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# Fascicle Length Change of the Human Tibialis Anterior and Vastus Lateralis During Walking

A muscle's ability to produce force during a specific movement is determined by the type of muscle action (concentric, eccentric, or isometric). For example, based on the force-velocity relationship of muscle, the muscle force decreases with increasing speed of movement during a concentric action, and the force increases during an eccentric action. Superimposing the force-velocity relationship on the length-tension relationship, the force will be optimal

at a certain muscle (sarcomere) length during isometric and slow concentric actions.<sup>22</sup>

The use of kinematics and electromy-

ography (EMG) to determine the type of muscle action assumes that the change in length of the muscle-tendon complex will reflect the change in length of the muscle

fibers.<sup>24</sup> However, it is well known that the compliance of the tendon and aponeurosis will affect the length of the muscle fibers.<sup>1,17,27,29,32</sup> Recently, several studies using ultrasonography have identified an interaction between the change in length of the muscle fascicles and tendon during fixed joint angle (isometric actions), as well as during dynamic activities in humans. For example, there has been much attention given to the mechanical properties of the tibialis anterior (TA) tendon and aponeurosis during fixed joint angle muscle contractions.<sup>6,27,29,32</sup> From these reports it is clear that the TA tendon and aponeurosis contribute substantially to the compliance of the muscle-tendon complex during isometric muscle actions, resulting in nonisometric behavior of the fascicles.<sup>17</sup> Similarly, during isometric actions of the medial gastrocnemius, the fascicles shorten and the tendon/aponeurosis lengthens.<sup>30,33</sup> It is generally understood that the plantar flexor muscles act eccentrically to control tibial advancement during mid and terminal stance.<sup>35,38</sup> However, it has recently been established that the medial gastrocnemius fascicles remain at constant length during stance, suggesting that they function isometrically.<sup>10,16</sup> During jumping, the medial gastrocnemius fascicles remain at constant length during the time just prior to toe-off, when the ankle plantar flexes and the muscle-tendon complex is

- **STUDY DESIGN:** A single-group descriptive experimental design.
- **OBJECTIVES:** To determine the fascicle length change in the tibialis anterior (TA) and the vastus lateralis (VL) muscles during walking.
- **BACKGROUND:** The length of the muscle fibers during isometric actions and during dynamic functional activities is affected by the compliance of the tendon and aponeurosis. The TA and VL muscles have important functions both in stance and swing phases of gait. Therefore, it is important to understand the dynamics of the muscle length change as it relates to the type of muscle actions in walking.
- **METHODS AND MEASURES:** Nine healthy subjects performed treadmill walking while fascicle length, muscle activity (electromyographic signal), and joint angle (knee and ankle) were recorded. Fascicle length was measured using real-time ultrasound imaging. Fascicle length and joint angle during the gait cycle were analyzed using a repeated-measures analysis of variance.

- **RESULTS:** During the initial portion of stance, when the TA and VL muscles were active, the ankle plantar flexed and the knee joint flexed, suggesting muscle-tendon complex lengthening, but the fascicle length of both muscles remained constant (TA,  $P = .93$ ; VL,  $P = .22$ ). The TA muscle was again active during the initial portion of swing phase, while the ankle dorsiflexed, and the fascicle length decreased ( $P < .05$ ). The VL muscle became active again at the end of swing as the knee extended, and the fascicle length decreased ( $P < .05$ ).
- **CONCLUSIONS:** The lack of change in fascicle length during the initial portions of stance phase suggests a nearly isometric muscle action of the TA and VL. There is a possible interaction occurring between the fascicle and tendon in the TA and VL such that the tendon lengthens to allow joint motion and potentially to store elastic energy. *J Orthop Sports Phys Ther* 2007;37(7):372-379. doi:10.2519/jospt.2007.2440
- **KEY WORDS:** muscle architecture, tendon compliance, ultrasound

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shortening.<sup>18,20,21</sup> On the other hand, the vastus lateralis (VL) fascicles lengthen during the eccentric phase of the squat jump and shorten during the concentric phase.<sup>14,15</sup> This suggests that the interaction between the fascicles and the tendon may be muscle specific.

The TA and the VL each have 2 distinct roles during human gait.<sup>31,34,35,38</sup> The TA is important as it controls the lowering of the foot to the ground after heel contact. Also, the TA allows for sufficient foot clearance during the swing phase by dorsiflexing the ankle. The VL is active just after heel contact to control knee flexion that occurs as weight is accepted on the lower extremity.<sup>31,34,35,38</sup> At the end of swing phase, the VL is again active to insure knee extension and to prepare for ground contact. The function of the TA and VL during gait is of particular interest because both potentially lengthen (eccentric action) in response to ground reaction forces in stance phase and shorten (concentric action) during the unloaded swing phase.

