DIFFERENCES IN ANKLE MUSCLE CONTROL STRATEGIES BETWEEN SYMPTOMATIC AND ASYMPTOMATIC PRONATED FEET DURING RUNNING

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This study aimed to quantify the differences in the control strategies of ankle muscles between symptomatic pronators (SP) and asymptomatic pronators (AP) during running. Thirty participants were measured by a motion capture system and a surface electromyography device. Results showed that during the swing phase, the SP had larger shortening of the soleus and peroneus longus (up to 3.6 mm and 4.0 mm, respectively), faster lengthening of the plantar flexors (up to 80.4 mm/s) but larger lengthening (up to 5.7 mm) and faster shortening (up to 46.2 mm/s) of the tibialis anterior. The SP also showed a lower median frequency of the soleus than the AP. These results indicated the different ankle muscle control between them, which might provide new insights into the understanding of pathology of the SP.

KEYWORDS: muscle-tendon unit, median frequency, surface electromyography

INTRODUCTION: A pronated foot is considered as having a lower arch, along with an everted rearfoot and an abducted forefoot in the static assessments, which is associated with the symptoms of pain and fatigue in the lower limbs (Zhang et al., 2022). However, there are some pronators without these symptoms and perform the normal motor abilities, demonstrating the limited accuracy of the static assessments (Zhang et al., 2019). Therefore, muscle control strategies (Park et al., 2022) based on kinematics and muscle activities should be considered for the further analysis of the differences between the symptomatic pronators (SP) and the asymptomatic pronators (AP).

Ankle muscles, which are crucial for the foot functions, regulate foot structure and provide cushioning and forward propulsion through different ankle muscle control strategies during running (Brockett & Chapman, 2016). Muscle-tendon unit (MTU) assists the favourable operation of the muscle (Monte et al., 2020) and helps to store elastic energy (Maharaj et al., 2016). Several studies have estimated the muscle functions by measuring the length changes in MTU based on kinematics (Baxter & Hast, 2019; Brennan et al., 2018), and the changing velocity of the MTU length is related to sports injuries (Soldatis et al., 1997). Furthermore, median frequency is widely used to detect fatigue in previous studies (Roman-Liu, 2016), which can divide the power spectrum of surface electromyography (sEMG) into two regions with the equal amplitude and the shifts in the median frequencies should reflect the recruitments of the active motor units (Farina et al., 2004).

However, the differences in the length changes and velocities of ankle MTU and the median frequencies of the ankle muscles between the AP and SP during running remain unclear. Thus, this study aims to quantify these differences between them, which may have implications for the understanding and treatment of the SP.

METHODS: A total of 30 participants (15 AP and 15 SP) were recruited in Belgium in this study, aged 24.6 ± 5.7 years, 1.75 ± 0.94 m tall, 69.7 ± 8.9 kg in weight. All participants were given informed written consent in accordance with the requirements of the Medical Ethics Committee of KU Leuven. The SP was determined by a foot posture index (FPI) score between 6 to 12 with any kind of symptoms of patellofemoral pain, medial tibial stress syndrome, plantar fasciitis or recurrent ankle trauma in the past 6 months before the test. The AP was defined with a FPI score between 6 to 12 but without any symptoms mentioned above.

Participants were instructed to perform treadmill running at 8 km/h barefoot. After familiarization, at least 5 successful running trials were recorded for each participant. sEMG sensors (Cometa srl, Milan, Italy, 2000 Hz) were applied on tibialis anterior (TA), soleus (SOL), peroneus longus (PL) and medial gastrocnemius muscle (GM). Fourteen cameras (OptiTrack, Prime 13, 100 Hz) were used to record the movement of a total of 33 reflective markers. Then, the MTU and median frequency analyses were conducted on these data from all the same

participants. The changes and the velocities of GM, SOL, PL and TA MTU lengths were calculated through OpenSim 3.3 based on kinematics (Baxter & Hast, 2019). The median frequencies of these ankle muscles were measured based on the complete gait phase of sEMG signals (Butterworth bandpass filter, 8^{th}-order, 20-400 Hz) during running, which were full wave rectified, segmented into steps by the heel strikes and time normalized into 0-100% of the gait cycles.
One-dimensional statistical parametric mapping (SPM) was performed to detect the significant differences in MTU between the AP and SP (https://spm1d.org/index.html). A two-sample t-test would be performed for the data of median frequency if they all followed the normal distributions, and the Wilcoxon rank sum test would be used if they did not. Data and statistical analysis were all processed in MATLAB (R2022a, MathWorks Inc., Natick, MA, USA). The alpha threshold value was set at 0.05.

