TOO MUCH WORK: REVISITING ULTRASOUND-BASED ESTIMATES OF ACHILLES TENDON ENERGY STORAGE AND RETURN

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INTRODUCTION

Ultrasound imaging is increasingly used with motion and force data to quantify tendon dynamics and to understand the functional role of tendons during human and other animal movement. Frequently, tendon dynamics are estimated indirectly from measures of muscle kinematics (by subtracting muscle length from muscle-tendon unit length), but there is mounting evidence that this approach, which we term the *Indirect* method, yields implausible tendon work loops (tendon force vs. elongation) [e.g., 1-2]. Since tendons are passive, viscoelastic structures, they should exhibit negative work loops (i.e., net negative work over a loading-unloading cycle). However, prior studies using Indirect estimates of tendon kinematics report large positive work loops, estimating that tendons return 100-400% more energy than they store [e.g., 1-2]. More direct ultrasound methods have emerged that estimate tendon elongation by tracking either the muscle-tendon junction (termed the *Direct MTJ* method) or localized tendon tissue stretch (termed the *Direct Tendon* method) [3]. However, it is unclear if these Direct estimates yield more plausible tendon work loops. Here, we estimated tendon work loops and hysteresis using these two Direct tendon kinematics estimates during human walking, then compared these results to previously reported values using Indirect kinematics estimates.

METHODS

We reanalyzed human walking data from our prior work (N=8, mean ± standard deviation, age: 23.9 ± 4.6 years) [3]. Subjects completed two 2-minute walking trials at three walking speeds (0.75, 1.00, and 1.25 m/s) - one trial for each of two probe locations. We collected human motion and force data using standard gait analysis procedures. Simultaneously, we collected raw radiofrequency (RF) data from longitudinal cross-sections through the right plantarflexor MTU using a 10-MHz, 38-mm linear array transducer (L14-5W/38, Ultrasonix, Richmond, BC) secured using an orthotic. For the Direct MTJ estimate, we recorded (128 frames/s) through a 3 cm depth from a probe centered on the distal lateral gastrocnemius (LG) MTJ, from which we estimated local MTJ displacements. For the Direct Tendon estimate, we recorded (155 frames/s) through a 2 cm depth from a probe on the distal free Achilles tendon. Custom 2D speckle-tracking estimated longitudinal free Achilles tendon tissue

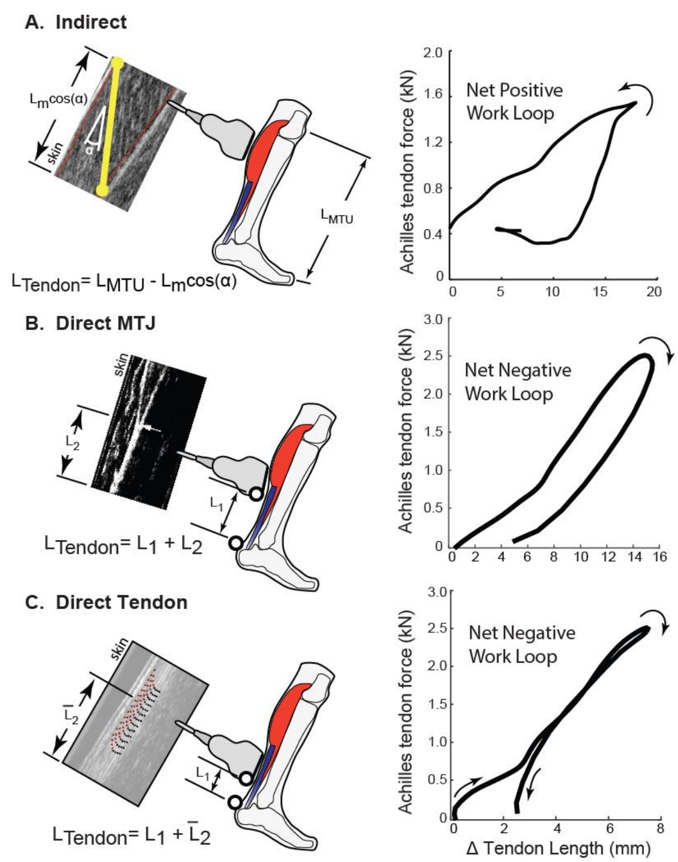

Figure 1. Tendon kinematic measurements and group-average tendon work loops during walking. (A) Indirect estimates from digitized published data [1] and Direct estimates via the (B) lateral gastrocnemius MTJ and (C) Achilles free tendon.

