axis representative of the perpendicular moment arm intersection, referred to as the joint center position vector.

The vertical components of the first and fifth metatarsal markers were then added back into their respective coordinates. The joint center position vector was then added to the fifth metatarsal marker to obtain the position along the oblique axis representative of the sliding joint center location in global space using the following equation.

$$Sliding\ MTP\ joint\ center = met5 + (FFrm$$
$$* jointcenter\ position\ vector)$$

where $met5$ is the global coordinate of the fifth metatarsal marker and $FFrm$ is the forefoot segment rotation matrix with respect to the global coordinate system.

An inverse dynamics approach was used to estimate joint moments resolved in the rearfoot coordinate system. The inertial effects of the forefoot were considered negligible (Stefanyshyn and Nigg, 1997). Moments were considered zero until the COP passed anterior to the joint center location.

A one-way repeated measures analysis of variance (ANOVA) was used to compare peak moments between joint center locations for both speeds. Pairwise comparisons with Bonferroni adjustments ($\alpha = 0.05/6 = 0.0083$) were used to further analyze main effects. One-dimensional, one-way repeated measures Statistical Parametric Mapping (SPM) ($\alpha = 0.05$) was used to assess differences in plantar flexor moment throughout stance (Pataky et al., 2013, 2016). Follow up pairwise comparison analyses were conducted using SPM t-tests with a Bonferroni corrected alpha level.

3. Results

Peak joint moments were significantly affected by joint center location for both speeds ($p < .001$) (Table 1). The trend in change of maximum moment was similar between speeds. More posteriorly oriented fixed joint centers resulted in larger peak moments.

The sliding joint center definition resulted in the smallest peak moments.

For the slow speed (3.89 m/s), the sliding ($p < .001$), second metatarsal ($p < .001$), and midpoint ($p = .002$) joint center definitions had significantly lower peak moments than the fifth metatarsal joint center. Peak moments for the midpoint ($p < .001$) and fifth metatarsal ($p < .001$) joint centers were significantly higher than the sliding joint center, but not the second metatarsal joint center ($p = .117$). Peak moments were not significantly different between the second metatarsal and midpoint definitions ($p = .164$).

For the fast speed (6.11 m/s), moments for the sliding ($p < .001$), second metatarsal ($p < .001$), and midpoint ($p = .006$) joint center definitions were all significantly lower than for the fifth metatarsal joint center definition. Peak moments for the second metatarsal ($p = .008$), midpoint ($p < .001$), and fifth metatarsal ($p < .001$) were all significantly higher than for the sliding joint center. Peak moments were not significantly different between the second metatarsal and midpoint joint centers ($p = .114$).

Statistical parametric mapping analysis revealed a significant main effect of joint center definition on estimated moments from 22 to 85% and 88–99% of stance phase when running at 3.89 m/s (Fig. 3). Post-hoc pairwise comparisons revealed significant difference for the fifth metatarsal definition compared to the other methods (Fig. 4). The midpoint and second metatarsal joint center definitions exhibited moments that were lower in early stance and higher in late stance, compared to the sliding joint center definition. Post-hoc analysis revealed no significant pairwise comparisons for the main effect from 88 to 99% of stance.

For the fast running condition (6.11 m/s) SPM analysis revealed a significant main effect of joint center definition on estimated moments from 22 to 86% of stance (Fig. 5). Post-hoc pairwise comparisons revealed significant differences for the fifth metatarsal definition compared to the other joint center conditions (Fig. 6). Comparison between the midpoint and sliding joint center definitions revealed a significant difference from 60 to 69% of stance.

4. Discussion

The purpose of this study was to investigate how MTP joint center definition affects estimated MTP joint moments during running. Results suggest that MTP joint center definition significantly affects both peak magnitude and magnitude of plantar flexor moment throughout stance. These differences were observed across running speeds.

