FORCE-SHARING BETWEEN TRICEPS SURAE MUSCLES DURING REHABILITATION EXERCISES FOR ACHILLES TENDINOPATHY

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The purpose of this study was to determine individual muscle forces of the Triceps Surae during a range of rehabilitation exercises for Achilles tendinopathy. We used experimental data (N=4) and musculoskeletal modelling to estimate muscle force (dynamic optimization). We observed clear peak muscle force differences between exercises. In addition, the force-sharing strategies used by the participants (i.e., individual muscle contribution to the total force produced within the Triceps Surae) were different between exercises. These preliminary results could be helpful to objectively determine the progression in exercise loading throughout rehabilitation programs. Additionally, new information regarding the influence of the type of exercise on load distribution within the Triceps Surae may better orientate practitioners in the choice of exercise.

KEYWORDS: tendon strain, muscle force, injury, tissue loading

INTRODUCTION: Achilles tendinopathy is one of the most common foot and ankle overuse injuries (Kvist, 1994), characterized by the combination of pain, swelling, and impaired performance. Previous studies reported clear alteration of the pathological tendon mechanical properties and morphology, increasing tendon strain for a similar tendon force compared to asymptomatic people (Nuri et al., 2018). Tendinopathy recovery is a complex process to manage for physiotherapists and doctors. In case of early return to play, potential incomplete recovery increases the risk of reinjury (Gajhede-Knudsen et al., 2013) and may negatively affect performance (Hägglund et al., 2013). Among different tendinopathy rehabilitation exercises used, eccentric strengthening has become the treatment of choice, with the greatest amount of evidence for its effectiveness (Alfredson et al., 1998). Moreover, functional exercises might also be interesting, especially before returning to activity (Cook & Screen, 2018). To date, progression through rehabilitation exercises is mainly based on the subjective feeling of pain in the patients. However, this approach does not give the actual loading of an exercise or the cumulative loading of a rehabilitation program. In fact, few objective information is available regarding the load induced by commonly used rehabilitation and functional exercises. A promising way to objectively quantify and monitor the rehabilitation load is to assess tendon strain. As tendon strain is an important mechanical trigger for tendon structural adaptation, better insight in the effect of exercises on tendon strain could be a better guide for progression. Achilles tendon strain is directly influenced by the force-shared within the Triceps Surae, as well as individual tendon geometry (e.g., cross-sectional area) and material properties (e.g., stiffness). Composed of sub-tendons originate from each of the three heads of the Triceps Surae (soleus [SOL], gastrocnemius medialis [GM], gastrocnemius lateralis [GL]), Achilles tendon exhibit non-uniform tissue displacements (Franz et al., 2015). Crouzier et al., (2019) recently observed a difference in force-sharing strategy within the Triceps Surae in people with Achilles tendinopathy compared to the controls during isometric plantarflexions (Crouzier et al., 2019). This is likely that muscle force imbalance induces different tendon loading and structural adaptations (Crouzier et al., 2018). However, estimating tendon strain and muscle force in dynamic conditions remain challenging and not convenient. Recent advances in musculoskeletal modelling open new perspectives for their estimations in ecological conditions. By combining experimental data and musculoskeletal modelling, individual muscle forces can be estimated. Thus, the aim of our study is to determine individualized muscle forces of the Triceps Surae during a range of rehabilitation and functional exercises. We expect to observe different loading between exercises, as well as different muscle force-sharing strategy within the Triceps Surae.