displacements [3]. Achilles tendon elongations were then estimated by co-registering local LG MTJ (Direct MTJ) and Achilles free tendon (Direct Tendon) displacements with the calcaneus marker position. Finally, we estimated Achilles tendon force as the net ankle moment divided by subject-specific measures of the Achilles tendon moment arm to create stance phase tendon work loops (tendon force vs. elongation). We integrated tendon work loops to calculate: (i) net stance phase work (J) and (ii) hysteresis (%), defined as one minus the positive work (energy returned during tendon unloading) divided by negative work (energy stored during loading). Tendon hysteresis from Direct MTJ and Direct Tendon methods were compared to Indirect values from literature [e.g., 1-2].

RESULTS AND DISCUSSION

Based on digitized data from previously published studies [e.g., 1-2], tendon length changes estimated from measured muscle fascicle kinematics consistently produced positive tendon work loops. For example, Achilles tendon hysteresis during walking derived indirectly from soleus and gastrocnemius fascicle kinematics elicited values of approximately -130% and -200%, respectively, indicating considerable but physiologically implausible net positive work performed by the tendon (Fig. 1A) [1].

In contrast to Indirect estimates, we found that both Direct methods yielded, on average, negative tendon work loops and thus positive tendon hysteresis values during the stance phase of walking. Across the range of speeds tested, peak Achilles tendon force during the stance phase averaged 2.2-2.7 kN. This range of peak forces was associated with tendon length changes of 14.3-15.2 mm estimated via LG Direct MTJ and 7.1-7.8 mm estimated via Direct Tendon approaches. Direct MTJ tendon hysteresis (net work) averaged 49.7% (-8.9 J), 37.9% (-8.2 J), and 9.2% (-5.1 J) for walking at 0.75, 1.00, and 1.25 m/s, respectively (Fig. 1B). Direct Tendon estimates averaged 32.9% (-3.4 J), 11.0% (-2.0 J), and 2.1% (-1.2 J), respectively (Fig. 1C). Net tendon work (main effect, $p=0.04$), but not hysteresis (main effect, $p=0.34$), differed significantly between the two Direct measurement techniques. Finally, both outcome measures decreased significantly and progressively with increasing walking speed (main effect, $p<0.01$). That hysteresis estimates were walking speed-dependent requires further study.

CONCLUSIONS

As we advance our scientific understanding of movement biomechanics, it is important to continue advancing and validating our experimental methods. It remains unclear which fundamental assumptions or measurement inaccuracies result in the substantial positive tendon work loops obtained from Indirect tendon estimates. Nevertheless, compared to Indirect tendon estimates, Direct estimates may be preferable for understanding tendon dynamics such as energy storage and return, especially during dynamic activities such as walking. The accuracy and completeness of our biomechanical estimates affect our scientific interpretations as well as our applied interventions. Indeed, our results are highly relevant to the degree to which tendon elastic energy storage and return facilitate economical locomotion, and to the bio-inspired design and prescription of assistive devices that seek to restore/augment human calf muscle-tendon function. Musculoskeletal simulations also rely on accurate empirical biomechanical estimates, either as direct inputs or indirectly for validation. Ultimately, we must understand the accuracy, precision, benefits, drawbacks, and assumptions of each measurement approach in order to appropriately interpret the functional role of muscle-tendon dynamics during movement.

REFERENCES

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