



Dynamic angular stiffness about the metatarsophalangeal joint increases with running speed

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ABSTRACT

Altering the longitudinal bending stiffness of footwear has the potential to affect mechanics of the metatarsophalangeal (MTP) joint. Recent efforts have been put forth to identify an optimal bending stiffness of footwear to improve running performance. However, little is known about how this optimal bending stiffness may change with running speed. The purpose of this study was to investigate how dynamic angular stiffness about the MTP joint changes across running speeds. Eighteen participants ran at five speeds from 3.89 to 6.11 m/s. Metatarsophalangeal joint angles, moments, and stiffness were estimated for each speed. Two MTPJ load-displacement metrics were defined, active and critical stiffness. Instantaneous stiffness of the MTP joint was also quantified. There was a significant main effect of speed on critical stiffness ($p < .001$), maximum MTP moment ($p < .001$), MTP moment at maximum dorsiflexion ($p < .001$), and MTP range of motion ($p = .013$). There was no effect of speed on active stiffness ($p = .094$). These results support the notion that involvement of the MTP joint increases with running speed. Individual contributions of the foot and shoe to the MTP joint moment and stiffness suggest that the foot appears to dominate the stiffness of the foot-shoe complex and torque generation about the MTP joint. Instantaneous stiffness fluctuated throughout stance phase, suggesting that foot-shoe complex stiffness is time dependent. The ratio by which critical stiffness and MTP joint range of motion increase with running speed may provide insight for how to guide construction of performance footwear. These results suggest that when utilizing MTP joint mechanics for insights into designing a shoe for performance purposes, the effect of speed should be taken into consideration.

1. Introduction

The metatarsophalangeal (MTP) joint serves as the base of support during running once the heel lifts off the ground (Goldmann & Brüggemann, 2012; Stefanyshyn & Nigg, 1997; Rolian, Lieberman, Hamill, Scott, & Werbel, 2009). The rearfoot pivots around the MTP joint axis as the whole body center of mass moves anteriorly, resulting in energy being absorbed at the MTP joint and very little being generated (Goldmann & Brüggemann, 2012; Stefanyshyn & Nigg, 1997; Roy & Stefanyshyn, 2006).

In the shod condition the foot and shoe act together to modulate mechanical function of the MTP joint. The foot and shoe act in series to provide linear stiffness to the foot-shoe complex (Kelly, Lichtwark, Farris, & Cresswell, 2016) and act in parallel to provide angular stiffness to the foot-shoe complex (Oleson, Adler, & Goldsmith, 2005). Changing the longitudinal bending stiffness of

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footwear via flat carbon fiber plates can affect mechanics of the MTP and other lower extremity joints (Stefanyshyn & Nigg, 2000; Willwacher, König, Pothast, & Brüggemann, 2013) by altering the lever arm from the joint centers to the resultant ground reaction force vector (Willwacher, König, Braunstein, Goldmann, & Brüggemann, 2014). Recent efforts have shown that a curved carbon fiber plate in combination with a more compliant foam in the midsole helps reduce the energetic cost of running (Hoogkamer et al., 2017). Increasing the longitudinal bending stiffness of footwear may influence a shift in muscle force-velocity operating points to a more favorable position (Madden, Sakaguchi, Wannop, & Stefanyshyn, 2015; Takahashi, Gross, Van Werkhoven, Piazza, & Sawicki, 2016; Willwacher et al., 2013) and improve running economy (Hoogkamer et al., 2017; Madden et al., 2015; Roy & Stefanyshyn, 2006) to help benefit overall running performance.

Recent efforts have been put forth to determine an optimal bending stiffness of footwear by utilizing the load-displacement plot of the MTP joint to quantify the critical stiffness, defined as the ratio between the moment observed at maximal dorsiflexion and the maximum MTP joint dorsiflexion angle (Oh & Park, 2017). It has been proposed that this critical stiffness represents the threshold for the bending stiffness that maximizes the elastic benefit of the shoe without inhibiting natural motion of the MTP joint (Oh & Park, 2017). The net angular impulse of the entire lower limb during running is the product of contributions from the musculoskeletal system and strain energy stored in the shoe. The use of footwear tuned to an optimal bending stiffness to store and return strain energy may reduce the required contribution from the musculoskeletal system to generate angular impulse, leading to a beneficial reduction in metabolic cost (Oh & Park, 2017).

