SPEED AND SLOPE EFFECTS ON METATARSOPHALANGEAL JOINT KINEMATICS IN RUNNING

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The purpose of this study was to describe the effects of running speed and slope on metatarsophalangeal (MTP) joint kinematics. 22 male and female runners underwent 3D motion analysis on an instrumented treadmill at three different speeds (2.5 m/s, 3.0 m/s, 3.5 m/s). At each speed, participants ran at seven slope conditions (downhill: -15%, -10%, -5%, level, and uphill: +5%, +10%, +15%). We found a significant main effect ($p < 0.001$) of running speed and slope on peak MTP dorsiflexion and a running speed by slope interaction effect ($p < 0.001$) for peak MTP dorsiflexion velocity. These findings highlight the need to consider running intensity and environmental factors like running surface inclination when considering MTP joint mechanics and technological aids to support runners.

KEYWORDS: locomotion, running mechanics, foot.

INTRODUCTION: The metatarsophalangeal (MTP) joints are essential for an effective push-off from the ground during human locomotion (Bojsen-Møller & Lamoreux, 1979; Rolian et al., 2009; Welte et al., 2018). MTP joint mechanics can be altered by changing footwear's longitudinal bending stiffness (Willwacher et al., 2013, 2014, 2016), and optimal bending stiffness can improve sports performance in sprinting and running (Roy & Stefanyshyn, 2005; D. Stefanyshyn & Fusco, 2004). Distance running training and competition often involve varying running speeds and running up and down inclined surfaces. Changing the slope of the running surface changes lower extremity running mechanics (Okudaira et al., 2020; Okudaira, Willwacher, Kawama, et al., 2021; Okudaira, Willwacher, Kuki, et al., 2021; Vernillo et al., 2017). Furthermore, running speed has been shown to affect MTP joint mechanics (E. M. Day & Hahn, 2019; D. J. Stefanyshyn & Nigg, 1997).

Optimal bending stiffness of footwear to improve running economy changes with running speed (E. Day & Hahn, 2020). Despite the known effects of slope and speed on lower extremity joint biomechanics, almost all biomechanical studies on MTP joint biomechanics were performed on level running surfaces. Only one study (Willwacher, Lichtwark, et al., 2021) has anaylzed MTP joint work during uphill and downhill running, yet.

As a consequence, little is known about the interaction between running speed and the slope on the running surface on MTP joint kinematics. However, knowledge about the impact of the running environment on MTP joint kinematics could aid in designing footwear with optimized bending stiffness. Further, an improved understanding on the effects of slope and speed on MTP joint kinematics will improve our understanding of how the working conditions of extrinsic and intrinsic foot muscles change in real world situations.

Therefore, the purpose of this study was to describe MTP joint kinematics in running when systematically varying running speed and inclination of the running surface. We hope that these results can inform training practice and the design of technological aids (e.g., running shoes).

METHODS: For this study, we recruited 22 (13 male, nine female; body mass 67.8 ± 4.0 kg, height: 1.76 ± 0.07 m, age: 24 ± 4 years) participants. Participants ran at three different speeds (2.5 m/s, 3.0 m/s, 3.5 m/s) on a force instrumented treadmill (Gaitway 3D, HP Cosmos, Traunstein, Germany) in their own running shoes. Within each running speed, we varied the slope of the running surface from 15% downhill to 15% uphill in steps of 5%, resulting in seven slope conditions. Running speeds were checked using a recently developed optical method (Willwacher, Oberländer, et al., 2021).

We captured MTP joint kinematics using a 17 camera, marker-based, 3D motion capturing systems (Qualisys AB, Gothenburg, Sweden). We analysed MTP kinematics within the ground contact period, which was determined using the normal component of the ground reaction force (threshold 20 N).

Raw 3D marker trajectories were filtered using a recursive digital 4th order Butterworth low-pass filter with a cut-off frequency of 20 Hz (Mai & Willwacher, 2019). MTP joint kinematics were tracked using three markers placed on the shoe upper over the medial, posterior and lateral parts of the calcaneus (proximal segment) and markers placed on the shoe over the proximal end of first and fifth phalangeal bones as well as on top of the big toe (distal segment). The five individual MTP joints were simplified to a single MTP joint with the joint centre aligning with the MTP joint of the first ray within the sagittal plane and a joint axis representing the line joining the MTP joints of the first two rays. Details of this method can be found in a previous publication (Willwacher et al., 2013).

We extracted the MTP joint angles and angular velocities within the sagittal plane (while considering the rotation of the rearfoot segment). We extracted the mean of the peak MTP dorsiflexion angles and angular velocities from a minimum of 22 steps per condition per participant.