Previous work comparing MTP joint axis definition demonstrated that estimated moments about a transverse axis from the fifth metatarsal overestimated plantar flexor moments by two to four times compared to an oblique axis (Smith et al., 2012). Our results are in agreement with these findings (Table 1). The fifth metatarsal head joint center definition resulted in peak MTP joint moments 105% and 109% greater than the sliding MTP joint center for the slow and fast conditions, respectively. The midpoint joint center resulted in peak moments 52% and 57% greater than the sliding joint center for the slow and fast conditions, respectively. The second metatarsal head approach resulted in peak moments 27% and 33% greater than the sliding joint center for the slow
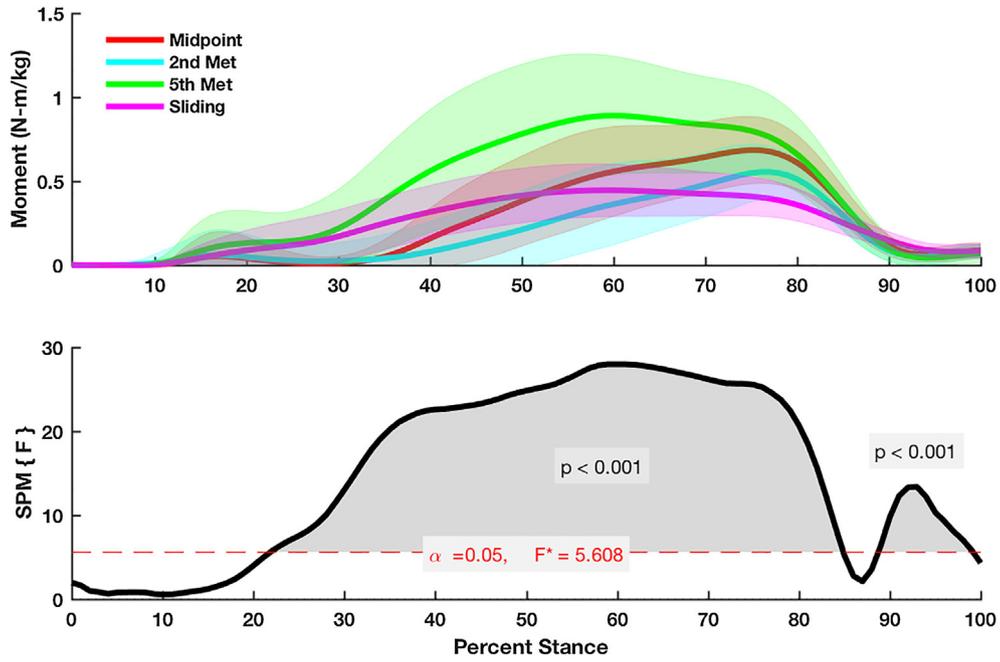
Table 1
Metatarsophalangeal joint moments (N-m/kg) as a function of velocity and joint center location; Mean ± SD.

Velocity (m/s)	Sliding	2nd Met. head	Midpoint	5th Met. head
3.89	0.464 ± .146[c,d]	0.590 ± .164[d]	0.704 ± .204[a,d]	0.952 ± .295[a,b,c]
6.11	0.802 ± .238[b,c,d]	1.07 ± .354[a,d]	1.26 ± .420[a,d]	1.68 ± .385[a,b,c]

a = significantly different from sliding, b = significantly different from 2nd met, c = significantly different from midpoint, d = significantly different from 5th met.
Significant difference, *p < 0.05*.

Fig. 3. Metatarsophalangeal joint moments during stance phase running at 3.89 m/s (top) and running F-critical value (solid line) and F-critical threshold (dashed line) (bottom). Shaded region represents duration of significant effect of joint center.
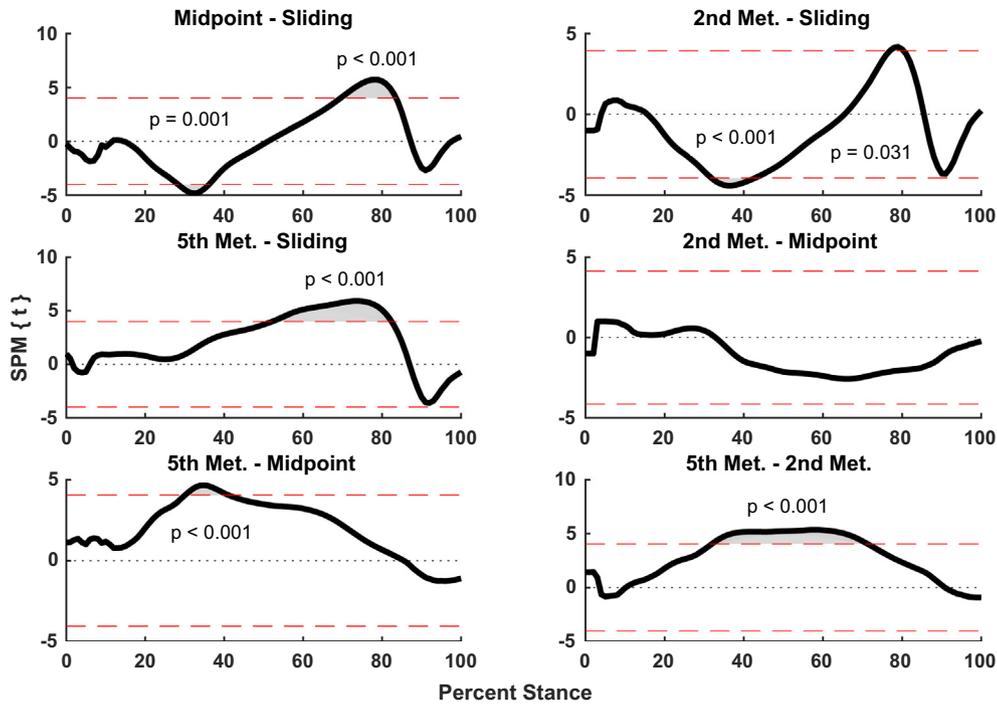