Because of a possible interaction between the muscle fascicles and the tendon as noted above, previous assumptions of the type of muscle action during gait may not be accurate. Measuring fascicle length changes (the in vivo estimate of fiber length changes) during gait will provide insight into the type of muscle action utilized and therefore the potential force contribution of the muscle. In addition, assumptions regarding the interaction between muscle fascicle and tendon length provide insight into the contribution of the tendon series elasticity to human movement and subsequently to the

types of therapeutic exercise prescribed in rehabilitation. Therefore, the purpose of this study was to determine the fascicle length change in the TA and VL muscles during gait.

## METHODS

### Subjects

NINE HEALTHY COLLEGE-AGED SUBJECTS volunteered to participate in this study (TABLE 1). Although data from all 9 subjects were used for the analysis of the TA during gait, data from only 7 of the subjects could be used for analysis of the VL due to technical problems that occurred during testing (TABLE 1). Subjects were excluded from the study if they had a history of orthopedic or neurological problems of the lower extremity, such as a fracture within the previous 5 years, torn ankle ligaments, pain from nerve compression, or neuromuscular pathologies of the lower extremity muscles. The study was approved by the Institutional Review Board of Ohio University. All subjects signed an informed consent form prior to participation in the study.

### Ultrasonography

Real-time ultrasonography was used to obtain images of the TA and VL fascicles during treadmill walking. A 5-MHz, 8.0-cm, linear-array, B-mode ultrasound probe (Acuson 128 XP; Soma Technology, Inc, Cheshire, CT) was secured to the lower leg over the longitudinal axis of the TA muscle belly, and then in a subsequent trial it was secured over the longitudinal axis of the VL. The probe was placed where fascicles were most

optimally viewed in the middle of each of the muscles. A custom-designed plastic mold held the transducer fixed to the leg and thigh by Velcro straps and tape to prevent transducer movement during data collection (FIGURE 1). Video output from the ultrasound unit was sampled at 30 Hz directly to a personal computer. Approximately 10 strides were recorded on each video clip. For 1 of the strides, each frame of the video clip was saved as a still image and exported to a digitizing program (Scion Image; Scion Corporation, Frederick, MD) for measurement of fascicle length. One rater measured each frame twice and the average fascicle length was calculated. The length of each fascicle was measured along the diagonal fiber echoes running from inside margins of the superficial to intermediate aponeuroses in the TA, and from the inside margins of the superficial to deep aponeuroses in the VL (FIGURE 2). Because the VL fascicle is sometimes longer than the available window in the ultrasound image, the lines for the aponeurosis and fascicle were extended such that the length of the fascicle could be extrapolated. There is no difference in fascicle length between the 2 unipennate sections of the

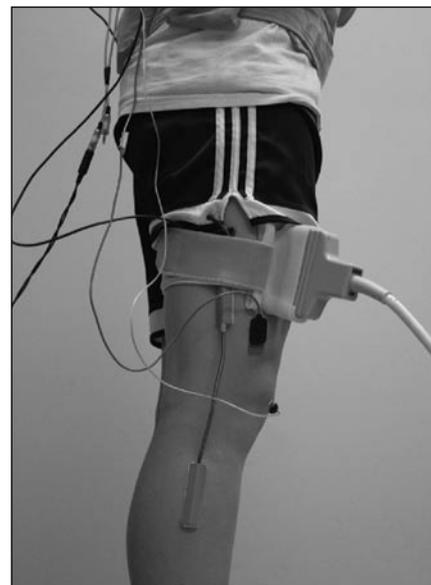


FIGURE 1. Experimental setup showing placement of ultrasound transducer, surface electrodes, and electrogoniometers.

TABLE 1		SUBJECT DEMOGRAPHICS			
Muscle Tested	Gender	Age (y)	Height (m)	Body Mass (kg)	
TA	Male (n = 6)	23.0 ± 1.4	1.80 ± 0.05	73.8 ± 3.7	
	Female (n = 3)	23.3 ± 0.6	1.63 ± 0.08	58.3 ± 7.3	
VL	Male (n = 5)	22.8 ± 1.5	1.81 ± 0.05	74.3 ± 3.9	
	Female (n = 2)	23.5 ± 0.7	1.63 ± 0.11	55.7 ± 8.0	