RESULTS: The lengthening and velocity of ankle MTU are shown in Figure 1. Significant differences between the AP and SP were found during the swing phase of running. The SP performed greater shortening of SOL MTU (p=0.013, mean difference=3.30~3.58 mm) and PL MTU (p=0.011, mean difference=2.90~4.00 mm) than the AP, and greater lengthening of TA MTU (p=0.002, mean difference=3.99~5.70 mm) than the AP. The SP performed faster lengthening speed of GM MTU (p=0.025, mean difference=72.66~80.45 mm/s), SOL MTU (p=0.006, mean difference=20.15~31.91 mm/s) and PL MTU (p=0.024, mean difference=16.95~19.86 mm/s) than the AP and faster shortening speed of TA MTU (p=0.002, mean difference=23.81~46.17 mm/s) than the AP.

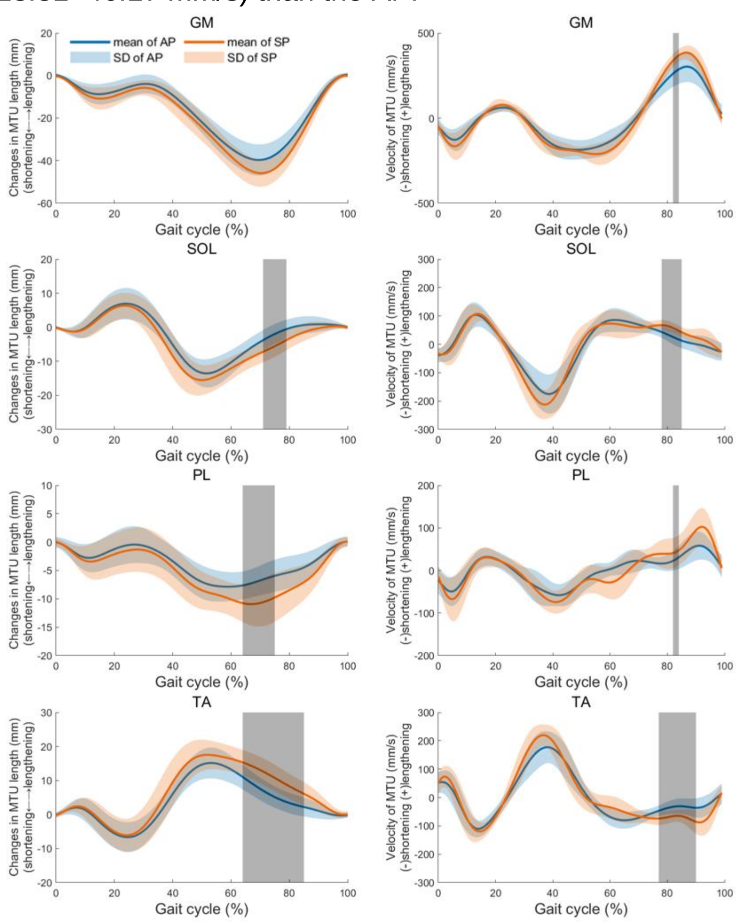

Figure 1: Mean and SD of the changes (left) and velocities (right) of MTU lengths time series plots for the AP (blue) and SP (orange). Black areas represent significant differences between the AP and SP during the gait cycle (p<0.05).

The SP had a significant lower median frequency of SOL than the AP (p=0.031, median difference=23.90 Hz) during running in Figure 2. Lower median values of median frequency of ankle muscles were found in the SP than AP in GM (p=0.184, median difference=11.16 Hz), PL (p=0.171, median difference=10.41 Hz), and TA (p=0.901, median difference=3.81 Hz).