Fig. 4. Post-hoc pairwise comparisons between individual joint center definitions with running t-statistic (solid line) and t-critical band (dotted line) and Bonferroni adjusted p-values for running at 3.89 m/s.

and fast conditions, respectively. These results are intuitive as the moment arms for the fixed joint centers may not be the shortest perpendicular distance from the COP to the MTP joint axis. A fixed joint center can be affected by toe-in or toe-out angle (Chang et al., 2007; Rolian et al., 2009). A toe-out orientation will extend the moment arm from the fixed joint centers to the COP, whereas a toe-in orientation will decrease the moment arm and position the oblique MTP axis into a more transverse orientation with

respect to a global coordinate system. Increased variability in our results for the fixed joint center conditions compared to the sliding joint center may be partially explained by variable toe-out angle.

An effect on moment magnitude throughout stance was observed in the slow running condition (Fig. 4). Post-hoc pairwise comparisons show that the fifth metatarsal joint center definition was significantly larger than from the other joint center definitions during some periods of stance. The fifth metatarsal definition is the
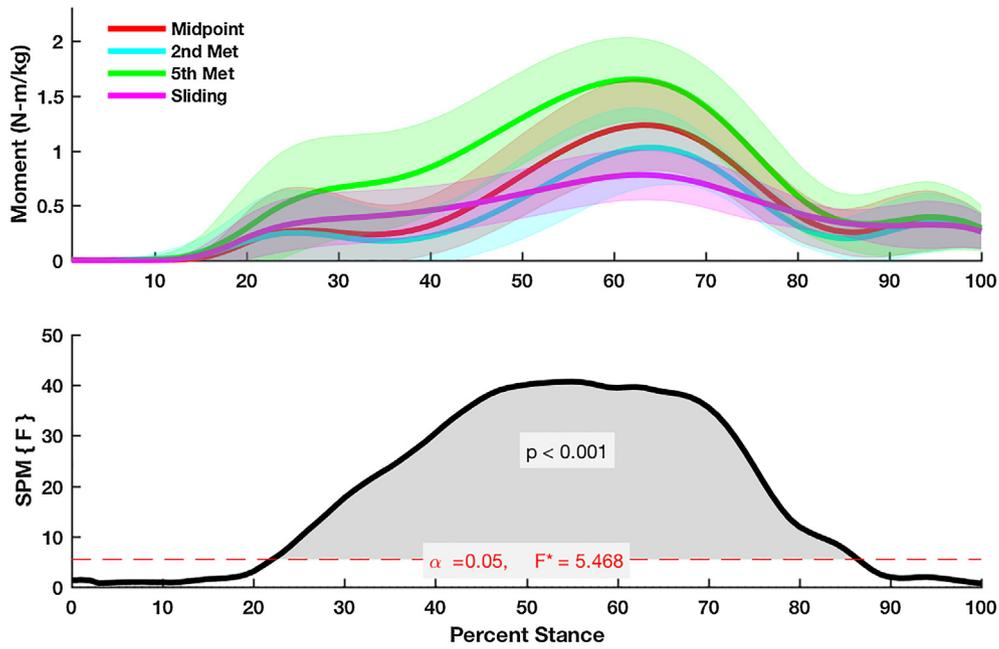
Fig. 5. Metatarsophalangeal joint moments during stance phase running at 6.11 m/s (top) and running F-critical value (solid line) and F-critical threshold (dashed line) (bottom). Shaded region represents duration of significant effect of joint center.
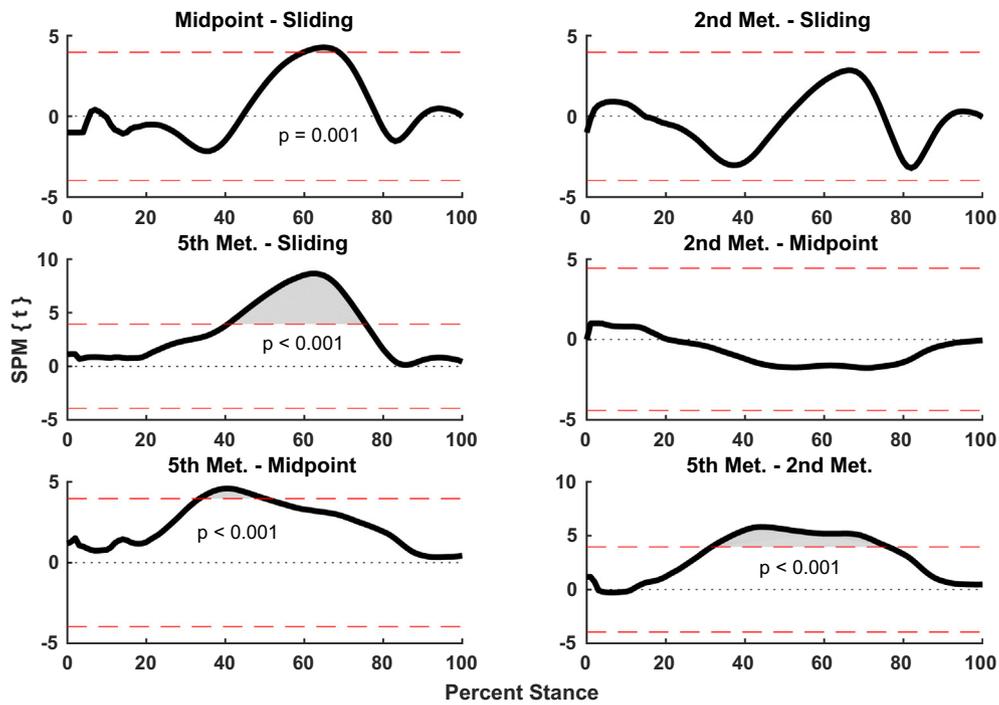

