COMPARISON OF MAXIMAL PASSIVE HALLUX DORSIFLEXION WITH MIDFOOT MOMENT IN PUSH OFF PHASE DURING GAIT

Anne Luchtenberg[1] and Richard Smith[2]

University of Twente, Enschede, The Netherlands[1]
University of Sydney, Sydney, New South Wales, Australia[2]

The purpose of this study was to relate 1st metatarsophalangeal (1MTP) joint stiffness caused by maximal passive hallux dorsiflexion with midfoot moment in the push off phase during gait. Hallux dorsiflexion and 1MTP joint stiffness was measured using a hallux dynamometer, while participants (n = 8) were relaxed in a purpose-built chair. Motion capture and kinetic data was collected during chair and gait measurements. Mean stiffness, calculated over the 1MTP joint range of motion of 0.04, 0.029 and 0.041 Nm/deg (ankle in maximal dorsiflexion, 90 deg and maximal plantar flexion respectively) was found. A regression analysis between timing of maximal midfoot sagittal plane moment in gait indicated that up to 60% of the variance in timing of the midfoot sagittal plane moment was explained by the mean stiffness of the 1MTP joint.

KEYWORDS: plantar fasciitis, kinematics, biomechanics.

INTRODUCTION: The most common cause of inferior heel pain is plantar fasciitis (Riddle, Pulisic, Pidcoe, & Johnson, 2003), an inflammatory reaction of the plantar fascia (PF) and the perifascial structures (Bolgla, 2004; Chen et al., 2014). Plantar fasciitis is the third most frequent injury in runners (Ribeiro et al., 2011), but it also affects other athletes and individuals with a sedentary lifestyle (Riddle, Pulisic, Pidcoe, & Johnson, 2003). Since the PF is crucial in enhancing both the shock-absorbing capacity of the longitudinal arch and the way the forces are transferred from rearfoot to forefoot, the fascia plays a vital role in walking and jogging (Caravaggi, Pataky, Gunther, Savage, & Crompton, 2010; Cheng, Lin, Chou, & Wang, 2008). During walking the PF is often stressed with high tension (Chen et al., 2014), especially when the foot flattens during weight bearing or when pushing off with the toes. Overload of the PF may lead to plantar fasciitis (Cheng et al., 2008). Chang et al. showed significantly greater maximum 1st metatarsophalangeal (1MTP) joint dorsiflexion for chronic plantar fasciitis compared to healthy individuals (Chang, Rodrigues, Van Emmerik, & Hamill, 2014). Knowledge about the biomechanics of the PF is important to understand its role in functional activities and to reduce risk of foot related injuries such as plantar fasciitis. Research has been done in PF stiffness and has shown an increase for increasing hallux dorsiflexion (Carlson, Fleming, & Hutton, 2000; Cheng et al., 2008; Garcia, Hoffman, Hastings, Klaesner, & Mueller, 2008). However, the relation of hallux dorsiflexion with PF stiffness during functional activities is poorly understood. The purpose of this study is to find the relationship between 1MTP joint range of motion (RoM) and 1MTP joint stiffness, knee and ankle flexion, and to relate 1MTP joint stiffness caused by maximal passive hallux dorsiflexion with the generation of midfoot plantarflexion moment in the push off phase during gait.

METHODS: Participants: Eight healthy participants (five males and three females; age 46.5 ± 25.5 years; height 171.05 ± 16.95 cm, mass 67.83 ± 22.57 kg) volunteered as participants in this study. After being informed about the research project and the use of the data collected, participants signed a consent form prior to participation in the study. **Testing and data processing**: Both chair and gait measurements were performed. During the chair measurements participants were tested unilateral (right leg) in six different positions of the lower limb representing various combinations of knee flexion (Kf) and ankle flexion. To fix the participant's lower limb in these positions, a purpose-built chair was used (Figure 1). The participant was positioned, relaxed, in the chair with the hip in approximately 100 deg. The knee angle was set to approximately full extension (named as 0 deg) and 45 deg flexion, and the ankle angle was set to 90 deg and to the participant's maximal Df and Pf. The knees and right foot were fixed to the chair and foot platform using a safety belt at the upper limb, and a foam strap in between the 1st metatarsophalangeal head and navicular, respectively. To measure PF stress a hallux dynamometer using a full strain gauge bridge was built and calibrated (Figure 2). The RMS between known weights and dynamometer output was 0.44% with $r = 1.000$, $p < 0.0001$. The dynamometer was calibrated to 2.44 Nm, beyond the maximum moment applied by any of the subjects in the study. A cord, attached to the hole at the top of the dynamometer, was used to pull the hallux (in Df). The hallux dynamometer was attached to the hallux using two Velcro straps (Figure 2). In each position one trial with a maximal duration of 30 s was captured. Participants were asked to pull their hallux three times per trial.