General lower extremity joint stiffness has been shown to increase with running speed (Jin & Hahn, 2018; Stefanyshyn & Nigg, 1998), but little is known about how MTP joint stiffness changes across running speeds. Because the MTP joint does not exhibit spring like behavior, we describe two measures of joint stiffness in this paper. The term ‘stiffness’ is adopted due to the quantification of change in moment over change in angle during a phase of stance (Hamill, Gruber, & Derrick, 2014; Stefanyshyn & Nigg, 1998). The purpose of this study was to investigate how these two measures of dynamic angular stiffness about the MTP joint change across running speeds. We hypothesize that MTP joint stiffness will increase with running speed.

2. Methods

Eighteen competitive runners (four female) were recruited for this study (Table 1). To be included participants had to have a 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.

A bilateral lower extremity marker set consisting of 41 *retro*-reflective markers defining nine segments (forefoot, rearfoot, shank, thigh, pelvis) was used. A two-segment foot model was defined by placing markers on the forefoot and calcaneus (Goldmann, Sanno, Willwacher, Heinrich, & Brüggemann, 2013). Windows were cut in the shoes to place markers directly on the foot (Bishop, Arnold, Fraysse, & Thewlis, 2014). Participants all wore the same footwear (Brooks Launch 3) to control for the effects of longitudinal bending stiffness on MTP joint mechanics. Individual *retro*-reflective markers were placed on the medial and lateral malleoli, medial and lateral femoral epicondyles, left and right greater trochanter, left and right posterior superior iliac spines, and the sacrum. Quadrad marker clusters were placed on the shank and thigh. Participants performed a static trial after which markers were then removed from the medial malleoli and femoral epicondyles so that they did not interfere with running movements.

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, 6.11 m/s. Data were collected at each speed for ten consecutive strides. Rest between conditions was self-selected. These speeds were chosen as they represent relevant training and racing paces for club level competitive runners.

A custom MATLAB (version R2016b; MathWorks, Natick, MA) program was used to calculate joint kinematics, kinetics, and stiffness. These metrics were calculated throughout the entire stance phase. Stance phase was defined as the phase when the vertical ground reaction force exceeded 5% of body weight. Raw marker coordinate data were filtered using a zero-lag, fourth-order low pass Butterworth filter with a 20 Hz cutoff frequency (Willwacher et al., 2013). The same cut-off frequency was used for force platform data to avoid artifact in joint moment estimations (Bezodis, Salo, & Trewartha, 2013). Joint angles were calculated using an Euler/Cardan rotation order of flexion/extension, abduction/adduction, and internal/external rotation. Sagittal plane MTP joint angles and moments were used for analysis.

Metatarsophalangeal joint moments were estimated using an inverse dynamics approach. The MTP joint was modeled as a hinge axis along the vector connecting the 1st and 5th metatarsal markers. The ground reaction force moment arm was estimated as the perpendicular distance between the center of pressure and the MTP oblique axis (Day & Hahn, 2019). Resultant forces and moments about the MTP joint were considered zero until the center of pressure passed anterior to the MTP oblique axis (Stefanyshyn & Nigg, 1997). Inertial effects of the forefoot were considered negligible (Stefanyshyn & Nigg, 1997). Joint moments were resolved in the

Table 1
Participant characteristics.

Sex	Age (yr)	Height (cm)	Mass (kg)	Weekly Mileage (km)	5000 m Best
Male	24 ± 6	180 ± 10	67 ± 8	90 ± 24	16:16 ± 0:57
Female	26 ± 7	165 ± 7	56 ± 8	77 ± 24	17:45 ± 1:07

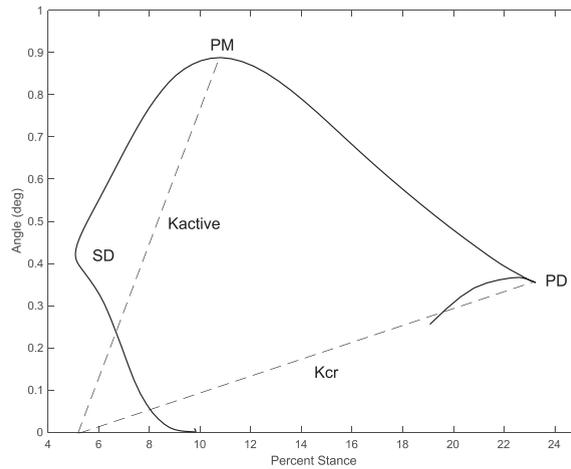


Fig. 1. Depiction of methodology for metatarsophalangeal joint stiffness calculations. SD = start dorsiflexion, PM = peak moment, PD = peak dorsiflexion.

rearfoot coordinate system for reporting and joint stiffness calculations. Kinematic and kinetic data were re-sampled to 101 data points per stance phase for time-normalized analysis.

