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# Plantarflexor fiber and tendon slack length are strong determinates of simulated single-leg heel raise height

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ABSTRACT

Achilles tendon ruptures have been linked with detrimental changes in muscle-tendon structure, which may help explain long-term functional deficits. However, the causal effects of muscle-tendon structure on joint function have not been tested in a controlled setting. Therefore, the purpose of this study was to test the implications of muscle-tendon unit parameters on simulated single-leg heel raise height. We hypothesized that muscle fiber length and resting ankle angle – a clinical surrogate measure of tendon slack length – would predict single-leg heel raise height more strongly than other parameters. To test this hypothesis, we developed a two-part simulation paradigm that recreated clinically relevant muscle-tendon scenarios and then tested these parameters on single-leg heel raise height. We found that longer muscle fibers had the greatest positive effect on single-leg heel raise height. However, tendon slack length, determined by simulating resting ankle angles in a secondary analysis, revealed a stronger negative correlation with heel raise height. Our findings support previous clinical observations that both muscle fascicle length and resting tendon length are important muscle-tendon parameters for patient function. In addition to minimizing tendon elongation following rupture, treatment plans should focus on preserving plantarflexor muscle structure to mitigate functional loses following Achilles tendon ruptures.



## 1. Introduction

Long-term functional deficits during running and jumping are associated with single-leg heel raise height following Achilles tendon ruptures (Brorsson et al., 2017). Improvements in rehabilitation protocols have helped reduced re-rupture rates to under 5%, regardless of whether the injury is treated surgically or conservatively (Willits et al., 2010). Despite these improvements in long-term tendon integrity, one-in-five patients do not return to the same activities they enjoyed prior to the injury (Zellers et al., 2016). Failure to achieve short-term functional goals are predictive of long-term plantarflexor strength and endurance deficits (Brorsson et al., 2017), which persist at least seven years following the initial injury (Brorsson et al., 2018). Despite these documented functional deficits, little is known about how muscle-tendon structure dictates function in this patient population. While muscle fascicle remodeling (Baxter et al., 2018) and tendon elongation (Silbernagel et al., 2012) have been proposed as mechanisms responsible for functional deficits during clinically relevant activities, the relationship between muscle-tendon structure and clinical function is not well understood.

Single-leg heel raise height is a key clinical benchmark for gauging patient function following Achilles tendon ruptures (Olsson et al., 2014) and return to activity (Toyooka et al., 2017). Despite being a simple sub-maximal activity for healthy adults, the single-leg heel raise stresses the plantarflexors of patients recovering from an Achilles tendon rupture. Deficits in heel rise height strongly correlate with tendon elongation, clinically defined as an increase in resting tendon length compared to the contralateral tendon, over the first year following tendon rupture (Silbernagel et al., 2012). These changes are likely permanent (Brorsson et al., 2018). Muscle remodeling following acute Achilles tendon ruptures (Baxter et al., 2018) and decreased resting ankle plantarflexion angle (Zellers et al., 2018) suggest that permanent changes to muscle-tendon unit (MTU) structure governs functional outcomes. Further, this proposed mechanism is supported by similar changes in muscle structure induced by joint immobilization (Williams and Goldspink, 1978) and changes in tendon excursion during muscle shortening (Koh and Herzog, 1998).

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Simple computational models can simulate how small deviations in plantarflexor MTU parameters directly affect ankle function during locomotion. Muscle fascicle length, pennation angle, and peak isometric force are critical parameters that are linked with muscle power (Baxter et al., 2012; Lee and Piazza, 2009; Lichtwark and Wilson, 2008; Scovil and Ronsky, 2006). Similarly, tendon stiffness and slack length impacts the shortening demands of the plantarflexor muscles and impacts movement efficiency (Lichtwark and Wilson, 2008; Orselli et al., 2017; Uchida et al., 2016). Achilles tendon slack length is difficult to measure *in vivo*, but quantifying resting ankle angle has proven to be an effective surrogate measurement (Hansen et al., 2017; Zellers et al., 2018). While the effects of MTU parameters on walking biomechanics have been studied in great detail (Baxter and Hast, 2019; Carbone et al., 2016; Lichtwark and Wilson, 2008; Xiao and Higginson, 2010), the multi-factorial implications of MTU parameters on single-leg heel raise performance are poorly understood.

The purpose of this study was to characterize the effects of plantarflexor MTU parameters on single-leg heel raise height. We hypothesized that single-leg heel raise performance would be strongly and positively influenced by both (1) optimal fiber length – the muscle length at which peak isometric force is generated – and (2) resting plantarflexion ankle angle – a clinical surrogate for resting tendon length (Hansen et al., 2017; Zellers et al., 2018). This hypothesis was supported by previous observations of shorter muscle fascicles (Baxter et al., 2018), longer tendons (Silbernagel et al., 2012), and reduced plantarflexion ankle angles at rest (Zellers et al., 2018) in patients who suffered Achilles tendon ruptures. Because the single-leg heel raise is a sub-maximal activity for individuals without plantarflexor pathology, we further hypothesized that peak isometric muscle force would have less impact on single-leg heel raise height than other MTU parameters that directly govern total muscle shortening. To test our hypotheses, we developed a simple musculoskeletal model that simulated a single-leg heel raise. We systematically changed five clinically-relevant MTU parameters in the musculoskeletal model to establish their effects on single-leg heel raise height: optimal fiber length, resting ankle angle, pennation angle, peak isometric muscle force, and tendon stiffness.