METHODS: We aim to measure fifteen healthy subjects during a protocol consisting of a series of rehabilitation, functional and sports exercises. We currently have measured and analysed four of them who performed the protocol in the MALL laboratory (KU Leuven, Belgium). Rehabilitation exercises (eccentric contractions), based on Alfredson's protocol (Alfredson et al., 1998), comprised two-legged heel drop without and with extra weight (+10 kgs), one-legged heel drop with and without bended knee. Functional exercises consisted of heel walking, toe walking, squatting and one-legged hopping. All participants were barefoot and repeated each exercise three times. Ten infrared cameras (Vicon, Oxford Metrics, UK) were used to capture the trajectories of thirty-five reflective markers at 150 Hz placed according to an extended Plug-in-Gait marker set. (Figure 1a). We used OpenSim 3.3 (OpenSim, Stanford, USA) (Delp et al., 2007) to first scale the generic gait2392 model (23-degree-of-freedom) based on the relative distances between the model markers and the experimental markers recorded during a static trial. Next, the Kalman smoothing algorithm was used to calculate joint angles (F. De Groote et al., 2008). Muscle-tendon unit lengths and moment arms were calculated throughout the movement (Muscle Analysis Tool, OpenSim; Figure 1a). Ground reaction force during rehabilitation and functional exercises were measured using a force plate embedded in the ground at a sampling frequency of 1000 Hz. We combined the force data and joint angles in an inverse dynamics analysis to calculate joint moments. We estimated Triceps Surae muscle forces using dynamic optimization. Inverse dynamic joint moments along with muscle-tendon unit lengths and moment arms were used as inputs to solve the muscle redundancy problem by minimizing muscle activations squared (Friedl De Groote et al., 2016). In contrast to commonly used static optimization approaches that simplify muscle-tendon dynamics by neglecting activation dynamics and assuming rigid tendons, muscle activation and contraction dynamics were considered (Friedl De Groote et al., 2016). Force-sharing strategies (i.e., muscle force distribution in %) within the Triceps Surae were calculated from individual peak muscle force values for the four subjects analysed during each exercise.

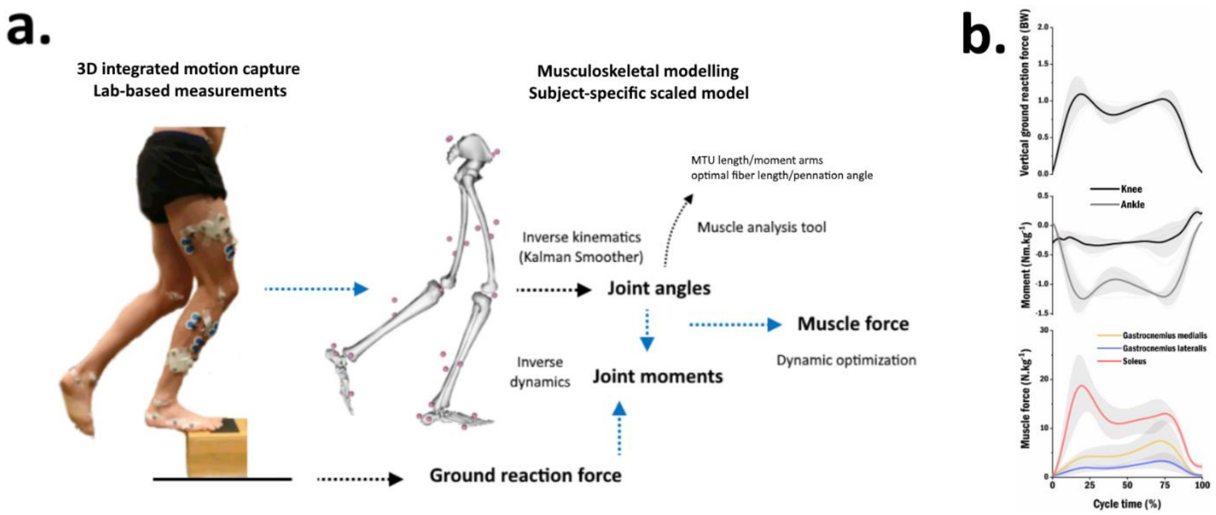

Figure 1: Overview of the experimental measurements and computational approach to estimate muscle forces (a). Data obtained on 4 subjects during walking on toes (b).

RESULTS: Figure 2a depicts peak muscle force of the three Triceps Surae muscles during each exercise. Exercises are ranged from the lowest to highest in terms of SOL peak muscle force. Heel walking exhibits the lowest level of peak muscle force produced for the three muscles of the Triceps Surae, while one-legged hopping represents the highest peak muscles forces. For comparisons, SOL peak muscle force is ~5-times greater during one-legged hopping than two-legged heel drop (58.2 ± 7.3 $N.kg^{-1}$ vs. 12.4 ± 6.0^{-1}) and ~3-times greater compared to toe walking (19.9 ± 5.2 $N.kg^{-1}$) (Figure 2a). Figure 2b represents the average force-sharing strategies within the Triceps Surae during each exercise for the four participants. This emphasizes the influence of the type of exercise on load distribution within the Triceps Surae.