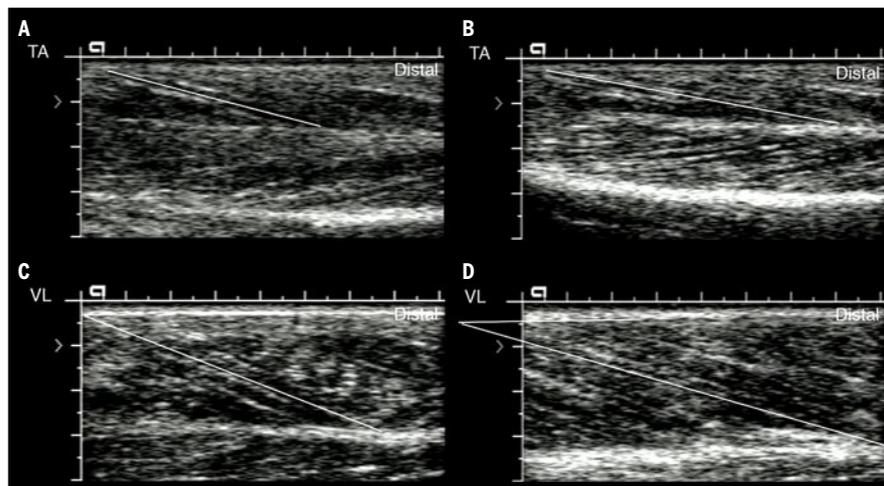
Abbreviations: TA, tibialis anterior; VL, vastus lateralis.

TA muscle,<sup>25</sup> therefore fascicle length was measured only in the superficial unipennate portion of the muscle.

Intrarater reliability for fascicle length measurement was determined separately for the TA and the VL using an intraclass correlation coefficient ( $ICC_{3,1}$ ), with the 2 measurements of fascicle length taken at the point of heel contact for all 9 subjects for the TA and all 7 subjects for the VL. The coefficient of variation of the fascicle measurement was also calculated. The accuracy of this method for determining muscle fascicle length has been established on cadaver biceps femoris muscles by comparing the fascicle length determined with ultrasound imaging to the fascicle length from dissection of a small bundle of fibers in the same area of the muscle.<sup>5</sup> The ultrasound image yielded a fascicle length of  $8.8 \pm 1.8$  cm, compared to  $8.0 \pm 1.5$  cm for the actual fiber bundle length.<sup>5</sup>

### Joint Kinematics and EMG

Joint kinematics and EMG were monitored by a second computer synchronized by a common voltage signal to the ultrasound video capture computer via the audio channel. Surface EMG was used to determine muscle activity of the TA and VL muscles. The skin was shaved and cleaned with alcohol to ensure appropriate contact with the electrode surface. Two 3-mm-diameter Blue Sensor disposable electrodes (Noraxon USA, Inc, Scottsdale, AZ) were then placed over each muscle at a center-to-center distance of 2 cm.<sup>2</sup> The ultrasound transducer was first placed directly over the TA or the VL muscle belly and then surface electrodes were placed immediately proximal to the transducer over the TA muscle and distal to the transducer for the VL muscle. Although this is not ideal placement for the EMG electrodes, this placement was most optimal for collecting EMG data after placement of the transducer. A single ground electrode was also placed over the patella. The EMG signal was sampled at 1000 Hz at a bandwidth of 20 to 500 Hz using an In-



**FIGURE 2.** Representative ultrasound images of fascicles from the tibialis anterior (TA) and the vastus lateralis (VL). The lines are drawn parallel to the fascicle. (A) The TA fascicle in a shortened length, at 0% of the gait cycle. (B) The TA fascicle lengthened, at 64% of the gait cycle. (C) The VL fascicle in a shortened length, at 0% of the gait cycle. (D) The VL fascicle lengthened, at 75% of the gait cycle. The horizontal line is the extension of the superficial fascia for purposes of measuring the fascicle length. Distal is to the right.

tronix Model 2024F amplifier (Intronix Technologies Corporation, Bolton, Ontario, Canada) and Spike 2, Version 3.13 software (Cambridge Electronics Design, Ltd, Cambridge, UK). Specifications of the amplifier include an input impedance of 300 M $\Omega$ , a common-mode rejection ratio of greater than 90 dB at 60 Hz, a signal-noise ratio of greater than 110 dB, and an amplifier gain of 1000. The raw EMG was processed by full-wave rectification, then smoothed using a moving average technique with a 50-millisecond time frame (51 points), and then normalized to the maximum averaged value during gait. For each subject, 8 strides were analyzed and an ensemble average of all subjects presented on a time-normalized graph.