## 2. Materials and methods

### *2.1. Simulation framework*

Single-leg heel raises were simulated by systematically adjusting the following MTU parameters of the right plantarflexor muscles (Fig. 1): optimal muscle fiber lengths, pennation angles, maximum isometric forces, resting ankle angles, and Achilles tendon stiffness values. To do this, we implemented a two-part simulation paradigm. First, we positioned the model prone and calculated the tendon slack lengths of the MTUs spanning the ankle to achieve static equilibrium with the desired MTU parameters. Second, we stood the model upright on one leg and used the variable MTU parameters and tendon slack lengths in a series of forward dynamic simulations to determine peak plantarflexion during a single-leg heel raise.

We modified an open-source musculoskeletal model (gait10-musc18dof) to test the isolated effects of the muscles that crossed the right ankle (Delp et al., 2007). 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 muscles. The soleus muscle is a uniarticular plantarflexor while the gastrocnemius is biarticular that plantarflexes the ankle as well as flexes the knee. In this set of simulations, we constrained the knee to be fully extended. We modeled these muscles as Hill-type muscle bundles, which included a contractile muscle element in series with an elastic tendon-like element (Fig. 1C) (Millard et al., 2013). Optimal fiber lengths, pennation angles at optimal fiber length, maximal isometric muscle forces, and tendon stiffness parameters were scaled in 10% increments from 50% to 150% of the default model values (Fig. 1A). Resting ankle angle varied from 20° plantarflexion to neutral position in 2° increments. In total, this parameterization study tested 161,051 combinations of optimal fiber length, pennation angle, maximal isometric force, ankle resting angle, and Achilles tendon stiffness values. Default values for optimal fiber lengths, pennation angles, and maximal isometric muscle forces were adopted from a large cadaveric investigation of architectural properties of lower extremity muscles (Ward et al., 2009), which has been implemented in a similar musculoskeletal model (Arnold et al., 2010). The ranges in which these MTU parameters changed were based on previous reports of MTU ranges in both healthy and pathologic populations (Agres et al., 2015; Arya and Kulig, 2010; Baxter et al., 2018; Zellers et al., 2018).

### *2.2. Slack length tuning – resting ankle angle*

In order to recreate clinically relevant ankle postures, we calculated the tendon slack lengths of each ankle muscle to simulate the resting ankle angle for each MTU parameter combination (Fig. 1A/D). To do this, we performed the computational analog of instructing the patient to lay prone on a treatment table with the foot and ankle freely hanging at a 'resting angle' (Zellers et al., 2018). First, the entire model was rotated 90° to simulate the subject resting in the prone position. The optimal muscle fiber lengths, pennation angles, maximal isometric forces, and tendon stiffness values were updated to the MTU parameters for each specific simulation iteration. Second, the ankle angle was set to the desired resting position between 0 and 20° of plantarflexion. Third, the plantarflexor muscle activations were set to 1%, and the dorsiflexor muscle activations were set between 1.5 and 4%. These increased dorsiflexor activation values were selected to balance the plantarflexor muscles, which had a combined maximal force capability of approximately 1.5–4 times that of the dorsiflexor. This was done to achieve ankle equilibrium near the desired resting ankle angle while also maintaining optimal fiber length. Finally, the slack lengths of the plantarflexor and dorsiflexor muscles were iteratively adjusted to minimize a cost function (Eq. (1)) consisting of (1) ankle joint torques and (2) differences between optimal fiber lengths and simulated fiber lengths. Ankle joint torque was calculated as a function of MTU forces and moment arms of both the plantar- and dorsiflexors. The ankle joint moment created by the weight of the foot segment was also included. The difference between resting muscle-fiber lengths and the prescribed optimal muscle-fiber lengths were minimized to recreate muscle parameters that are measured experimentally using ultrasonography (Baxter and Piazza, 2014). This cost function (Eq. (1)) was evaluated using a gradient-based optimization approach (fsolve, MATLAB, The Mathworks, Natick, MA).

$$minimize\begin{cases} \sum_{i=1}^{npf}\left(\frac{isomax_{pfi}}{isomax_{pf}}\right)\times\left|\vec{r}_{TA}\times\vec{F}_{TA}+\vec{r}_{foot}\times\vec{F}_{foot}+\vec{r}_{pfi}\times\vec{F}_{pfi}\right| \\ \sum_{i=1}^{nmusc}\left|l_{fiberi}-l_{optimali}\right| \end{cases} \quad (1)$$

$$where\begin{cases} \vec{F}_{musc}(l_{slack}) \\ l_{fiber}(l_{slack}) \end{cases}$$

where $l_{tendon}$ – slack length, *r* – distance from force to ankle joint, *F* – force of MTU or foot segment, *pf* – plantarflexor muscles (gastrocnemius, soleus), *TA* – tibialis anterior, and *musc* – all