We used a two-way repeated-measures ANOVA to identify the potential effects of speed, incline, or their interaction on peak dorsiflexion angles or angular velocity.

RESULTS: We identified significant main effects of running speed ($p < 0.001$) and slope of the running surface ($p < 0.001$) on peak MTP dorsiflexion during the stance phase (Fig. 1). When averaged over all slope levels, peak MTP dorsiflexion angles increased by 2.3°(+12.1%) when increasing running speed from 2.5 m/s to 3.5 m/s. When averaged over all speeds, peak MTP dorsiflexion increased by 8.2° (+48.6%) when changing from 15% downhill to 15% uphill running.

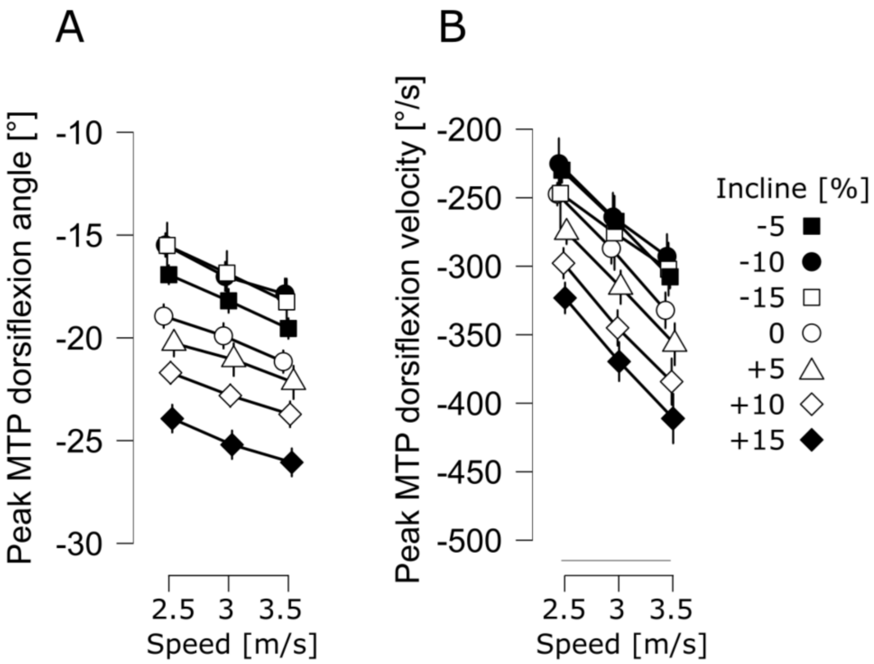

Figure 1: Effects of running speed and inclination of the running surface on peak MTP dorsiflexion and dorsiflexion velocity.

We further identified a significant running speed by slope interaction effect ($p < 0.001$) for peak MTP joint dorsiflexion velocity (Fig. 1). The increase in peak MTP dorsiflexion velocity was higher at 3.5 m/s running speed (+109.0 °/s, +36.1%), compared to 3.0 m/s running speed (+94.0 °/s, +34.1%), and 2.5 m/s running speed (+76.3 °/s, +30.1%).

DISCUSSION: The purpose of the present study was to describe the effects of running speed and slope on MTP joint kinematics. We could show that running speed and slope systematically affect both peak MTP dorsiflexion and dorsiflexion angular velocity. Our findings concerning speed effects on peak MTP dorsiflexion replicate previous findings (E. M. Day & Hahn, 2019). Further, our results extend previous findings of increased peak MTP dorsiflexion angles from walking studies (Kersting et al., 2021; Mistretta et al., 2018). While we did not observe a speed by slope interaction effect for peak MTP dorsiflexion angle, we found such interaction for peak MTP dorsiflexion velocity.

These results highlight the need to consider running intensity and the training environment when addressing, e.g., technological interventions like running shoes whose material properties might be sensitive to the bending range of motion or peak bending velocity. Our results might further provide baseline data for improving humanoid robot or prosthetic foot structures.
However, this study has some limitations. We could address only relatively slow running speeds (up to 3.5 m/s). We have chosen this approach since we wanted all recreationally active participants to reach all running speeds even in the steepest slope condition. Future studies should explore MTP mechanics at higher running speeds. Further, we placed markers on the shoe upper instead of directly applying markers to the skin. Since this might affect the kinematic results (Jewell et al., 2017; Trudeau et al., 2017), future studies should apply more sophisticated methods of marker placement. Finally, our study did not consider potential fatigue effects that might be relevant in distance running (Sanno et al., 2021; Willwacher et al., 2020).

CONCLUSION: This study identified that peak MTP dorsiflexion and dorsiflexion velocity increase with running speed and increasing incline levels of the running surface when running in an unfatigued state.

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