TRICEPS SURAE MUSCLE FORCES DURING WALKING AND DANCING ACROSS VARIED FOOTWEAR

Wallnöfer Elias[1,2,3,] Egner Clara[1,2,] Robert Csapo[1], Arnold Baca[1], Hans Kainz[1,2]

[1]Department of Sport and Human Movement Science, Centre for Sport Science and University Sports, University of Vienna, Vienna, Austria.
[2]Neuromechanics Research Group, Centre for Sport Science and University Sports, University of Vienna, Vienna, Austria.
[3]Vienna Doctoral School of Pharmaceutical, Nutritional and Sport Sciences, University of Vienna, Vienna, Austria

Despite a high prevalence for Achilles tendinopathies in athletic populations, research on individuality in muscle coordination, a possible contributor to this disorder, is limited. Effects of shoe condition and kinematics on force share between triceps surea muscles during normal gait and a dance step were investigated and compared between two methodological approaches. Muscle coordination was analyzed based on musculoskeletal simulations in a generic and an electromyography-informed approach. The electromyography-informed mode revealed higher individuality and a higher force production in medial gastrocnemius for the dance step in high heels compared to bare foot. The study underscores the importance of viewing Achilles tendon loads from an individual's perspective and recommends personalized musculoskeletal simulations for studies on muscle coordination.

KEYWORDS: muscle coordination, triceps surae, high heels, musculoskeletal simulation.

INTRODUCTION: Tendinopathies are common overuse injuries with no exempt for the strongest human tendon, the Achilles, showing a lifetime incidence of 24% and 6% for athletes and non-athletic population, respectively (Kujala, Sarna, and Kaprio 2005). The tendon is formed by the joining of the triceps surae (TS) muscles: gastrocnemius medialis (GM), gastrocnemius lateralis (GL) and soleus (SOL). Those individual subtendons fuse into the Achilles tendon where heterogenous movement of fascicles and resulting shear forces are present (Sun et al. 2015). The distribution of load within the Achilles tendon is hence influenced by changes in length and force production of the TS muscles (Lersch et al. 2012) and an unfavorable force share is considered to contribute to Achilles tendinopathy (Hug and Tucker 2017). Muscle coordination, defined as the force share between synergist muscles, can show a high inter-individual variability for the execution of a given task. For example, a study on gait observed two GM/GL activation strategies among individuals, with commonly GM higher activated than GL and a smaller number of participants with equal GM/GL ratio (Ahn et al. 2011). Despite the high prevalence of tendinopathies, there is limited research on the individuality of muscle coordination during sports movements. The potential influences on muscle force share, such as biomechanics of the movement or configuration of the equipment, are insufficiently understood both on a global and even more on a person-specific level. This leaves a gap in knowledge for performance enhancement and preventions of overuse injuries such as Achilles tendinopathy (Hug and Tucker 2017).

Musculoskeletal (MSK) simulations are utilized for research on muscle coordination due to their advantage of non-invasive estimation of muscle forces during human movements (Delp et al. 2007). The theoretically vast range of coordination strategies is kept within biomechanical and physiological constraints as such simulation models incorporate physical principals and generic data on muscle architecture. A better understanding on inter-individual variability, which is thought to be influenced by muscle morphology, training history and personal habits, could however be gained by the personalization of MSK models. A possible approach for this purpose is to inform the simulation by electromyography (EMG) data, as this shifts the focus from finding the most efficient muscle activation to the goal of consistency between recorded EMG signal and estimated activation pattern.

Practical implication of this research lies in understanding potential effects of shoe change within high repetitive movement training - such as in high heels practiced Latin dance sport - to prevent overuse by redistributing the load of the Achilles' subtendons. Using a dataset of dancers performing normal gait and a basic dance step ("Rumba walk") in two shoe conditions, i.e. barefoot (BF) and dance high heels (HH), the study aimed to investigate influencing factors on the force share within the TS during the steps' push-off phase. Including gait broadens the topic and brings knee joint kinematics, a main difference to the dance step, into context. To address the proposed potential of personalization in MSK modeling, a conventional simulation approach based on generic, simplified motor control will be compared to an EMG-informed approach. It is hypothesized that variations in ankle and knee mechanics between movements and shoe conditions will impact coordination of SOL relative to TS. Additionally, it is assumed that force share between GL and GM is individual among participants and leads to variations in responses to movement and shoe conditions. Both simulation approaches were expected to come to the same conclusions regarding SOL force share. Non-EMG-informed approach was hypothesized to show less variation in GM/GL force ratio.