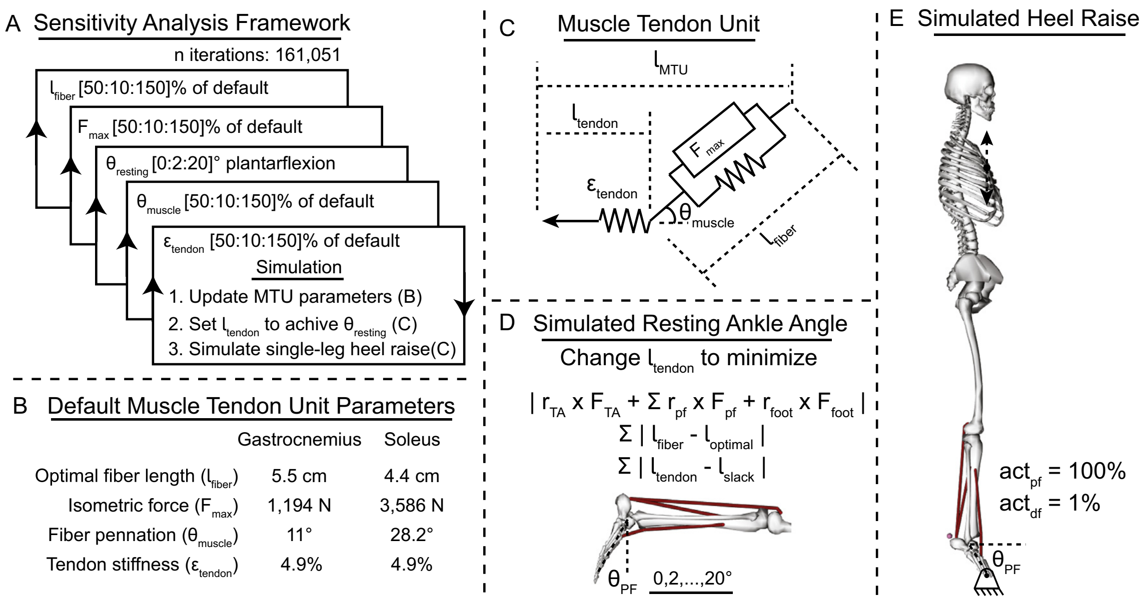


**Fig. 1.** A sensitivity analysis was performed to study the effects of each muscle tendon unit (MTU) parameter on a simulated single-leg heel raise. For each test iteration (A), the MTU parameters were set (B), tendon slack lengths were changed to achieve ankle static equilibrium at the desired resting ankle angle (C), and the single-leg heel raise was simulated (D).

muscles (gastrocnemius, soleus, tibialis anterior), and $F_{musc}$ and $L_{fiber}$ were both functions of tendon slack length ($l_{slack}$).

In order to confirm that these optimized tendon slack lengths produced the desired resting ankle angles, we performed forward simulations for each parameterized model. To do this, the pelvis and all joints except for the right ankle were locked to prevent undesired motions. Plantarflexor activations were held at 1% maximal contraction, while dorsiflexor activation matched the calculated activations for each MTU permutation. Each condition was simulated forward in time for 5 s to ensure ankle angular velocity was zero. To confirm that the resting angle was not dependent on the starting position of the simulation, each model configuration was tested at initial positions that were offset from the desired resting ankle angle by 10° plantarflexion and 10° dorsiflexion. These simulations (N = 322,102) always converged on the same resting ankle angle for the same condition (root mean square error: 0.15°).

### *2.3. Forward simulation – single-leg heel raise*

We simulated single-leg heel-raises using the simplified musculoskeletal model to test the implications of MTU parameters on heel-raise height for the 161,051 test permutations (Fig. 1). Because patients typically use the assistance of a wall to maintain their balance during clinical tests, we applied motion constraints to the model to mimic the clinical environment and eliminate the need for a control algorithm. The right metatarsophalangeal joint was constrained with the ground using two point constraints in order to limit foot motion with the ground along a foot-fixed medial-lateral axis. The sternum was constrained to move the center of gravity of the torso along a vertical axis as a means to ensure the model was in an upright posture during the simulated heel-raise. The joints of the left leg, lumbar, and right knee and hip were ‘locked’ but allowed to move in small amounts (<0.1°) to satisfy the kinematic constraints of the model. The knee was locked into full extension throughout all simulations, effectively converting the gastrocnemius muscle to a uniarticular muscle. Nonetheless, both plantarflexors were included because of the functional differences in MTU parameters (Arnold and Delp, 2011) and shortening dynamics during plantarflexion contractions (Franz and Thelen, 2016; Miaki et al., 1999).

To determine the maximal ankle plantarflexion that could be achieved based on the MTU parameters, we performed forward dynamic simulations of the single-leg heel raise. Although the single-leg heel raise is a submaximal activity for most healthy adults, we decided to maximally excite the plantarflexors in these simulations because two-thirds of patients with Achilles tendon ruptures show deficits in heel raise height (Brorsson et al., 2017). The tibialis anterior muscle was set to 1% of maximal contraction. Each model was simulated for 1 s forward in time. These simulations of single-leg heel raises had a ceiling effect, where some MTU parameters extended the ankle past 75°, which would result in the model jumping. Although the physiologic range of the ankle joint under load is less than 75° (Lindsjö et al., 1985), we allowed this motion in the model to raise the ceiling of the simulated task.

To determine how sensitive single-leg heel raise tests are to muscle-tendon parameters, we used a multivariate linear regression model (fitlm, MATLAB) to quantify the effect a 1% change in each of the MTU parameters. We decided to utilize peak plantarflexion angle as our performance criterion rather than heel or pelvic vertical displacement. This measure provides more straightforward translation to the clinic, as it does not depend on stature or foot length. To provide additional clinical relevance to this regression model, we normalized changes to resting ankle angle by the physiologic range of 0–20° plantarflexion. For example, changing the resting ankle angle by 2° was effectively a 10% change in the model.

To further test our hypothesis that tendon length is a primary driver of single-leg heel raise height, we plotted peak ankle angle as a function of tendon slack length for both plantarflexor muscles and performed univariate linear regressions. These plots were visualized as heat maps showing how frequently each isolated MTU parameter produced each possible plantarflexion value. Because certain combinations of MTU parameters resulted in no plantarflexion or plantarflexion greater than 75°, we included additional visualizations to demonstrate the frequencies of those simulation results. Since each plantarflexor muscle had unique tendon slack lengths for each simulation, separate linear regressions were performed for the gastrocnemius and soleus muscles and each tendon slack length was normalized by the range of simulation slack lengths in this study. Tendon slack lengths were normalized by the simulated range for each plantarflexor MTU. The ability to perform a complete single-leg heel raise is a clinical test for patient function following Achilles tendon injuries (Toyooka et al., 2017). Therefore, we also calculated the effects of MTU parameters on the ability to complete a single-leg heel raise.