Two measures describing the load-displacement relationship of the MTP were quantified, active stiffness (K_{active}) and critical stiffness (K_{cr}) (Fig. 1). Load-displacement measures were calculated as follows:

$$K_{\text{active}} = \frac{\text{Max MTP Moment}}{\theta_{\text{MTP(at max moment)}} - \theta_{\text{MTP min}}}$$

$$K_{\text{cr}} = \frac{\text{MTP moment(at max dorsiflexion)}}{\theta_{\text{MTP max}} - \theta_{\text{MTP min}}}$$

Active stiffness represents the phase during which energy is delivered into the forefoot as this phase is when the MTP plantar flexor moment is increasing. Critical stiffness represents the functional stiffness of the foot-shoe complex about the MTP joint and may be used to identify the stiffness threshold for the elastic benefit of footwear without inhibiting natural motion of the MTP joint (Oh & Park, 2017). However, as the MTP joint does not behave as a spring mechanism during running, and because a substantial amount of energy has been dissipated up to the occurrence of peak MTP dorsiflexion, we acknowledge that this phase represents a simplified measure of stiffness. We utilize this terminology to reflect a mechanical moment-angle relationship up to the occurrence of peak flexion angle.

Instantaneous stiffness was calculated by taking the first derivative of the load-displacement curve. Footwear stiffness was calculated from Instron (Norwood, MA) mechanical testing results provided by the manufacturer (Brooks Sports, Seattle, WA). Passive footwear torque throughout stance was calculated by multiplying the footwear bending stiffness by the MTP joint angle. While the terms joint stiffness is used throughout this paper, these values represent the behavior of the foot-shoe complex about the MTP joint as modulated by passive and active internal and external structures.

Individual repeated measures univariate analysis of variance (ANOVA, $\alpha < 0.05$) tests were used to analyze the main effect of running speed on active stiffness (K_{active}), critical stiffness (K_{cr}), MTP joint range of motion, maximum MTP plantar flexor moment, and MTP plantar flexor moment at maximum dorsiflexion. Mauchly's test of Sphericity ($\alpha < 0.05$) was used to check for equal variance. Greenhouse-Geisser corrections were used when violations of sphericity were detected. Pairwise comparisons with Bonferroni adjustments ($\alpha = 0.05/10 = 0.005$) were used post-hoc to analyze main effects. Tests of within-subject contrasts were analyzed to determine the linearity of the change in measures across running speeds ($\alpha < 0.05$).

3. Results

There was a main effect of speed on critical stiffness ($p < .001$), maximum MTP plantar flexor moment ($p < .001$), MTP plantar flexor moment at maximum dorsiflexion ($p < .001$), and MTP joint range of motion ($p = .013$) (Figs. 2 and 3). Pairwise comparisons are presented in Tables 2 and 3. There was no main effect of speed on active stiffness ($p = .094$).

Significant linear trends were detected for critical stiffness ($p < .001$), maximum MTP plantar flexor moment ($p < .001$), MTP plantar flexor moment at maximum dorsiflexion ($p < .001$), and MTP range of motion ($p < .01$). Critical stiffness, maximum MTP moment, and MTP moment at maximum dorsiflexion all increased as running speed increased.

Instantaneous MTP joint stiffness of the foot-shoe complex was much greater than that of the shoe throughout stance phase (Fig. 4). The slow (3.89 m/s) and medium (5.00 m/s) speeds displayed plateau regions from approximately 55–70% stance whereas the fastest (6.11 m/s) speed did not exhibit a plateau region. Instantaneous stiffness fluctuated throughout stance at all speeds.

