Simulated Single-Leg Heel Raise Function is Governed Primarily by Optimal Fiber Length

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Introduction

Long-term functional deficits are associated with poor outcomes in many patients following Achilles tendon ruptures[1]. Structural changes to both the plantarflexor muscles[2] and Achilles tendon[3] may be predictors of patient function. Single-leg heel raise performance is a key clinical benchmark for quantifying patient function following Achilles tendon ruptures and return to activity. Simple computational models can simulate the effects of small deviations in plantarflexor muscle-tendon unit (MTU) parameters and objectively quantify how these changes affect ankle and locomotor function. Therefore, the purpose of this study was to characterize how changes to various MTU parameters (optimal fiber length, resting ankle angle, pennation angle, maximum isometric force, and tendon stiffness) influence the model's ability to perform a single-leg heel raise. We hypothesized that muscle fiber length and resting ankle angle—a clinical surrogate for tendon length—would have the greatest effect on single-leg heel raise performance.

Methods

Resting ankle angle and MTU parameters were iteratively tested to estimate the effects of these parameters of single-leg heel raise function. The MTU parameters that were tested in this simulation study were optimal muscle fiber lengths, pennation angles, maximum isometric forces, and Achilles tendon stiffness values (Figure 1A); as well as resting ankle angle (Figure 1B), a surrogate measure of tendon slack length. First, the soleus and gastrocnemius MTU parameters were iteratively adjusted between 50% and 150% of model default values[5]. Next, the resting ankle angle was set to physiologic ranges between 0 and 20 degrees plantarflexion in order to provide clinical relevance. We performed the computational analog of instructing the patient to lay prone on a treatment table while the foot and ankle freely hangs at a 'resting angle'. Tendon slack lengths were changed in order to minimize the resultant ankle torque while keeping the muscle fibers near their optimal lengths.

Single-leg heel-raises were then simulated using a simplified musculoskeletal model that was constrained to move in along a vertical line travelled during a single-leg heel raise[4] (Figure 1C). The ankle was modeled as a pin-joint that was flexed by a single dorsiflexor muscle, the tibialis anterior, and extended by two plantarflexor muscles, the soleus and gastrocnemius. Single-leg heel raises were simulated for 3,125 combinations of these five MTU parameters. The effect of a 1% change in each of the MTU parameters (normalized by the physiologic ranges tested in this study) on heel-raise function (peak ankle angle) was calculated using a multi-variate linear regression model.

Results

Simulated single-leg heel raises were most affected by the optimal fiber lengths and the resting ankle angle (Figure 2). Reducing optimal fiber lengths, muscle strength, and decreasing resting ankle plantarflexion all decreased the likelihood of a successful heel raise. Changes in muscle pennation and tendon stiffness had much smaller effects on heel raise function.

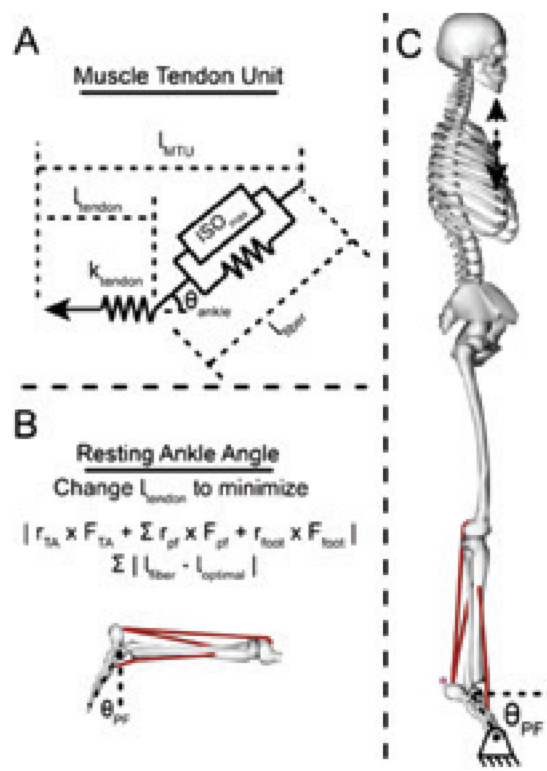

Figure 1. Muscle-tendon unit (MTU) parameters were perturbed to test their effect on heel raise function **(A).** Tendon slack lengths were calculated for each MTU combination to recreate a resting ankle angle **(B).** These MTU parameters were then simulated using simplified musculoskeletal model of a single-leg heel raise **(C).**

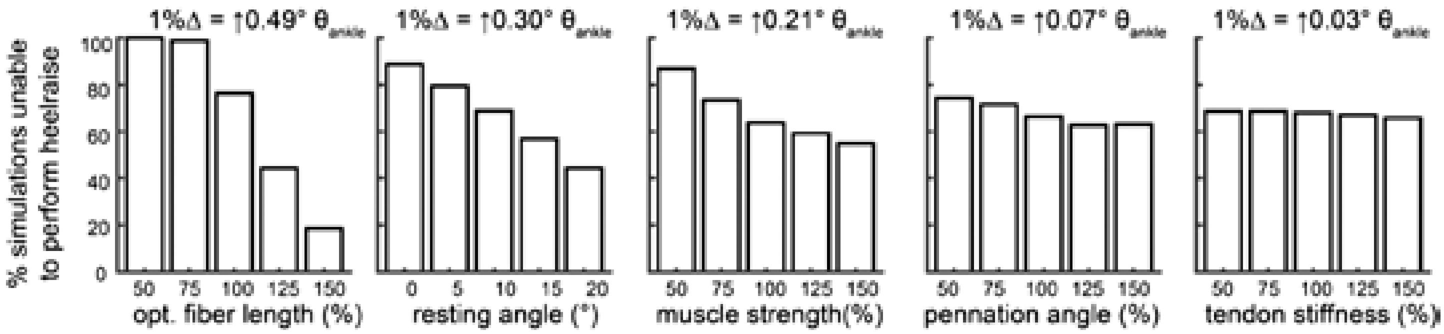

Figure 2. The ability to perform a single-leg heel raise (45 degrees of plantarflexion) was partially governed by each of the tested MTU, which each had an effect on the amount of ankle plantarflexion (1% change in MTU had some documented effect, top values). Shorter optimal fiber lengths were unable to complete the heel raise regardless of other MTU parameters. Resting ankle angle—a surrogate measure of tendon slack length—and muscle strength were also stronger predictors of heel raise function. Muscle pennation and tendon stiffness had a smaller effect on the heel raise simulations.

Discussion

In this study we tested the simulated effects of physiologically feasible changes to MTU parameters on single-leg heel raise function[2,3,6]. In support of our hypothesis, we found that heel-raise function was most sensitive to changes in optimal fiber length and resting ankle angle (achieved through changing the resting ankle angle). Additionally, these findings support prior work, which found excessive muscle fascicle length and tendon length to be associated with functional deficits[2,3]. Although the single-leg heel raise is a submaximal activity, it is an effective clinical tool for gauging plantarflexor function. Minimizing tendon elongation following surgical repair should be investigated further in order to improve long-term patient outcomes.This simplified model had motion constraints and used generic MTU parameter data from the literature[4]. Therefore, these findings should be considered in the context of ranking the effects of each MTU parameter rather than a predicted effect on patient function.

Clinical Relevance

Preserving muscle fiber and tendon slack length should be considered the most important objectives when treating acute Achilles tendon ruptures.

References

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