## 3. Results

Peak ankle angle during simulated single-leg heel raises was positively affected by optimal fiber length (Table 1, Fig. 2). Despite having no effect on absolute muscle strength, optimal fiber length had a 2.5 times greater effect on heel raise height compared to peak isometric force of the plantarflexor muscles. Muscle pennation and tendon stiffness had the smallest effects on peak ankle angle during the simulated heel raise (0.08° for a 1% change in pennation and 0.03° for a 1% change in stiffness). Eight percent of simulations fully extended the ankle, which would have resulted in the foot leaving the ground (Fig. 2 top panel). Conversely, one percent of simulations were unable to generate any active plantarflexion.

Tendon slack length was the strongest predictor of peak ankle angle, which was negatively correlated with peak plantarflexion angle (Table 1, Fig. 3). The gastrocnemius slack length ranged from 0.9 to 1.1 and the soleus tendon slack length ranged from 0.85 to 1.13 times their default lengths. When controlling for these simulated ranges of tendon slack length, a one percent change in the gastrocnemius and soleus tendon slack lengths resulted in 0.76 and 0.81° decrease in peak ankle angle, respectively (Table 1). Gastrocnemius and soleus tendon slack lengths each explained approximately two-thirds of the variability in peak ankle plantarflexion ($R^2$ = 0.70 and 0.67, respectively).

**Table 1**
Effect of 1% change of MTU parameters on ankle angle during simulated single-leg heel raise.

| 1% Δ MTU parameters → | Δ in peak $\theta_{ankle}$ |
|---|---|
| *Multivariate linear regression model* | |
| Optimal fiber length | 0.49° |
| Resting ankle angle | 0.31° |
| Peak isometric force | 0.20° |
| Muscle pennation | 0.08° |
| Tendon stiffness | −0.03° |
| *Univariate linear regression model* | |
| Gastroc. tendon slack length | −0.76° |
| Soleus tendon slack length | −0.81° |

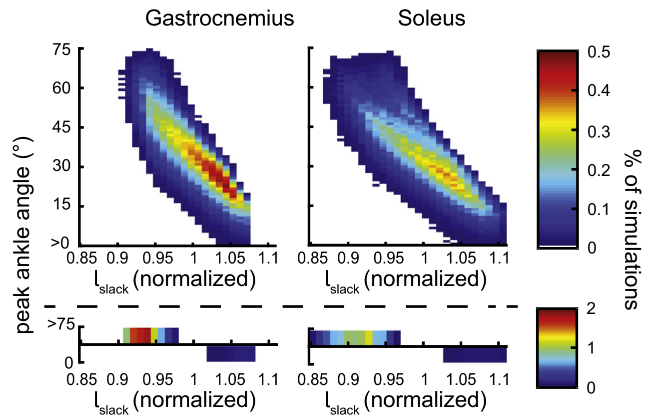


**Fig. 3.** Peak ankle angle during simulated single-leg heel raises (*top panel*) were sensitive to small changes in tendon slack length (normalized by default slack length). Shorter slack lengths resulted in greater peak ankle angles while longer slack lengths resulted in smaller ankle plantarflexion *(bottom panel)*. Some simulations (*bottom panel*) resulted in the model plantarflexing past a physiologic range (>75°) or generating no ankle plantarflexion at all (0°).

Two-thirds of the MTU combinations resulted in simulations that did not produce 45° of plantarflexion (Fig. 4). Sixty-three percent of simulations produced at least 30° of plantarflexion while only eight percent of simulations produced less than 15° of peak plantarflexion. Longer optimal muscle fibers and shorter tendons were most common in simulations that generated at least 30° of peak plantarflexion. Conversely, simulations that were unable to produce at least 15° of plantarflexion had shorter muscle fibers that acted on longer tendons.

## 4. Discussion

Achilles tendon ruptures elicit structural and functional changes to the plantarflexor MTU (Agres et al., 2015; Baxter et al., 2018; Silbernagel et al., 2012) that may explain long-term function deficits (Brorsson et al., 2018). However, the effects of these MTU parameters on clinical function have not yet been defined. Therefore, the purpose of this study was to test our hypothesis that shorter muscle fibers and a decreased resting ankle angle would lead to compromised heel-raise performance. Using a simple musculoskeletal model, we simulated the effects of five parameters that dictate musculo-tendinous function: optimal fiber length, fiber pennation angle, peak isometric force, tendon