Electrogoniometers (Penny & Giles, Biometrica Ltd, Gwent, UK) were used to monitor the ankle and knee angle throughout the gait cycle. The electrogoniometers were adhered to the skin of the right ankle and knee with adhesive tape. The electrogoniometers were calibrated prior to data collection on each subject. An ankle position of 90° (shank-foot angle) was considered 0°. Movement into plantar flexion was represented by positive angles and move-

ment into dorsiflexion was represented by negative angles. Knee flexion was represented by positive angles. Joint position was sampled at 300 Hz using Spike 2, Version 3.13 software.

Foot switches (Noraxon USA, Inc) were adhered to the skin with adhesive tape at the posterior plantar surface of the heel, head of the first metatarsal, and great toe. Prior to testing each subject, the foot switches were calibrated by pressing on each foot switch sequentially and recording the magnitude of the deflection of the voltage signal. This enabled the differentiation between stance and swing phases during the gait cycle.

### Procedures

Subjects were asked to walk barefoot on a motor-driven treadmill (Quinton Medtrack ST55; Quinton Cardiology, Deerfield, WI) at a speed of 1.3 m/s, which represents average walking speed.<sup>10,34</sup> While subjects walked, muscle activity, fascicle length, and joint angles were collected simultaneously from the right lower extremity. The subjects walked on the treadmill for 1 to 2 minutes to accommodate to the instrumentation and to normalize the gait pattern at the chosen speed. Data were collected over

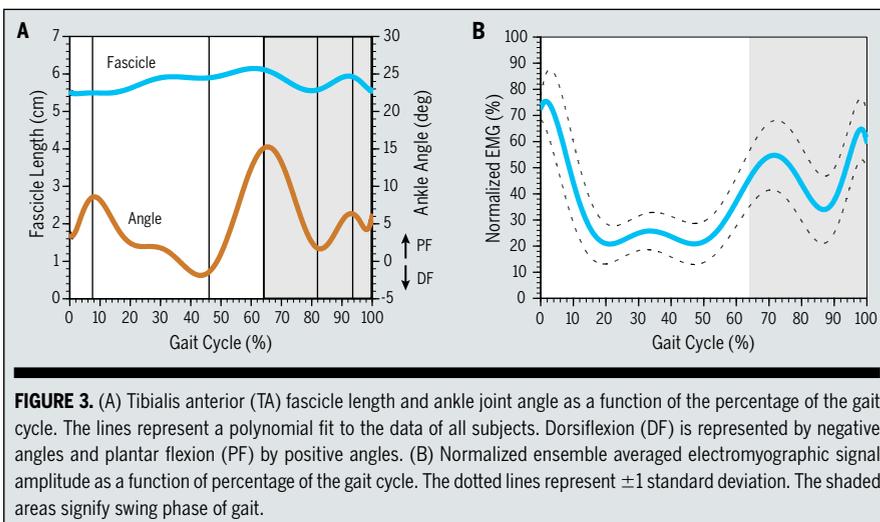
TABLE 2

## TIBIALIS ANTERIOR FASCICLE LENGTH AND ANKLE ANGLE AT EACH INTERVAL OF THE GAIT CYCLE

Gait Cycle (%)	Ankle Angle (°)	Fascicle (cm)
0	3.5 ± 5.2	5.47 ± 0.79
7	9.0 ± 3.3*	5.48 ± 0.99
46	-2.8 ± 4.3*	5.80 ± 1.08
64	19.7 ± 4.6*	6.24 ± 1.02*
82	2.2 ± 3.1*	5.50 ± 0.73*
94	6.7 ± 3.6*	5.81 ± 0.87
100	5.6 ± 3.5	5.61 ± 0.85

Positive angles represent plantar flexion and negative angles represent dorsiflexion.

\*Significantly different than the previous point in the gait cycle ( $P < .05$ )



**FIGURE 3.** (A) Tibialis anterior (TA) fascicle length and ankle joint angle as a function of the percentage of the gait cycle. The lines represent a polynomial fit to the data of all subjects. Dorsiflexion (DF) is represented by negative angles and plantar flexion (PF) by positive angles. (B) Normalized ensemble averaged electromyographic signal amplitude as a function of percentage of the gait cycle. The dotted lines represent  $\pm 1$  standard deviation. The shaded areas signify swing phase of gait.

a period of 5 to 10 seconds encompassing several strides. One stride from the middle of the series of strides for each subject was chosen for analysis. Although there is some stride-to-stride variability in the kinematics of gait, we found that the variability of knee and ankle angle was minimal, and therefore we chose to analyze only 1 stride.