Figure 1. Purpose-built chair for chair measurements, a = foot platform, b = shelf to support heel and preventing slipping off platform, c = steel frame for adjustment leg size, d = leg frame for adjustment knee angle.

Figure 2. Foot platform with hallux dynamometer attached to the participant's foot and straps to fix the foot (chair measurements).

The gait measurements consisted of five walking and five jogging trials, in which data were captured for 3 s. The starting point of gait was varied until participants placed their right foot on the force plate. Practising prior to the tests was allowed as often as the participant desired. Both, chair and gait measurements, were performed within three hours.

Motion capture data (chair and gait measurements) were collected in a laboratory equipped with fourteen cameras (Eagle, Motion Analysis Corporation, USA) and a force-plate (Model 9281B, Kistler, Switzerland) both with a sampling rate of 100 frames/s (chair measurements) and 200 frames/s (gait measurements). An experienced researcher attached a total of 25 reflecting spherical markers to the participant's lower limb. Prior to the chair and gait measurements, static and dynamic reference measurements were performed to create a participant specific identifying template and to identify joint centres and embed segment coordinate systems. Data collection and post processing were performed using Cortex (Version 5.0, Motion Analysis Corporation, USA) and KinTrak (7.0, The University of Calgary, Canada).

Statistical analysis for the chair measurements was performed using a 2x3x3 (2 knee angles, 3 ankle angles and 3 cycles respectively) repeated measure ANOVA with a simple contrast for knee angle, and a polynomial contrast for ankle angle and cycle. Regression analysis was used to find the association between 1MTP joint RoM and stiffness, and knee and ankle flexion.

RESULTS AND DISCUSSION: The purpose of this study was firstly, to find the effect of knee and ankle flexion on 1MTP joint RoM and 1MTP joint stiffness, and secondly to find the relation between 1MTP joint stiffness and the timing of peak midfoot plantarflexion moment. The repeated ANOVA measures showed no effects for cycle (pulling the hallux in chair measurements). This implies that the movement was repeatable.

Figure 3 shows 1MTP joint moment – angle curves for one trial from a subject with the knee in 0 deg and ankle in neutral (90 deg) position. The 1MTP joint moment increases for increasing 1MTP angle.
Considering the 1MTP joint range of motion (RoM) in chair measurements, there was an overall effect for ankle angle ($p < 0.001$, effect size (ES) = 0.802) and there were no significant interaction with knee angle (Figure 4). A linear increase in 1MTP joint RoM in ankle angle going from Df through 90 deg to Pf was found. There was no effect for knee angle ($p = 0.113$, ES = 0.319).

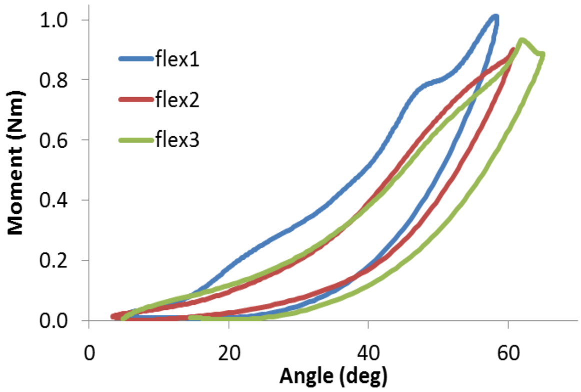

Figure 3. 1MTP joint moment – angle curves for one trial (chair measurement): three successive dorsiflexions (flex1-3) with the hallux dynamometer. Example from one subject with knee in 0 deg and ankle in 90 deg.

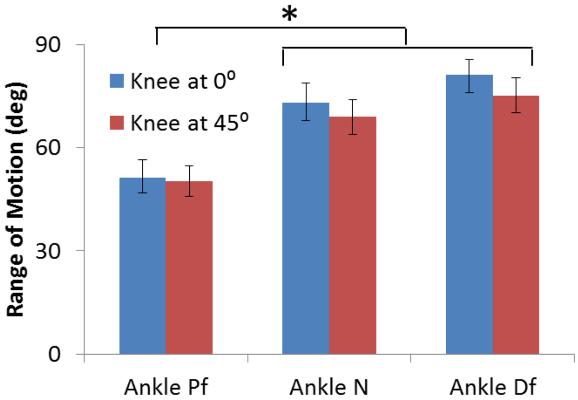

Figure 4. 1MTP joint range of motion under two knee flexion (0 and 45 deg) and three ankle flexion conditions (DF = dorsiflexed, N = neutral (90 deg), PF = plantarflexed). ∗ = significant at $p < 0.001$.