Fig. 6. Post-hoc pairwise comparisons between individual joint center definitions with running t-statistic (solid line) and t-critical band (dotted line) and Bonferroni adjusted p-values for running at 6.11 m/s.

most posterior and thus has the longest moment arm to the COP. Comparison to the sliding and second metatarsal joint centers show that the difference is near the timing of maximum moment. The midpoint joint center definition was only different from the fifth metatarsal definition from 30 to 40% of stance, at onset of the plantar flexor moment.

The midpoint and second metatarsal joint center definitions both exhibit significantly smaller and larger moments than the sliding joint center. From 30 to 40% stance is when the moments were smaller. The fixed joint center definitions may have later plantar flexor moment onset due to a later passing of the COP across the MTP axis, as the COP tends to move lateral to medial during running (Becker et al., 2014). If the COP crosses the MTP axis lateral to the fixed joint centers, then the sliding and fifth metatarsal joint center definitions will register earlier plantar flexor moment onset due to the oblique nature of the MTP joint.

The second phase of significant difference is when the midpoint and second metatarsal joint center definitions have significantly larger moments during late stance when their peak moments occur. The larger moments in late stance may be due to supination (Novacheck, 1998) causing lateral movement of the COP (Becker et al., 2014). Though the ground reaction force decreases in late stance, lateral and anterior movement of the COP will lengthen the moment arm with respect to the midpoint and second metatarsal joint centers, resulting in a later peak moment.

Joint center definition primarily only affected the plantar flexor moment during mid-stance for the fast running condition (Fig. 6). The fifth metatarsal definition displayed significant difference from the other definitions during mid-stance. From 60 to 69% of stance the midpoint joint center had a significantly larger moment than the sliding joint center, when peak moment occurred. During sprinting the COP tends toward the medial side of the foot, causing the COP to be anterior to the axis across the first and second metatarsals (Smith et al., 2012). A more medial COP passage may explain why there was no difference in time of plantar flexor moment between joint center definitions. The observed higher moments for the fifth metatarsal definition compared to other joint center definitions and for midpoint compared to sliding appears due to the change in moment arm.