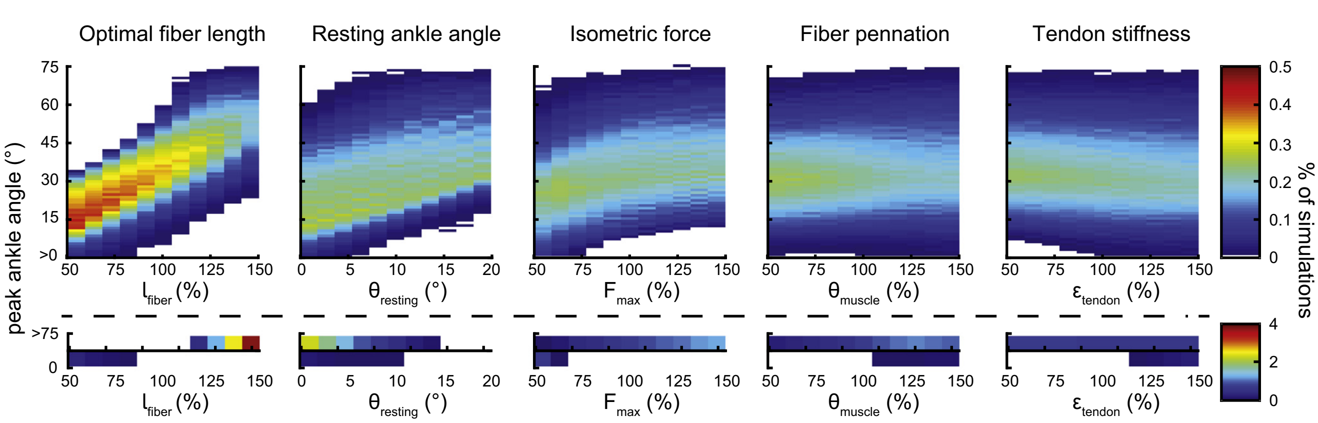


**Fig. 2.** Peak ankle angle during simulated single-leg heel raises (*top panel*) were affected by muscle-tendon unit (MTU) parameters (in decreasing order from left to right, see Table 1 for effects of 1% changes in MTU parameters on peak plantarflexion angle during single-leg heel raise): optimal fiber length, resting ankle angle, maximum muscle force, muscle pennation, and tendon stiffness. Heat maps visualize how changes to each MTU parameter affected peak plantarflexion during simulated heel-raises (N = 161,051). Some simulations (*bottom panel*) resulted in the model plantarflexing past a physiologic range (>75°) or generating no ankle plantarflexion at all (0°).

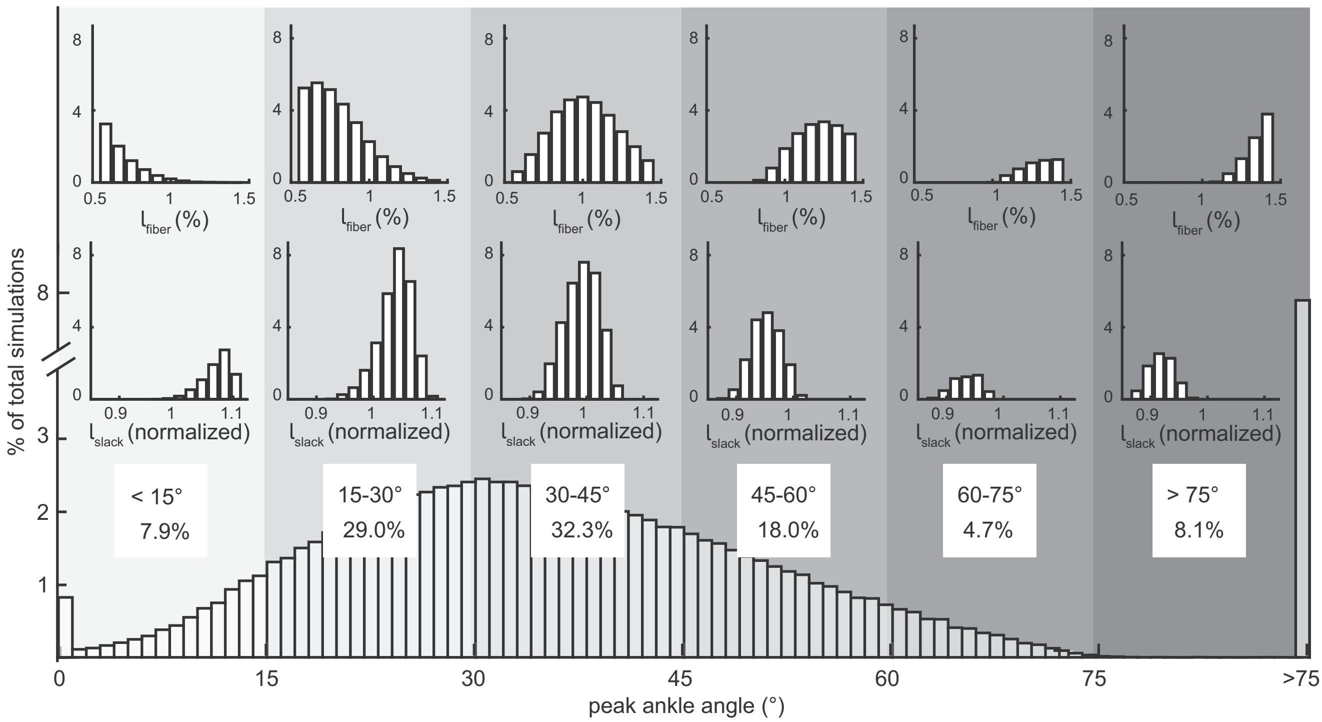


**Fig. 4.** Two-thirds of muscle-tendon unit (MTU) combinations resulted in single-leg heel raises that did not achieve at least 45° of peak ankle plantarflexion. Optimal fiber and tendon slack lengths were the strongest predictors of peak ankle angle. Longer muscle fibers paired with shorter tendons increased single-leg heel raise function.

stiffness, and tendon slack length – the latter being calculated using a novel MTU tuning algorithm in order to achieve clinically relevant resting ankle angles (Zellers et al., 2018). Our simulation results supported our hypothesis that optimal fiber length and resting ankle angle – the two key factors that dictate the length of the MTU – were the primary determinants of single-leg heel raise height.