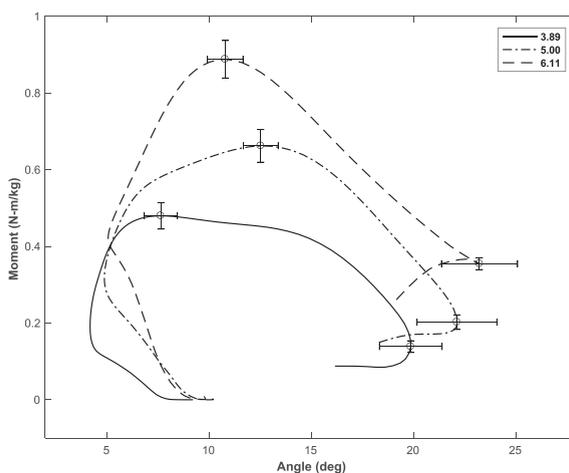


Fig. 2. Average angular load-displacement of the metatarsophalangeal joint across speeds (m/s).

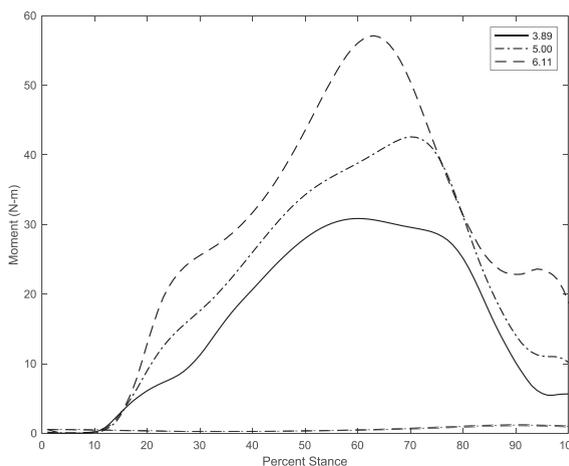


Fig. 3. Average metatarsophalangeal joint moment across speeds (m/s). The lower dashed line represents passive elastic torque of the footwear.

Table 2
Dynamic angular stiffness (N-m/kg/deg) across running speeds; Mean ± SD.

Velocity (m/s)	K _{active}	K _{cr}
3.89	0.144 ± 0.102	0.009 ± 0.004 ^{c,d,e}
4.44	0.132 ± 0.114	0.010 ± 0.005 ^{c,d,e}
5.00	0.116 ± 0.103	0.013 ± 0.007 ^{a,b,d,e}
5.56	0.097 ± 0.038	0.015 ± 0.008 ^{a,b,c}
6.11	0.153 ± 0.074	0.017 ± 0.006 ^{a,b,c}

Pairwise comparisons showing significant differences ($p < .05$): ^a different from 3.89 m/s, ^b different from 4.44 m/s, ^c different from 5.00 m/s, ^d different from 5.56 m/s, ^e different from 6.11 m/s.

Table 3
Metatarsophalangeal joint range of motion and kinetics across running speeds; Mean ± SD.

Velocity (m/s)	Range of Motion (deg)	Maximum Moment (N-m/kg)	Moment at Maximum Dorsiflexion (N-m/kg)
3.89	17.1 ± 4.3 ^{b,c,e}	0.500 ± 0.146 ^{b,c,d,e}	0.143 ± 0.065 ^{c,d,e}
4.44	18.5 ± 5.0 ^a	0.570 ± 0.154 ^{a,c,d,e}	0.168 ± 0.067 ^{c,d,e}
5.00	18.7 ± 5.3 ^a	0.674 ± 0.181 ^{a,b,d,e}	0.215 ± 0.080 ^{a,b,d,e}
5.56	19.0 ± 5.6	0.741 ± 0.180 ^{a,b,c,e}	0.269 ± 0.096 ^{a,b,c}
6.11	20.0 ± 6.0 ^a	0.899 ± 0.210 ^{a,b,c,d}	0.316 ± 0.066 ^{a,b,c}

Pairwise comparisons showing significant differences ($p < .05$): ^a different from 3.89 m/s, ^b different from 4.44 m/s, ^c different from 5.00 m/s, ^d different from 5.56 m/s, ^e different from 6.11 m/s.