Swing and stance phases of gait were identified by using foot switches to signify the time at which heel-strike and toe-off occurred. Stance phase took place from 0% to 63.9% ( $\pm 6.6\%$ ) of the gait cycle. For the TA, the ankle joint angle and the fascicle length were analyzed at 7 points of the gait cycle (0%, 7%, 46%, 64%, 82%, 94%, and 100%), corresponding to the points of maximum dorsiflexion and plantar flexion, as well as heel contact. For the VL, the knee joint angle

and the fascicle length were analyzed at 5 points of the gait cycle (0%, 15%, 42%, 75%, and 100%), corresponding to maximum knee flexion and extension as well as heel contact.

### Data Analysis

Descriptive statistics were calculated for ankle and knee angles, fascicle length, and EMG signal. A 1-way repeated-measures analysis of variance was performed to determine the differences in fascicle length and joint angle between each of the 7 points in the gait cycle for the TA and ankle joint and each of the 5 points in the gait cycle for the VL and knee joint. Multiple comparisons for significant main effects were analyzed using the least significant difference post hoc test. Significant changes were accepted at an alpha level of less than .05.

## RESULTS

### Reliability

INTRARATER RELIABILITY BASED ON ICC<sub>3,1</sub> for the fascicle length measurement from the ultrasound images was 0.93 for the TA and 0.90 for the VL. The standard error of the measurement was 0.06 cm for the TA and 0.10 cm for the VL. The coefficient of variation was 2.8% and 3.5% for the TA and the VL, respectively. The values for the reliability of our measurements compare favorably with the values reported by others who have measured the TA and the VL fascicle length.<sup>9,14,25,26</sup>

### Tibialis Anterior

The ankle joint angle was significantly different between each consecutive time point in the gait cycle except between 94% and 100% of the gait cycle (TABLE 2). On average the ankle plantar flexed 5.5° between heel contact and 7%, dorsiflexed 11.8° between 7% and 46%, plantar flexed 22.5° between 46% and 64%, dorsiflexed 17.5° between 64% and 82%, and plantar flexed 4.5° between (82% and 94% of the gait cycle (FIGURE 3A). Despite the significant changes in ankle joint angle that occurred throughout the gait cycle, the TA fascicle length changed significantly only between 46% and 64% (an average of 0.45 cm lengthening) and between 64% and 82% (an average of 0.75 cm shortening).

The TA had the highest EMG activity between 0% and 7%, between 64% and 82%, and between 94% and 100% of the gait cycle (FIGURE 3B). Toward the end of stance phase, the TA normalized EMG activity begins to increase and continues to be active until just before maximum dorsiflexion (82% of gait cycle).

### Vastus Lateralis

The knee joint angle was significantly different between each consecutive time in the gait cycle (TABLE 3). On average, the knee flexed 12.2° between heel contact and 15%, extended 12.1° between 15% and 42%, flexed 53.7° between 42% and 75%,

and extended 54.7° between 75% and 100% of the gait cycle (FIGURE 4A). The VL fascicle lengthened significantly (an average of 2.57 cm) between 42% and 75% and shortened significantly (an average of 2.64 cm) between 75% and 100% of the gait cycle; but the fascicle length did not change in the first and second portions of the gait cycle. The VL was active during the first portion of stance phase from heel contact to 15% of the gait cycle and at the end of swing phase from 85% to 100% of the gait cycle (FIGURE 4B).

## DISCUSSION

**T**HE TA AND THE VL ARE CRUCIAL FOR normal function during gait. The TA controls the lowering of the foot to the ground after heel contact to avoid foot slap, and it dorsiflexes the foot during swing phase to insure toe clearance. The VL controls knee flexion that occurs after heel contact and insures knee extension during terminal swing. This study confirms, as others have shown, that the TA and the VL are active during the expected phases of the gait cycle.<sup>7,8,31</sup> The change in fascicle length provides insight into the dynamics of muscle function and inferences can be made concerning the interaction between muscle fascicle and tendon length change during different phases of the gait cycle.