METHODS: Data from ten actively competing female Latin American dancers (average age: 25 ± 3.5 years, body mass: 56.5 ± 5.5 kg), without lower limb injuries, were analyzed. Full walking trials of the four movement-shoe conditions gait-BF, dance-BF as well as gait-HH, and dance-HH with Latin dance HH of 6.3 cm height were performed. Dance steps were timed to music, gait speed was freely chosen by the participants. Using 3D motion capture (Vicon Motion System, Oxford, UK), markers, ground reaction forces (Kistler Instruments AG, Winterthur, CH), and EMG data (Cometa SRL, Bareggio, IT) for GM, GL, SOL, and tibialis anterior muscles were collected. Musculoskeletal simulations were performed based on the experimental data using OpenSim 4.2 (Delp et al. 2007). The "gait2392" model with three hip, one knee and two ankle joint degrees of freedom was scaled to participants' anthropometry (Kainz et al. 2017). Three trials of each condition were cut to their push-off phase and analyzed by inverse kinematics. Based on the added ground reaction forces, inverse joint dynamics were calculated. Those built the basis for the estimation of needed muscle forces to overcome the external loads of the movements. A common generic optimization, i.e., minimizing squared muscle activations, and an EMG-informed approach (Falisse et al. 2017), which adds a term to minimize the difference between estimated muscle activation and measured EMG to the optimization, were performed for that purpose. EMG-informed mode was first run on gait-BF with scaling boundaries for the filtered and enveloped (50ms window) EMG signal peaks to 0.10 and 0.6 in gait-BF, reflecting the movement's peak activation range in TS (Ahn et al. 2011). Resulting estimations of muscle activity were used to normalize the pre-processed EMG signals of the individual participants to the models' maximum TS force capacity. Following, all trials of the four conditions were run in EMG-informed mode involving a constraint of 5% deviation between normalized EMG signal and estimated activity for each mesh point. Outcome measures included force integral during push-off and relative muscle distributions to summed TS forces. Validation involved comparing marker errors and residuals to recommended thresholds as well as a qualitative comparison of estimated tibialis anterior activity to recorded EMG signals (Hicks et al. 2015). Statistical parametric mapping (Pataky 2010) was used to compare kinematics, 2-way ANOVA tested effects of shoe and movement across all participants, while a one-way repeated measures ANOVA determined similarities in force share changes between the four conditions on an individual level. Subsequent post-hoc pairwise comparisons, were conducted using the Bonferroni correction. All statistical analyses were performed with a significance level of 0.05. Furthermore, Pearson correlation was utilized to compare GM and GL force share.

RESULTS:
Key difference in the kinematics of the movements was primarily reflected in the knee angle, with gait transitions from knee extension to knee flexion opposed to a more constant angle in dance (**Figure *1***). Additionally, less plantarflexion as well as higher loading and unloading rates in ground reaction forces were displayed for gait. Main difference between shoes was characterized by higher plantarflexion angles during movements in HH.

Force share averaged over all participants displays no movement or shoe effect between the four conditions when analyzed by the EMG-informed approach (**Figure 2A**). Hence, no universal SOL/TS pattern for any condition was present. Only when performing repeated measures ANOVA differences between conditions were revealed for GM/TS ($p = 0.001$) but not for GL/TS force share ($p = 0.39$) with post-hoc analysis indicating higher GM force share for dance-HH compared to gait-HH and dance-BF.

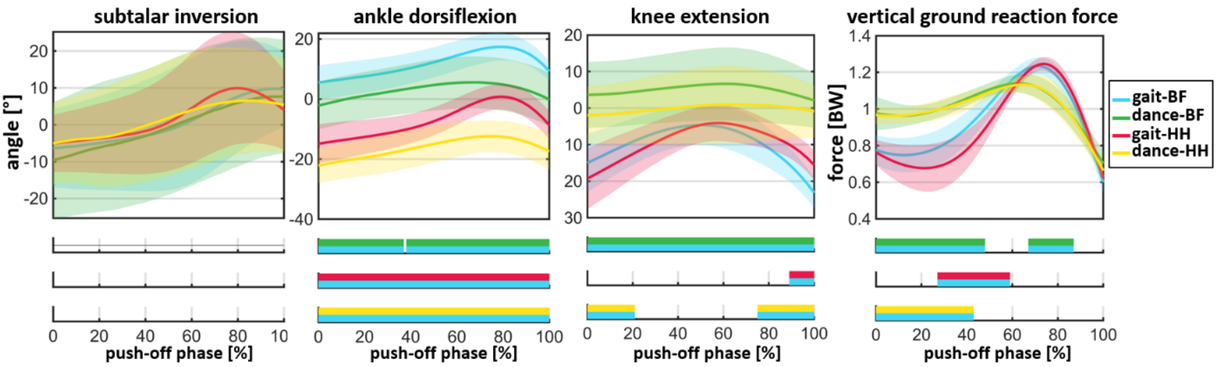

Figure 1: Mean and standard deviation (n=10) in kinematics of subtalar, ankle and knee joint in degree and vertical ground reaction forces in times bodyweight (BW) compared between gait-BF (blue), gait-HH (red), dance-BF (green) and dance-HH (yellow) push-off phases. Bars underneath indicate significant differences between gait-BF and the respectively colored condition.