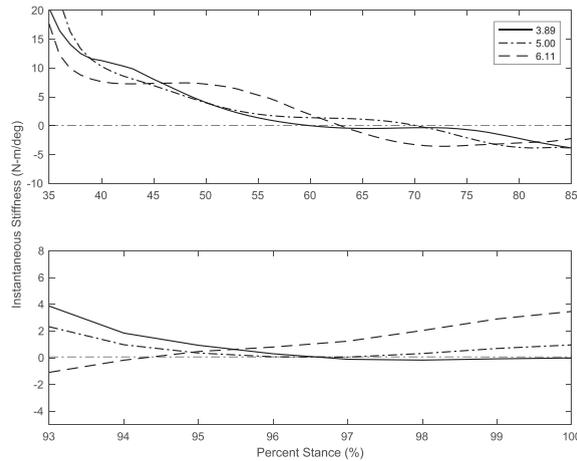


Fig. 4. Instantaneous metatarsophalangeal joint stiffness during loading (top) and push-off (bottom). Horizontal line represents footwear stiffness.

4. Discussion

The purpose of this study was to investigate how dynamic angular stiffness about the MTP joint changes across running speeds. The load-displacement plot of the MTP joint exhibits a notable amount of hysteresis (Fig. 2), resulting in the peak moment and peak dorsiflexion not occurring simultaneously as observed at the ankle and knee (Hamill et al., 2014; Jin & Hahn, 2018; Stefanyshyn & Nigg, 1998). Because the peak moment and dorsiflexion occur at different time points during stance, two measures from the load displacement plot were quantified, active stiffness (K_{active}) and critical stiffness (K_{cr}).

These results corroborate previous reports suggesting that lower extremity joint stiffness increases with running speed (Jin & Hahn, 2018; Stefanyshyn & Nigg, 1998). Our hypothesis that MTP joint stiffness will increase with running speed was partially supported. Critical stiffness (K_{cr}) increased with running speed ($p < .001$), but there was no effect of speed on K_{active} ($p = .096$). While the maximum MTP moment increased with running speed ($p < .001$), there was no increase in K_{active} due to differences in MTP joint angle excursion between speeds within this phase (Fig. 2). While the phase of the load-displacement plot defined by K_{active} most closely represents that of quasi-stiffness spring behavior (Latash & Zatsiorsky, 1993), the energy stored during this phase is not quickly returned. Thus, we interpret K_{active} as a representative measure for energy absorption in structures modulating forefoot mechanics. We speculate that the lack of observed change in K_{active} may be a protective mechanism to maintain a lower loading rate of the bone and soft tissues. It may also be the result of an increase in MTP dorsiflexion angular velocity as joint angle excursion increased with running speed. Increased dorsiflexion angular velocity may have been the reason more dorsiflexion occurred by the time of peak MTP moment. The increase in K_{cr} with running speed was due to an increase in the MTP moment at maximum MTP dorsiflexion, as MTP range of motion also increased with running speed. The observed ratio of the change in K_{cr} across speeds may be of use to provide a guide for how to tune footwear stiffness to running speed. The linear trends observed for K_{cr} , MTP joint range of motion, and plantar flexor moment at maximum dorsiflexion suggest that effectively tuning footwear structures may be a linear function of speed.

Metatarsophalangeal joint motion is controlled by the intrinsic and extrinsic toe-flexor musculature (Goldmann & Brüggemann, 2012; Mann & Inman, 1964; Mckeon, Hertel, Bramble, & Davis, 2015; Miyazaki & Yamamoto, 1993). Indwelling electromyography studies of the intrinsic foot musculature have shown that their level of activation increases with gait speed (Kelly, Cresswell, Racinais, Whiteley, & Lichtwark, 2014; Kelly, Lichtwark, & Cresswell, 2015). Our results support these findings by providing evidence that the toe-flexors increase in mechanical function with running speed. This increase in mechanical function is evidenced by the larger MTP plantar flexor moments as running speed increases that have near negligible contribution from the shoe. Additionally, the increase in K_{cr} suggests an increase in endpoint stiffness as running speed increases. Vertical ground reaction force increases with running speed (Clark & Weyand, 2014), resulting in a larger external dorsiflexion moment about the MTP joint that the toe-flexor musculature has to internally counteract (Goldmann & Brüggemann, 2012). As observed in the load-displacement curves across running speeds (Fig. 2), there are regions of relative plateau during mid-stance at the slowest speed. These plateau regions were not observed at the faster speeds, where more prominent loading and un-loading of the forefoot is occurring, as indicated by the steeper slopes. This observation provides further evidence that in addition to larger peak MTP moments and K_{cr} , the general shape of the load-displacement plot reveals increased mechanical function of the forefoot.