The simulation results presented in this study compare favorably with other musculoskeletal simulations of plantarflexion contractions as well as physical measurements of patients with Achilles tendon ruptures. Our results suggest that optimal fiber length is a strong predictor of heel raise height, which agrees with other concentric plantarflexion simulations. For example, previous ultrasound measurements in patients have revealed reduced resting gastrocnemius fascicle length (Baxter et al., 2018; Hullfish et al., 2018; Peng et al., 2017) that may lead to permanent muscle remodeling and functional deficits (Baxter et al., 2018). We also found that tendon elongation – modeled as increased tendon slack lengths – negatively affects the model's capacity to generate large angle plantarflexion angles (Fig. 3). These findings strongly agree with a previous clinical study that suggests that tendon elongation causes nearly two-thirds of functional deficits in patients performing single-leg heel raises (Silbernagel et al., 2012). Our simulation findings suggest that tendon elongation coupled with shorter optimal fiber lengths place functional constraints and limit ankle angle excursion (Fig. 4). In contrast to ultrasound findings that muscle pennation increases following Achilles tendon ruptures (Hullfish et al., 2018), our current findings that peak plantarflexion angle during a heel-raise was not sensitive to pennation angle suggests that muscle pennation angle has nominal effects on heel-raise height. Based on our current findings and past observations that decreased fascicle length is coupled with increased pennation (Baxter et al., 2018), we posit that increases in muscle pennation following rupture are geometric responses to muscle unloading following rupture with smaller impacts on function compared to reduced fascicle length. Additionally, while our preliminary findings suggest that pennation is increased immediately following rupture (Hullfish et al., 2018), long-term muscle pennation appears to revert back to normal values when compared to the contralateral side while fascicle length reductions (Peng et al., 2017) and functional deficits (Brorsson et al., 2018) persist.

Maintaining muscle fiber length while minimizing tendon elongation should be a primary goal when treating acute Achilles tendon ruptures. Limited patient function has been linked to shorter and more pennate plantarflexor muscles (Baxter et al., 2018) and elongated tendon (Silbernagel et al., 2012). Although surgically repairing the rupture restores resting tendon length, fluoroscopic studies have demonstrated that the rupture site tends to retract and lead to tendon elongation following the first two months of surgery (Kangas et al., 2007; Mortensen et al., 1999, 1992). Early ankle motion prescribed immediately following surgical repair decreases the magnitude of tendon elongation compared to 6-weeks of immobilization in a plaster cast (Kangas et al., 2007). Surgical repair also may provide improved long-term plantarflexion power compared to non-surgical treatment of Achilles tendon ruptures (Willits et al., 2010). However, the link between surgical repair and improved patient function is tenuous (Brorsson et al., 2018), and tendon elongation appears to be a primary predictor of patient function (Pajala et al., 2009; Silbernagel et al., 2012). Findings from a small animal model have shown that surgically shortening tendon length stimulates muscle remodeling that results in larger, longer, and more powerful skeletal muscle (Krochmal et al., 2008). Although this prior report highlights the plasticity of skeletal muscle, similar findings in patient populations have not been reported.

This study was affected by several limitations. The musculoskeletal model was a simplified representation of the complicated plantarflexor mechanism. Other factors such as plantarflexor moment arm (Baxter and Piazza, 2014), muscle composition (Trappe et al., 2015), and foot length (van Werkhoven and Piazza, 2017) affect plantarflexor function but were excluded in this study. Instead, the goal of this study was to focus on MTU parameters that are documented to change in response to Achilles tendon ruptures (Agres et al., 2015; Baxter et al., 2018; Silbernagel et al., 2012). The plantarflexors were represented by a single gastrocnemius MTU and a soleus MTU (Fig. 1). Other muscles that cross behind the ankle joint have been documented to change their structure following Achilles tendon injuries (Hahn et al., 2008). These muscles were excluded from this study because they have limited mechanical advantages and force generating capabilities in comparison to the primary plantarflexors. The muscle model did not account for differences in muscle volume or thickness, which may have an affect mechanical advantage (Maganaris et al., 1998) and muscle gearing during maximal contractions (Azizi et al., 2008). Finally, it should be noted that the gastrocnemius and soleus muscles begin to carry load at different resting ankle angles (Hirata et al., 2015). However, we made the assumption that the slack lengths of both muscles are similar after the ruptured Achilles tendon heals.

In conclusion, we simulated the effects of plantarflexor MTU parameters on a single-leg heel raise, a common clinical test of patient function. These simulations revealed optimal fiber length and resting ankle angle (a surrogate for tendon slack length) both had greater effects on peak ankle angle during the heel raise than muscle strength. Traditional rehabilitation plans for acute Achilles tendon ruptures typically focus on strengthening the plantarflexor muscles. Results from this study suggest that minimization of tendon elongation and reductions in muscle fascicle length should also be considered in post-injury care.

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## Authors' contributions

JB developed the model; JB performed the simulations and analyzed the data; JB, DF, and MH analyzed and interpreted the data; JB drafted the manuscript; JB, DF, and MH revised the intellectual content of the manuscript; JB, DF, and MH approved the final version of the manuscript; and JB, DF and MH agreed to be accountable for all aspects of the study.

## Conflict of interest

The authors have no conflicts of interest that are relevant to this work.

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## References

Agres, A.N., Duda, G.N., Gehlen, T.J., Arampatzis, A., Taylor, W.R., Manegold, S., 2015. Increased unilateral tendon stiffness and its effect on gait 2–6 years after Achilles tendon rupture. Scand. J. Med. Sci. Sports 25, 860–867. https://doi.org/10.1111/sms.12456.

Arnold, E.M., Delp, S.L., 2011. Fibre operating lengths of human lower limb muscles during walking. Philos. Trans. R. Soc. Lond. B Biol. Sci. 366, 1530–1539. https://doi.org/10.1098/rstb.2010.0345.

Arnold, E.M., Ward, S.R., Lieber, R.L., Delp, S.L., 2010. A model of the lower limb for analysis of human movement. Ann. Biomed. Eng. 38, 269–279. https://doi.org/10.1007/s10439-009-9852-5.

Arya, S., Kulig, K., 2010. Tendinopathy alters mechanical and material properties of the Achilles tendon. J. Appl. Physiol. 108, 670–675. https://doi.org/10.1152/japplphysiol.00259.2009.