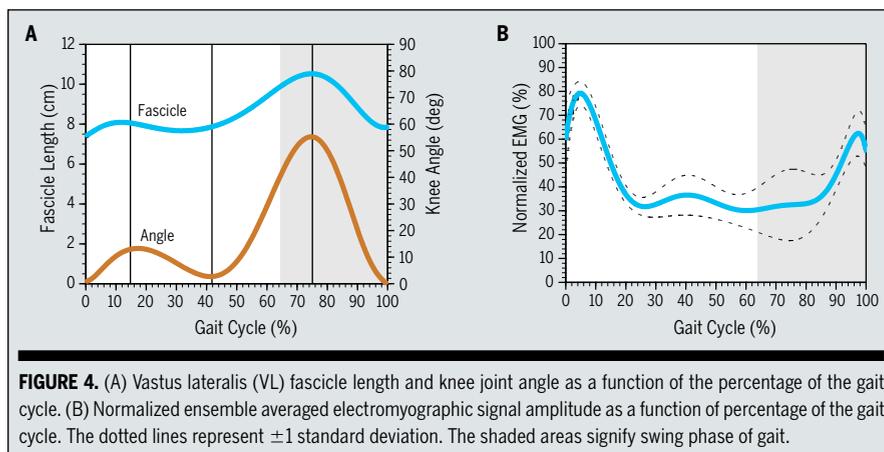
During the initial portions of the stance phase of gait, the ankle joint angle and the knee joint angle change significantly, the TA and the VL muscles are active, but the fascicle length of both muscles does not change significantly. As the ankle plantar flexes and the knee flexes, the assumption is that the TA and VL muscle-tendon complex of each muscle is lengthening, suggesting an eccentric muscle action. However, given the present data in which the muscle fascicles are remaining at constant length, the muscles are acting essentially isometrically. Therefore any lengthening of the muscle-tendon complex in the TA and VL is most likely due to the lengthening of the tendon and its extension into the muscle.

**TABLE 3**

**VASTUS LATERALIS FASCICLE LENGTH AND KNEE ANGLE AT EACH INTERVAL OF THE GAIT CYCLE**

Gait Cycle (%)	Knee Angle (°)	Fascicle (cm)
0	0.4 ± 5.8	751 ± 1.32
15	12.6 ± 4.4*	778 ± 1.28
42	0.5 ± 4.4*	791 ± 0.88
75	54.2 ± 2.0*	10.48 ± 1.14*
100	-0.5 ± 4.3*	784 ± 1.78*

*Positive angles represent knee flexion angles and negative angles represent hyperextension.  
\*Significantly different than the previous point in the gait cycle (P<.05).*



**FIGURE 4.** (A) Vastus lateralis (VL) fascicle length and knee joint angle as a function of the percentage of the gait cycle. (B) Normalized ensemble averaged electromyographic signal amplitude as a function of percentage of the gait cycle. The dotted lines represent ±1 standard deviation. The shaded areas signify swing phase of gait.

When the TA is active without joint motion, the tendon exhibits considerable displacement, resulting in fascicle shortening.<sup>17,27-29,32</sup> In addition, during isokinetic eccentric muscle actions, the TA muscle fascicles lengthen only slightly and are considered to be acting “quasi-isometrically.”<sup>36</sup> Therefore, during an eccentric action, the tendon compliance allows the muscle-tendon complex to lengthen and joint motion to occur.

The lack of fascicle shortening or lengthening during the first 7% of the gait cycle in the present study suggests that the TA attempts to store energy by allowing the tendon to lengthen while the muscle produces high forces isometrically. This proposed interaction is similar to the interaction that has been shown between the medial gastrocnemius and the Achilles tendon during countermovement jumps and during walking.<sup>10,16,18</sup> If a muscle-tendon complex stores energy while lengthening, the assumption is that the energy will be released to per-

form some useful function. In the case of the TA during walking, the function of the TA tendon may be related to its stiffness. The TA tendon has been reported to have a stiffness value of 161 N/mm, which was determined in response to electrical stimulation of the TA muscle.<sup>28</sup> The stiffness of the TA tendon alone is slightly higher than the combined stiffness of the dorsiflexor muscle group,<sup>6</sup> but remains within the toe region of the stress-strain relationship.<sup>6,29</sup> Although it is difficult to compare the tension during electrical stimulation<sup>6,28</sup> to the level of EMG signal during the first 7% of the gait cycle in the present study, the TA tendon and muscle stiffness (due to the increased EMG signal) may function to limit the amount of plantar flexion and therefore assist in maintaining forward momentum of the tibia during the heel rocker action at the ankle.

The assumption that the TA tendon lengthens during loading response may be affected by the compliance of the an-

terior retinaculum at the ankle. A significant change in TA moment arm between rest and maximum isometric voluntary contraction suggests that the retinaculum stretches, potentially resulting in less tendon elongation than would be expected.<sup>26</sup> Based on a 40% increase in moment arm at a neutral ankle position during a maximal isometric voluntary contraction, and estimates of resting tendon length,<sup>26</sup> tendon elongation would be decreased by approximately 1.6%. TA tendon and aponeurosis strain have been reported to be 4.8%,<sup>27</sup> so the effect of the retinaculum compliance is substantial during maximal actions. As noted, these measurements of retinaculum stretch were made at maximum isometric voluntary contraction, and the effect on tendon elongation at force levels less than maximum isometric voluntary contraction, such as those produced in walking, is most likely less.