While K_{cr} did increase as a result of larger MTP moment, MTP joint range of motion also increased by 2.9° from the slowest to fastest running speeds. This increase in range of motion may be due to an increase in hip extension and ankle plantarflexion with running speed (Orendurff et al., 2018). A more extended hip will position the foot further posterior relative to the pelvis, requiring an increase in MTP dorsiflexion to maintain a surface contact area by which to transmit force. Secondly, force generating capacity of the toe-flexor musculature decreases when the ankle is plantar-flexed but increases with MTP dorsiflexion (Goldmann & Brüggemann, 2012). Thus the increase in MTP dorsiflexion with running speed may also be a mechanism to retain force-generating capacity of the toe-flexors (Goldmann & Brüggemann, 2012). On the contrary, the increase in dorsiflexion may also be due to the toe-flexor

musculature being unable to eccentrically generate enough force and subsequent internal joint moment to resist MTP dorsiflexion. The intrinsic foot muscles can only generate approximately 6 N-m of torque as a result of their small pennation angles, muscle volume, and muscle moment arms to the MTP axis of rotation (Farris, Kelly, Cresswell, & Lichtwark, 2019; Ledoux, Hirsch, Church, & Caunin, 2001). In addition, the function of individual intrinsic foot muscles may vary between modulating MTP joint motion and stabilizing the medial and longitudinal arches of the foot (Tosovic, Ghebremedhin, Glen, Gorelick, & Brown, 2012). If the primary function of the intrinsic foot muscles is to stabilize the arches of the foot and aid in the transfer of force from the leg to the ground (Kelly et al., 2014, 2015), then this may explain the observed increase in MTP plantar flexor moment and joint range of motion.

While the precise physiological mechanism behind the increase in range of motion remains unknown, this kinematic change may have application to the design of footwear midsoles. An increase in joint range of motion will affect muscle-tendon unit properties such as force-length and force-velocity operating points. Recent footwear design efforts that make use of a curved carbon fiber plate in the midsole (Hoogkamer et al., 2017) may also benefit by taking changes in MTP dorsiflexion range of motion into consideration. The observed increase in MTP range of motion with speed may serve as a framework for how to shape the curvature of an embedded plate if tuning footwear for optimal performance at a specific running speed. It has been demonstrated that the carbon fiber plates in footwear serves as a lever, not a spring (Hoogkamer, Kipp, & Kram, 2018). A plate shaped to the curvature of the foot will theoretically not store as much energy through bending, but rather serve as a lever and potentially facilitate a difference in perceived 'ride' of the shoe, defined as the peak anterior-posterior velocity of the center of pressure (Lam, Mohr, Nigg, & Nigg, 2018). A curved plate may result in a lower peak center of pressure velocity, resulting in a roll-through feeling from weight acceptance to push-off phases of stance. A curvature too concave or too shallow compared to natural MTP dorsiflexion range of motion may result in a user not perceiving as smooth of a ride in the shoe as they possibly could. Additionally, a curved plate may affect force-length and force-velocity operating points of the musculature about the MTP and ankle joints based upon gearing effects of a stiffened shoe (Takahashi et al., 2016; Willwacher et al., 2014). Due to the carbon fiber plate primarily acting as a lever and not a spring, it may be of relevance to methodically consider the curvature of the plate in footwear to match natural range of motion of the foot, and how these kinematics change with running speed.

The MTP moment is the net product of passive torque contribution from the shoe and active contribution from the musculoskeletal system (Fig. 3). The musculoskeletal system appears to be the dominant contributor to the MTP joint moment, as the passive torque contribution from the shoe in this study did not exceed 2 N-m. The near negligible passive torque contributions from the shoe observed across speeds suggest that the use of a stiffer shoe that increases the amount of elastic energy stored and returned may be beneficial to running performance by increasing the passive contribution to the net angular impulse (Oh & Park, 2017). However, when increasing shoe stiffness it is important to note that restriction of MTP dorsiflexion may lead to altered joint mechanics, soft tissue function within the foot, and power generating capacity of the lower extremity (Bojsen-Møller & Lamoreux, 1979; Goldmann & Brüggemann, 2012; Oh & Park, 2017; Thewlis, Paul, & Bishop, 2012; Willwacher et al., 2013). A shoe that is too stiff may also increase the energetic cost of running and potentially facilitate detrimental biomechanical parameters such as increased trunk lean or contact time (Madden et al., 2015; Oh & Park, 2017; Roy & Stefanyshyn, 2006; Willwacher et al., 2014). While there appears to be merit to increasing the stiffness of footwear to increase the passive torque contribution of the shoe to the net angular impulse, care should be taken in ensuring that natural motion of the MTP joint is not inhibited (Oh & Park, 2017). It may be of greater importance to tune the stiffness to running velocity. While the passive torque contribution is small, when seeking to optimize running performance we should not neglect to maximize contribution of the shoe to forward propulsion. It may be important to maintain the shoe functioning as a lever by which a stiffer plate will resist the greater MTP moment as speed increases. The ratio of the increase in K_{cr} , reflective of the increase in MTP moment at maximum dorsiflexion, may serve as a reference for how to increase stiffness of a shoe with running speed. It is most likely that the increased net joint moment at maximum dorsiflexion is due to a required greater torque output in late stance from the leg and foot to generate enough impulse for forward propulsion at the faster running speeds.