At both speeds the COP passed anterior to the MTP axis at approximately 10% of stance and the midpoint and 2nd metatarsal head joint center techniques exhibit a small sinusoidal pattern in plantar flexor moment in the first half of stance before increasing toward the peak moment. This sinusoidal pattern may be attributable to inter-subject differences in the percent of stance phase at which the COP passed anterior to the MTP axis. Foot strike pattern was not controlled for and thus may be the cause of this observation. In a forefoot/midfoot strike pattern the COP moves posteriorly during weight acceptance before moving anteriorly during push-off (Cavanagh and Lafortune, 1980). This may explain the initial increase in plantar flexor moment early in stance before a decrease and subsequent increase once again. The sinusoidal pattern may also be attributable to a bending moment error as a result of the force distribution under the MTP joint axis (Oleson et al., 2005). While the metatarsal heads are in contact with the ground, force is being transmitted anteriorly and posteriorly to the MTP joint. The resultant COP may pass anteriorly and posteriorly across the MTP axis when the COP anterior-posterior coordinate is close to the axis. Shod participants in the current study may have further induced this error by distributing force over the larger area of the shoe outsole. In analyzing MTP kinetics while the metatarsal heads are in contact with the ground, caution should be used with respect to the potential limitations from COP coordinate calculations.

While this study focused only on MTP joint kinetics, it is intuitive that the effects would carry over into joint energetic calculations as joint work is the integral of joint power, and angular velocity will not change based on MTP joint center definition. While these resultant energetic calculations will not affect the consensus that the MTP joint functions primarily as a damper (Stefanyshyn and Nigg, 1997), it will affect net work and power estimations. Negative work estimations will be more severely overestimated due to the toe-flexors primarily acting eccentrically throughout stance phase.

Results from this study may be applicable to running footwear and prosthetic designers. Optimal footwear bending stiffness may improve performance by reducing the energetic cost of running (Hoogkamer et al., 2017; Roy and Stefanyshyn, 2006). In addition, footwear bending stiffness can alter mechanical function of the MTP joint by shifting the joint moment arm anteriorly (Willwacher et al., 2014) resulting in a reduction of angular deflection and increased plantar flexor moment (Stefanyshyn and Nigg, 2000; Willwacher et al., 2013). Recent efforts have utilized the load-displacement patterns of the MTP joint to tune footwear bending stiffness (Oh and Park, 2017). From the current results, it is evident that such efforts should potentially take into consideration joint center and axis definition (Smith et al., 2012). Larger moments may lead to custom tuned footwear being more stiff. If a shoe is too stiff, gait mechanics and running economy are both negatively affected (Madden et al., 2015; Willwacher et al., 2014). Individuals fit with improperly tuned footwear may exhibit changes in gait mechanics that are potentially detrimental to running performance.

Prosthetic engineers interested in developing a foot with a functional MTP joint based on anatomical limb data should take into consideration how MTP joint center definition will affect estimated energy absorption, generation, and stiffness. When tuning dynamic angular stiffness of the prosthetic foot, overestimation of the MTP plantar flexor moment may result in an individual adopting a metabolically costly gait pattern due to alteration of load and energy transfer between the lower extremity joints.

One limitation of this study is that results can be affected by marker placement error. Any error in the placement of retro-reflective markers on the metatarsal heads to define the MTP axis will affect joint moment estimations by altering the axis orientation and joint centers in global reference. Additionally, potential errors in COP calculation may exacerbate differences between joint center definitions.

In conclusion, this study has demonstrated that MTP joint center definition significantly affects estimated moments about the MTP joint. Researchers that include the MTP joint in inverse dynamics analysis and footwear and prosthetic designers that are interested in tuning forefoot bending stiffness should take MTP joint center location into consideration, as well as MTP joint axis definition. Due to the observed difference in moments during stance across joint center definitions and the complex anatomy of the foot, it may be more anatomically and mechanically representative for the MTP joint to be modeled as a hinge axis between the first and fifth metatarsal heads (Smith et al., 2012) with a non-fixed joint center where moments are estimated via a perpendicular moment arm from the COP to the MTP. Researchers should be aware of differences in timing of moment onset and magnitude that can result from differing MTP joint center definitions.

Conflict of interest

The authors of this paper have no financial or personal relationships with other people or organizations that could inappropriately influence the work presented.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jbiomech.2019.01.044.

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