Mean stiffness, calculated over the whole 1MTP joint RoM, showed no effect for knee angle ($p = 0.291$, ES = 0.157) but an effect for ankle angle ($p = 0.017$, ES = 0.440). No significant interactions were found. The effect for ankle angle was quadratic ($p = 0.004$, ES = 0.716). For the ankle in maximal Df the mean stiffness was 0.040 Nm/deg, at 90 deg ankle angle 0.029 Nm/deg, and for the ankle in maximal Pf 0.041 Nm/deg.
The relation between 1MTP joint stiffness and peak midfoot sagittal plane moment in gait measurements was complex. The timing of the peak midfoot walking plantarflexion moment was significantly correlated with the 1MTP joint stiffness when the knee was flexed at 45 deg in combination with all three variations in ankle angle, and zero knee flexion in combination with Pf only. Between 40% and 58% of the variance in midfoot peak moment timing was explained by the 1MTP joint stiffness. For the jogging data only when the knee was at 0 deg and ankle plantarflexed was there a significant correlation ($R^2 = 0.47$, $r = 0.68$, $p = 0.03$). Remarkably, the stiffness was inversely related to peak moment timing in the walking cases and directly related to timing in the jogging case. That is, for walking the stiffer the 1MTP joint, the later was the timing of the midfoot peak plantarflexion moment. For jogging the stiffer the 1MTP joint, the earlier was the timing of the midfoot peak plantarflexion moment.

CONCLUSION: The purpose of this study was to compare 1MTP joint stiffness caused by maximal hallux dorsiflexion with midfoot moment generation in the push off phase during gait.
Mean stiffness, calculated over the 1MTP joint RoM, of 0.04, 0.029 and 0.041 Nm/deg (ankle in maximal dorsiflexion, 90 deg and maximal plantar flexion respectively) was found. A regression analysis between timing of maximal midfoot sagittal plane moment in gait indicated that up to 60% of the variance in timing of the midfoot sagittal plane moment was explained by the mean stiffness of the 1MTP joint.
This study is a step towards better insight in the biomechanics of the plantar fascia (PF). Differences in passive and active PF stiffness between healthy and chronic plantar fasciitis

individuals should be investigated to get a better understanding of plantar fasciitis and help in development and improvement of injury prevention and treatments.
Stiffness of the 1MTP joint may reflect the stiffness of the plantar fascia and has implications for shoe design, particularly the flexibility of the sole at the position of the 1MTP joint. . Future work will be focusing on building an individual foot arch model to compare PF biomechanics of different individuals.

REFERENCES:

Bolgla, L. A. M., T.R. (2004). Plantar Fasciitis and the Windlass Mechanism: A Biomechanical Link to Clinical Practice. *Journal of Athletic Training, 39*(1), 77-82.

Caravaggi, P., Pataky, T., Gunther, M., Savage, R., & Crompton, R. (2010). Dynamics of longitudinal arch support in relation to walking speed: contribution of the plantar aponeurosis. *Journal of Anatomy, 217*(3), 254-261.

Carlson, R. E., Fleming, L. L., & Hutton, W. C. (2000). The biomechanical relationship between the tendoachilles, plantar fascia and metatarsophalangeal joint dorsiflexion angle. *Foot & Ankle International, 21*(1), 18-25.

Chang, R., Rodrigues, P. A., Van Emmerik, R. E. A., & Hamill, J. (2014). Multi-segment foot kinematics and ground reaction forces during gait of individuals with plantar fasciitis. *Journal of Biomechanics, 47*(11), 2571-2577.

Chen, D. W., Li, B., Aubeeluck, A., Yang, Y. F., Huang, Y. G., Zhou, J. Q., & Yu, G. R. (2014). Anatomy and Biomechanical Properties of the Plantar Aponeurosis: A Cadaveric Study. *Plos One, 9*(1).

Cheng, H. Y. K., Lin, C. L., Chou, S. W., & Wang, H. W. (2008). Nonlinear finite element analysis of the plantar fascia due to the windlass mechanism. *Foot & Ankle International, 29*(8), 845-851.

Garcia, C. A., Hoffman, S. L., Hastings, M. K., Klaesner, J. W., & Mueller, M. J. (2008). Effect of metatarsal phalangeal joint extension on plantar soft tissue stiffness and thickness. *The Foot, 18*(2), 61-67.

Ribeiro, A. P., Trombini-Souza, F., Tessutti, V. D., Lima, F. R., Joao, S. M. A., & Sacco, I. C. N. (2011). The effects of plantar fasciitis and pain on plantar pressure distribution of recreational runners. *Clinical Biomechanics, 26*(2), 194-199.

Riddle, D., Pulisic, M., Pidcoe, P., & Johnson, R. E. (2003). Risk factors for plantar fasciitis: A matched case-control study. *Journal of Bone and Joint Surgery-American Volume, 85A*(5), 872-877.

A*cknowledgement*
The authors would like to thank Ray Patton for assisting in this study's setup.