Azizi, E., Brainerd, E.L., Roberts, T.J., 2008. Variable gearing in pennate muscles. Proc. Natl. Acad. Sci. U. S. A. 105, 1745–1750. https://doi.org/10.1073/pnas.0709212105.

Baxter, J.R., Hast, M.W., 2019. Plantarflexor metabolics are sensitive to resting ankle angle and optimal fiber length in computational simulations of gait. Gait Posture 67, 194–200. https://doi.org/10.1016/j.gaitpost.2018.10.014.

Baxter, J.R., Hullfish, T.J., Chao, W., 2018. Functional deficits may be explained by plantarflexor remodeling following Achilles tendon rupture repair: preliminary findings. J. Biomech. 79, 238–242. https://doi.org/10.1016/j.jbiomech.2018.08.016.

Baxter, J.R., Novack, T.A., Van Werkhoven, H., Pennell, D.R., Piazza, S.J., 2012. Ankle joint mechanics and foot proportions differ between human sprinters and non-sprinters. Proc. R. Soc. B Biol. Sci. 279, 2018–2024. https://doi.org/10.1098/rspb.2011.2358.

Baxter, J.R., Piazza, S.J., 2014. Plantar flexor moment arm and muscle volume predict torque-generating capacity in young men. J. Appl. Physiol. 116, 538–544. https://doi.org/10.1152/japplphysiol.01140.2013.

Brorsson, A., Grävare Silbernagel, K., Olsson, N., Nilsson Helander, K., 2018. Calf muscle performance deficits remain 7 years after an Achilles tendon rupture. Am. J. Sports Med. 46, 470–477. https://doi.org/10.1177/0363546517737055.

Brorsson, A., Willy, R.W., Tranberg, R., Silbernagel, K.G., 2017. Heel-rise height deficit 1 year after achilles tendon rupture relates to changes in ankle biomechanics 6 years after injury. Am. J. Sports Med. 45, 3060–3068. https://doi.org/10.1177/0363546517717698.

Carbone, V., van der Krogt, M.M., Koopman, H.F.J.M., Verdonschot, N., 2016. Sensitivity of subject-specific models to Hill muscle–tendon model parameters in simulations of gait. J. Biomech. 49, 1953–1960. https://doi.org/10.1016/j.jbiomech.2016.04.008.

Delp, S.L., Anderson, F.C., Arnold, A.S., Loan, P., Habib, A., John, C.T., Guendelman, E., Thelen, D.G., 2007. OpenSim: open-source software to create and analyze dynamic simulations of movement. IEEE Trans. Biomed. Eng. 54, 1940–1950. https://doi.org/10.1109/TBME.2007.901024.

Franz, J.R., Thelen, D.G., 2016. Imaging and simulation of Achilles tendon dynamics: implications for walking performance in the elderly. J. Biomech., 1403–1410

Hahn, F., Meyer, P., Maiwald, C., Zanetti, M., Vienne, P., 2008. Treatment of chronic achilles tendinopathy and ruptures with flexor hallucis tendon transfer: clinical outcome and MRI findings. Foot Ankle. Int. Am. Orthop. Foot Ankle Soc Swiss Foot Ankle Soc. 29, 794–802. https://doi.org/10.3113/FAI.2008.0794.

Hansen, M.S., Barfod, K.W., Kristensen, M.T., 2017. Development and reliability of the Achilles Tendon Length Measure and comparison with the Achilles Tendon Resting Angle on patients with an Achilles tendon rupture. Foot Ankle Surg. 23, 275–280. https://doi.org/10.1016/j.fas.2016.08.002.

Hirata, K., Kanehisa, H., Miyamoto-Mikami, E., Miyamoto, N., 2015. Evidence for intermuscle difference in slack angle in human triceps surae. J. Biomech. 48, 1210–1213. https://doi.org/10.1016/j.jbiomech.2015.01.039.

Hullfish, T.J., O'Connor, K.M., Baxter, J.R., 2018. Gastrocnemius fascicles are shorter and more pennate immediately following acute Achilles tendon rupture. BioRxiv Prepr. 445569. https://doi.org/10.1101/445569.

Kangas, J., Pajala, A., Ohtonen, P., Leppilahti, J., 2007. Achilles tendon elongation after rupture repair: a randomized comparison of 2 postoperative regimens. Am. J. Sports Med. 35, 59–64. https://doi.org/10.1177/0363546506293255.

Koh, T.J., Herzog, W., 1998. Excursion is important in regulating sarcomere number in the growing rabbit tibialis anterior. J. Physiol. 508, 267–280. https://doi.org/10.1111/j.1469-7793.1998.267br.x.

Krochmal, D.J., Kuzon, W.M., Urbanchek, M.G., 2008. Muscle force and power following tendon repair at altered tendon length. J. Surg. Res. 146, 81–89. https://doi.org/10.1016/j.jss.2007.04.030.

Lee, S.S.M., Piazza, S.J., 2009. Built for speed: musculoskeletal structure and sprinting ability. J. Exp. Biol. 212, 3700–3707. https://doi.org/10.1242/jeb.031096.

Lichtwark, G.A., Wilson, A.M., 2008. Optimal muscle fascicle length and tendon stiffness for maximising gastrocnemius efficiency during human walking and running. J. Theor. Biol. 252, 662–673. https://doi.org/10.1016/j.jtbi.2008.01.018.

Lindsjö, U., Danckwardt-Lillieström, G., Sahlstedt, B., 1985. Measurement of the motion range in the loaded ankle. Clin. Orthop., 68–71

Maganaris, C.N., Baltzopoulos, V., Sargeant, A.J., 1998. Changes in Achilles tendon moment arm from rest to maximum isometric plantarflexion: in vivo observations in man. J. Physiol. 510, 977–985. https://doi.org/10.1111/j.1469-7793.1998.977bj.x.