Although the VL fascicle length change exhibits a similar pattern as the TA during the initial portions of the stance phase, the implications of the VL fascicle length change may be somewhat different than for the TA. The knee joint flexes about 12° from full extension and the VL muscle activity is at its highest level during the time from heel contact to 15% of the gait cycle. During the knee flexion phase of a drop jump, the knee flexes from 0° to 75°, with a corresponding lengthening of the VL fascicles of about 1.5 to 2.0 cm.<sup>14,15</sup> If the current change in fascicle length during the first 12° of knee flexion (about 0.25 cm) is extrapolated to the same range of motion as the drop jump, the fascicle length change during the loading response of gait is comparable to the amount seen in the drop jump. This suggests that we might be seeing the beginning of an eccentric action in loading response. Whether this is an isometric action or the beginning of an eccentric action is difficult to know and may not be as important as the potential tendon interaction. Because there is only a small (statistically nonsignificant) amount of VL fascicle lengthening in the

initial portion of stance, the VL tendon is most likely lengthening to account for the significant change in knee flexion, which is similar to what happens in the braking phase of a drop jump. With a larger sample size, the VL fascicle lengthening may have been significant. The VL fascicles lengthen somewhat in the drop jump, but the tendon lengthens to a greater degree, storing energy to be used in the subsequent push-off phase of the jump.<sup>14,15</sup> This suggests that the VL tendon may contribute to the storage of elastic strain energy in movements such as the drop jump and walking, and this stored energy could be used to assist with the subsequent knee extension. In addition, the potential tendon elongation may act as a mechanical buffer limiting the amount of fascicle lengthening and muscle injury from eccentric muscle action.<sup>12,23</sup>

The intensity of the activity may also affect the length of the VL fascicle. As the intensity of the drop jump increases, the fascicle lengthens less during the braking or knee flexion phase.<sup>14,15</sup> Although the tendon does not lengthen more with increasing intensity during the braking phase, the tendon does shorten more with increasing intensity during the push-off or knee extension phase of the drop jump.<sup>14,15</sup> There is some indication that the interaction of the fascicles and tendon may be muscle specific. The nature of this specificity is not necessarily known at this time, but may be due to factors such as intrinsic differences in tendon material properties<sup>14,15,19,28</sup> or that the VL is uniaxial and the TA is multiarticular.

During the stance phase of walking, it appears that the predominant type of muscle action is isometric in the TA, VL, and medial gastrocnemius,<sup>10,16</sup> despite muscle-tendon complex lengthening. By acting isometrically, the muscle has the potential to produce high forces based on the force-velocity relationship, to avoid muscle injury from eccentric actions, and to store energy through the elastic properties of the tendon. Because muscles produce higher forces and are sustaining greater strain during eccentric compared

to isometric actions, the muscle is more susceptible to injury during eccentric actions. The tendon compliance allows the muscle to limit some of its lengthening and possible subsequent muscle injury, but still maintain a relatively high potential force. On the other hand, eccentric exercises are commonly suggested as part of the rehabilitation of tendon injuries.<sup>37</sup> Because it is possible that there is substantial strain on the tendon during eccentric muscle actions, eccentric exercises should be used with caution at certain stages of healing to avoid re-injuring the tendon. Based on the current data and that of others, one could argue that isometric exercises (which result in tendon strain) could be effectively used in rehabilitation of tendon injuries. This may be an appropriate first step in the rehabilitation of tendon injuries prior to the initiation of eccentric exercises.

There are 2 possible mechanisms for energy storage in the tendon. Fukunaga et al<sup>10</sup> have proposed a spring-like mechanism that accounts for the energy storage in the Achilles tendon, whereas Ishikawa et al<sup>16</sup> have proposed that the energy storage occurs as the result of a catapult action because of the slow cycle time and long ground contact time in gait. Additionally, it has been suggested that the sarcomeric elastic protein titin may play a role as a muscular spring during eccentric actions.<sup>24</sup> Whichever mechanism is at work, the end result is that the joint motion at the knee and ankle during stance phase appears to occur because of a change in length of the tendon rather than the muscle fascicle.

Toward the end of stance phase, the ankle plantar flexes and the knee flexes. The TA muscle activity is minimal until the very end of stance, where the activity begins to increase in preparation for toe-off. The VL, on the other hand, continues to have minimal activity throughout the end of stance phase. The fascicle length of both the TA and VL increases during this portion of the stance phase primarily due to the passive lengthening of the muscle-tendon complex. The exception to this is

the increase in TA activity toward the end of stance that could attenuate the amount of the lengthening of the TA fascicle.