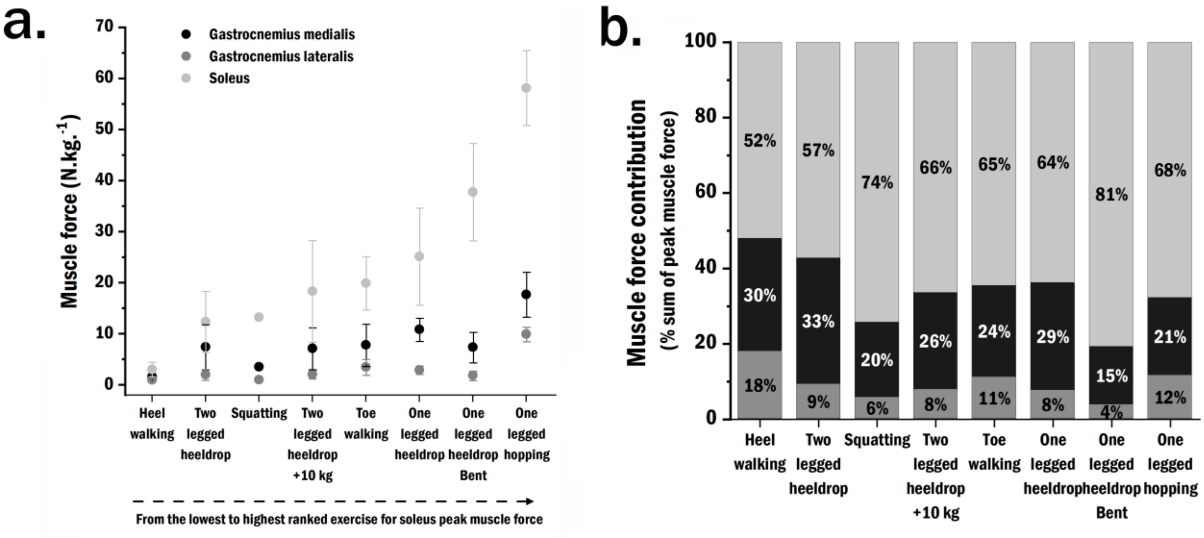

Figure 2: Triceps Surae peak muscle force estimated during a range of rehabilitation and functional exercises (a). Force distribution among individual muscles of the Triceps Surae (b).

DISCUSSION: Using experimental data and musculoskeletal modelling, we have estimated individual muscle force of the Triceps Surae during a range of rehabilitation and functional exercises used to treat Achilles tendinopathy. We also determined force-sharing strategy within the Triceps Surae between exercises. Our primary results show the feasibility to objectively quantify the influence of common rehabilitation and functional exercises on Triceps Surae load distribution. This is of interest in the pursuit of the appropriate loading to reverse the pathological changes in geometry and mechanical properties of the tendon. The objective quantification of muscle force emphasizes the difference in exercise intensity and can serve as a guideline for exercise progression throughout a rehabilitation program. In addition, force-sharing strategies were different between exercise. For instance, when participants performed one-legged heel drop with extended knee, the contribution of GM (+14%) and GL (+4%) was greater than when the same exercise was performed with the knee bent. On the opposite, bending the knee during a one-legged heel drop increased the contribution of the SOL by 18% (Figure 2b). This imbalance of muscle force within the Triceps Surae between exercise is likely to result in different Achilles tendon strain and structural adaptation. Together, these preliminary results could be helpful to define the appropriate tendon loading during rehabilitation programs in order to optimize the progression between and within exercises throughout the recovery process. In a near future, individual muscle force estimations could serve as boundaries for the implementation of validated 3D finite element model to estimate tendon strain (Shim et al., 2014, 2018; Pizzolato et al., 2019) during rehabilitation and functional exercises in order to better design rehabilitation programs for Achilles tendinopathy.

CONCLUSION: We observed different force-sharing strategy and load distribution within the Triceps Surae between exercises. By combining recent computational approach for estimating muscle force and freehand 3D ultrasound method for estimating tendon morphology, we will be able to better understand tendon loading during different exercises in symptomatic people. Such perspectives might help to better personalize the content of rehabilitation programs (i.e., optimal loading/'sweet spot') and improved the recovery process for patients/elite athletes with Achilles tendinopathy. This may include practical suggestions for coaches and players to improve performance, reduce the risk of injury, or expedite recovery.

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