In the generic optimization approach, an effect of movement but not of shoe condition was identified in all three muscles when compared between group means force share. SOL/TS demonstrated a reduction for dance-BF compared to gait-BF. Force share ratio between GM and GL suggest a correlation ($r = 0.84$) between the two muscles' force production (**Figure 2B**). Notably, no correlation ($r = -0.003$) was observed in the EMG-informed approach.

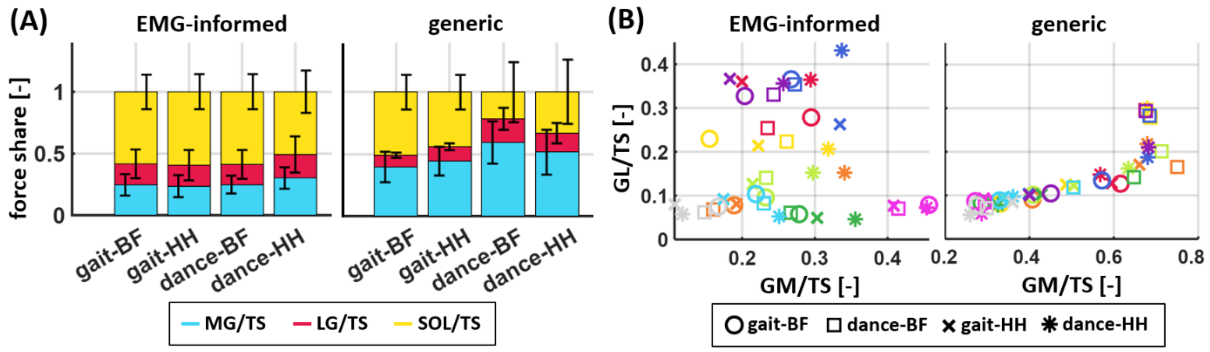

Figure 2: (A) Bar graphs of mean and standard deviation (n=10) in force share of GM (blue), GL (red) and SOL (yellow) relative to the summed TS forces during push-off for EMG-informed and generic approach. (B) Scatter plots comparing GM/TS to GL/TS with individual color for each participant and markers indicating conditions gait-BF (circle), gait-HH (x), dance-BF (square) and dance-HH (*) for EMG-informed and generic approach.

DISCUSSION: This study aimed to investigate influences of movement and shoe condition on TS muscle coordination during push-off phase, comparing two MSK simulation approaches.
Results of the EMG-informed approach did not align with our hypothesis of differences in SOL/TS force share over the group mean, despite significant differences in kinematics between all four conditions. However, a decrease in SOL/TS could be observed for example from dance-BF to dance-HH when taking individual muscle coordination strategies by repeated measures ANOVA into account. GM/GL ratio showed individual variations. These findings suggest that the present biomechanical differences in knee and ankle angle do not provoke the same behavior in overall TS force share of individuals. As shoe condition showed influences on force share, a practical implication could be to switch between barefoot and HH during dance training in order to redistribute load in Achilles subtendons and prevent overuse.

In contrast to these results, the generic simulation suggested higher differences in force share between conditions and a correlation between GM/GL ratio regardless of movement, shoe condition and participant.

Despite limitations, such as lacking EMG measurements for maximal isometric contractions, the EMG-informed approach demonstrated higher agreement between estimated tibialis anterior activity patterns and recorded EMG when compared to the generic approach.

The presented differences between the two simulation approaches lead to the recommendation of personalized MSK simulations in studies on muscle coordination. With its advantage of non-invasive force estimations on validated models, we encourage researchers to consider this approach, emphasizing further investigation into the influences and interactions of additional personalization factors like muscle force-generating capacity, muscle moment arms, or bony geometries.

CONCLUSION: The high variability in TS force share during push-off phase of steps with differences in knee and ankle kinematics underscore the importance of viewing Achilles tendon loads from an individual perspective. Discrepancies between simulation approaches lead to the recommendation of personalized MSK simulations which have potential in further individualization for studies on muscle coordination.

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