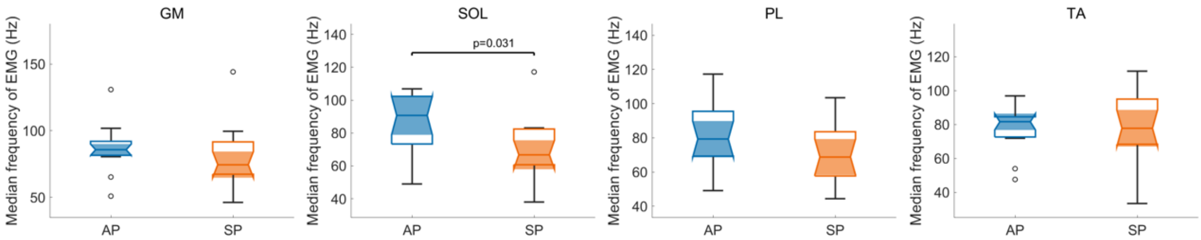

Figure 2: Median frequencies of sEMG of ankle muscles plots for the AP (blue) and SP (orange).

DISCUSSION: The SP might perform different ankle muscle control strategies compared to the AP based on ankle MTU and muscle activities. Thus, this study estimated the differences in the length changes and the velocities of ankle MTU and the median frequencies of ankle muscles between the AP and SP during treadmill running. Results showed that the SP had the greater changes and velocities of SOL, PL and TA MTU lengths and lower median frequency of SOL than the AP, indicating different ankle muscle control strategies between them.
The SP performed greater changes and velocities in ankle MTU lengths than the AP during the swing phase of running, which might demonstrate a greater demand for energy. The stored energy within the lengthened MTU was subsequently released to generate the required power when MTU shortened rapidly (Maharaj et al., 2016). Thus, the faster shortening velocity of TA MTU in the SP might indicate the greater demands for the energy consumption of ankle dorsiflexion during the terminal swing phase of running. The greater shortening and then faster lengthening of SOL and PL MTU in the SP during the swing phase of running might indicate the requirements for the extra storage of energy. These might be the compensations for the malfunctions of the feet in the SP, with the smaller cross-sectional areas of both extrinsic and intrinsic foot muscles than the AP (Zhang et al., 2019).
The changes and velocities of ankle MTU lengths in the SP were also related to the sports injuries. According to the unique structure of the ankle plantar flexor MTU with short muscle fibres and a long tendon, the primary displacements of the MTU were achieved by the Achilles tendon (Monte et al., 2020). Besides, the lengthening of the MTU would increase the loading or strain on it. Therefore, the extra changes in the MTU lengths in the SP might be a challenge for the maximum tension and the ductility of MTU. In addition, the acceleration-deceleration mechanism is related to most of the sports-related Achilles tendon ruptures (Soldatis et al., 1997). The faster lengthening velocities of GM, SOL and PL MTU and faster shortening velocity of TA MTU in the SP during the swing phase of running might demonstrate a relatively sudden or violent ankle dorsiflexion, which is related to the typical injuries of the Achilles tendon (Gulati, 2015; Tarantino et al., 2020). These hurried preparations of the ankle MTU during the swing phase might also have an impact on the leg stiffness adjustments, which might lead to injuries during the heel strikes in the stance phase of running (Blum et al., 2011). Furthermore, the greater shortening of SOL and PL MTU in the SP might also cause or even aggravate the development of the flat arches in the SP, since the shortening of ankle plantar flexor MTU will increase the force on the medial column and cause arch to flatten (Arangio et al., 2009).
The SP might perform a lower force output according to the observed lower median frequency of SOL in the SP. SOL played an important role in the propulsion and weight support during the stance phase of running (Hamner et al., 2010). However, the lower median frequency of SOL in the SP might demonstrate a lower level of the recruitments of the active motor units (Farina et al., 2004) and therefore, a lower force output of the SOL (Roman-Liu, 2016). Additionally, since the decreased intracellular pH determined the decrease in the muscle fibre conduction velocity, which would cause the decline of the median frequency (Cifrek et al., 2009), it could be inferred that the SP were more likely to feel fatigued during running.

CONCLUSION: This study quantified the differences between the SP and AP by analysing their ankle muscle control strategies based on ankle MTU and muscle activities during treadmill running. Results showed that the SP and AP had different length changes and velocities of ankle MTU during the swing phase, with the SP having larger shortening of the soleus and peroneus longus, faster lengthening of the plantar flexors but larger lengthening and faster shortening of the tibialis anterior. The SP also showed a lower median frequency of the soleus than the AP, suggesting that the SP might have greater energy demands, higher injury risks and lower force outputs than the AP during running. This study might give new insights into the understanding and treatment of symptomatic pronated feet.

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