Miaki, H., Someya, F., Tachino, K., 1999. A comparison of electrical activity in the triceps surae at maximum isometric contraction with the knee and ankle at various angles. Eur. J. Appl. Physiol. 80, 185–191.

Millard, M., Uchida, T., Seth, A., Delp, S.L., 2013. Flexing computational muscle: modeling and simulation of musculotendon dynamics. J. Biomech. Eng. 135, 0210051–02100511. https://doi.org/10.1115/1.4023390.

Mortensen, H.M., Skov, O., Jensen, P.E., 1999. Early motion of the ankle after operative treatment of a rupture of the Achilles tendon. A prospective, randomized clinical and radiographic study. J. Bone Joint Surg. Am. 81, 983–990.

Mortensen, N.H.M., Saether, J., Steinke, M.S., Staehr, H., Mikkelsen, S.S., 1992. Seperation of tendon ends after Achillse tendon repair: a prospective, randomized, multicenter study. Orthopedics 15, 899–903. https://doi.org/10.3928/0147-7447-19920801-06.

Olsson, N., Karlsson, J., Eriksson, B.I., Brorsson, A., Lundberg, M., Silbernagel, K.G., 2014. Ability to perform a single heel-rise is significantly related to patient-reported outcome after Achilles tendon rupture. Scand. J. Med. Sci. Sports 24, 152–158. https://doi.org/10.1111/j.1600-0838.2012.01497.x.

Orselli, M.I.V., Franz, J.R., Thelen, D.G., 2017. The effects of Achilles tendon compliance on triceps surae mechanics and energetics in walking. J. Biomech. 60, 227–231. https://doi.org/10.1016/j.jbiomech.2017.06.022.

Pajala, A., Kangas, J., Siira, P., Othonen, P., Leppilahti, J., 2009. Augmented compared with nonaugmented surgical repair of a fresh total Achilles tendon rupture. A prospective randomized study. J. Bone Joint Surg. Am. 91, 1092–1100. https://doi.org/10.2106/JBJS.G.01089.

Peng, W.-C., Chang, Y.-P., Chao, Y.-H., Fu, S., Rolf, C., Shih, T.T., Su, S.-C., Wang, H.-K., 2017. Morphomechanical alterations in the medial gastrocnemius muscle in patients with a repaired Achilles tendon: associations with outcome measures. Clin. Biomech. 43, 50–57. https://doi.org/10.1016/j.clinbiomech.2017.02.002.

Scovil, C.Y., Ronsky, J.L., 2006. Sensitivity of a Hill-based muscle model to perturbations in model parameters. J. Biomech. 39, 2055–2063. https://doi.org/10.1016/j.jbiomech.2005.06.005.

Silbernagel, K.G., Steele, R., Manal, K., 2012. Deficits in heel-rise height and Achilles tendon elongation occur in patients recovering from an achilles tendon rupture. Am. J. Sports Med. 40, 1564–1571. https://doi.org/10.1177/0363546512447926.

Toyooka, S., Takeda, H., Nakajima, K., Masujima, A., Miyamoto, W., Pagliazzi, G., Nakagawa, T., Kawano, H., 2017. Correlation between recovery of triceps surae muscle strength and level of activity after open repair of acute achilles tendon rupture. Foot Ankle Int. 38, 1324–1330. https://doi.org/10.1177/1071100717728686.

Trappe, S., Luden, N., Minchev, K., Raue, U., Jemiolo, B., Trappe, T.A., 2015. Skeletal muscle signature of a champion sprint runner. J. Appl. Physiol. Bethesda Md. 1985 (118), 1460–1466. https://doi.org/10.1152/japplphysiol.00037.2015.

Uchida, T.K., Hicks, J.L., Dembia, C.L., Delp, S.L., 2016. Stretching your energetic budget: how tendon compliance affects the metabolic cost of running. PLOS ONE 11, e0150378. https://doi.org/10.1371/journal.pone.0150378.

van Werkhoven, H., Piazza, S.J., 2017. Foot structure is correlated with performance in a single-joint jumping task. J. Biomech. 57, 27–31. https://doi.org/10.1016/j.jbiomech.2017.03.014.

Ward, S.R., Eng, C.M., Smallwood, L.H., Lieber, R.L., 2009. Are current measurements of lower extremity muscle architecture accurate? Clin. Orthop. 467, 1074–1082. https://doi.org/10.1007/s11999-008-0594-8.

Williams, P.E., Goldspink, G., 1978. Changes in sarcomere length and physiological properties in immobilized muscle. J. Anat. 127, 459–468.

Willits, K., Amendola, A., Bryant, D., Mohtadi, N.G., Giffin, J.R., Fowler, P., Kean, C.O., Kirkley, A., 2010. Operative versus nonoperative treatment of acute Achilles tendon ruptures: a multicenter randomized trial using accelerated functional rehabilitation. J. Bone Jt. Surg. 92, 2767–2775. https://doi.org/10.2106/JBJS.I.01401.

Xiao, M., Higginson, J., 2010. Sensitivity of estimated muscle force in forward simulation of normal walking. J. Appl. Biomech. 26, 142–149. https://doi.org/10.1123/jab.26.2.142.

Zellers, J.A., Carmont, M.R., Silbernagel, K.G., 2018. Achilles tendon resting angle relates to tendon length and function. Foot Ankle Int. 39, 343–348. https://doi.org/10.1177/1071100717742372.

Zellers, J.A., Carmont, M.R., Silbernagel, K.G., 2016. Return to play post-Achilles tendon rupture: a systematic review and meta-analysis of rate and measures of return to play. Br. J. Sports Med. 50, 1325–1332. https://doi.org/10.1136/bjsports-2016-096106.