Instantaneous MTP joint stiffness of the foot-shoe complex fluctuated throughout stance phase and was of greater magnitude than that of the shoe (Fig. 4). The fluctuating instantaneous stiffness suggests that the contribution to the MTP joint moment is largest from the foot and very small for the shoe. Additionally, the fluctuating instantaneous stiffness suggests that the foot-shoe complex is also time dependent, as the shoe exhibits constant stiffness when dorsiflexed less than thirty degrees. These results are in agreement with previous efforts that have investigated contributions of the foot and shoe to forefoot stiffness (Oleson et al., 2005). The time dependent nature of the instantaneous MTP joint stiffness may be of use to footwear designers to improve energy storage and return dynamics in the midsole. The positive regions during the loading phase are when the MTP moment is increasing at a greater rate than the dorsiflexion angle, indicative of when the foot is performing work on the midsole. The negative regions are when the MTP moment is decreasing while dorsiflexion is still occurring, indicative of when energy should be returned. We speculate that these negative regions are when the shoe midsole is expanding after being compressed during the energy absorption phase over the first half of stance. Thus, the energy returned to the foot during these phases is likely to be oriented normal to the midsole. Combining the instantaneous stiffness data with center of pressure or pressure insole data may then provide insight as to where within the midsole to place compliant or resilient materials. An improved understanding of where within the midsole to position varying materials or how to guide the foot within the shoe based upon the location of where work is being performed on the midsole or energy is being returned may be of use to improve dynamics of the foot-shoe interaction.

As exhibited by the large amount of hysteresis present in the MTP joint load-displacement plot (Fig. 2), the use of the term joint stiffness does not represent the same behavior as stiffness estimations at the ankle and knee. Stiffness implies that the system is in equilibrium and that elastic energy is being stored and returned (Latash & Zatsiorsky, 1993). Joint stiffness is often referred to as a quasi-stiffness behavior, yet the damper function of the MTP joint suggests that there is little to no spring behavior and that negligible strain energy stored during energy absorption is utilized for push-off. Though this is not a standard definition of material stiffness, we

use the term to describe the resistance to dorsiflexion comprised of contributions from the shoe, musculoskeletal system, and passive soft tissues such as the plantar aponeurosis. Individual contributions of the foot and shoe to this stiffness may also vary with speed as footwear and soft tissue elicit viscoelastic behavior.

One limitation to this study is that the testing speed of the Instron (Norwood, MA) used to determine the bending stiffness of the footwear was unable to match the MTP plantarflexion velocity observed during running. Because running shoe midsoles are often comprised of viscoelastic materials, their resistance to deformation will be greater with the higher loading rates of running gait. In addition, the midsole is compressed in a linear fashion by the human body during running, whereas the shoe is unloaded during bending stiffness tests. It is possible that the shoe is dynamically stiffer than mechanical testing data would suggest and may contribute more to the stiffness of the foot-shoe complex and MTP plantar flexor moment than described.

5. Conclusions

The present study provides evidence that dynamic angular stiffness about the MTP joint increases across running speeds. These findings provide a reference for how to potentially tune the longitudinal bending stiffness and shape of midsole structures in footwear to improve running performance. It is suggested that the bending stiffness of footwear should be increased as the passive torque contribution of the footwear was minimal. Further, it appears that an optimal footwear bending stiffness may be dependent upon running speed.

Declaration of Competing Interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.humov.2019.102501>.

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