Just prior to the beginning of swing phase, the TA EMG activity increases and remains high as the ankle dorsiflexes and the TA fascicles shorten, confirming that during this unloaded motion of the ankle the TA muscle action is concentric. The TA fascicle shortens from 6.24 to 5.50 cm during the initial swing phase (from nearly 20° to 2° of plantar flexion), which is comparable to the values reported for isokinetic concentric actions at 50°/s (5.4 cm at 8° of plantar flexion).<sup>36</sup> The TA fascicle lengths in the present study are slightly longer than those reported by Reeves and Narici<sup>36</sup> and could be due to a lower muscle force during walking than during maximal isokinetic actions. This lower muscle force may be due to a low external torque (only the effect of gravity on the foot), and the higher angular velocity (95°/s) during the concentric action in gait, resulting in lower muscle force.<sup>36</sup>

During the latter portion of the swing phase (75%-100%) corresponding to terminal swing, the knee extends from about 55° of flexion to 0° and the VL muscle activity increases only in the last 15% of swing. The VL fascicles begin to shorten prior to the increase of muscle activity, suggesting that the change in fascicle length is primarily a function of passive knee motion until the last 15% of swing phase. The 2.64-cm fascicle shortening seen in this portion of swing phase is slightly less than the 3.0-cm changes seen during isokinetic concentric muscle actions.<sup>9,13</sup> This discrepancy could be because of the smaller range of motion (55°-0° versus 90°-20°), higher angular velocity of motion (260°/s versus 150°/s), or less muscle force during gait than during maximal isokinetic testing. It is interesting that the knee flexes and extends equally about 54° and the VL fascicle length change is nearly identical in both flexion and extension. This would suggest that there is no interaction between the muscle and the tendon during this

unloaded motion of the knee. Therefore, the muscle-tendon complex shortening is accounted for by the fascicle shortening that is initially passive and then becomes an active concentric action. The knee flexion that occurs in the early portion of swing lengthens the largely passive VL, thus potentially stretching the elastic protein titin, which could assist in the beginning of knee extension in the same manner that titin augments myocardial contraction.<sup>11</sup>

Although there was very little EMG activity during the majority of the stance phase in either the TA or the VL, the normalized EMG baseline levels are relatively higher than would be expected (20%-30% of the dynamic maximum) during gait. There are 2 factors that potentially could account for the higher baseline. First, the EMG was normalized to the maximum activity during the gait cycle. Because the maximum EMG activity during gait is relatively low compared to a maximum isometric action, the baseline activity would be amplified. Second, the electrodes were not placed over the center of the muscle. This would most likely decrease the amplitude of the EMG signal during muscle contraction, but not affect the baseline noise during periods when the muscle is relaxed, and therefore increase the normalized baseline EMG activity. As a comparison, our EMG data for the VL are similar to data in which dynamic maximum normalization was compared to other methods of normalization, including maximum voluntary isometric contraction.<sup>3</sup>

The accuracy of fascicle length measurements using ultrasound imaging during motion is limited by the ability to maintain the transducer in the plane of the fascicle as the muscle changes shape during motion. If the transducer is not in the plane of the fascicle, the measurement will underestimate the actual length of the fascicle. In addition, the interpretation of the type of muscle action based on fascicle length changes is limited by the fact that fascicle length changes may not accurately represent sarcomere length

changes. For example, a lack of change in fascicle length may be the sum of random shortening and lengthening of serial sarcomeres. Although the number of subjects in this study was small and consisted of only young healthy college age participants, thus limiting the generalizability of the results, the results are consistent with other studies using similar methodology.

## CONCLUSION

**T**HE TA AND VL APPEAR TO ACT nearly isometrically during the beginning of stance phase, despite a change in joint angle corresponding to a potential lengthening of the muscle-tendon complex. During swing phase of gait, the TA and VL fascicles shorten as the ankle dorsiflexes and the knee extends, suggesting a concentric action. The isometric action of the TA and VL during stance phase allows the muscles to produce high forces, avoid injury from eccentric actions, and to store potential energy in the tendon that can then be used to decrease the energy demands of walking.

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## REFERENCES

1. Alexander RM, Bennet-Clark HC. Storage of elastic strain energy in muscle and other tissues. *Nature*. 1977;265:114-117.
2. Basmajian J, DeLuca C. *Muscles Alive: Their functions Revealed by Electromyography*. Baltimore, MD: Williams & Wilkins; 1985.
3. Burden AM, Trew M, Baltzopoulos V. Normalisation of gait EMGs: a re-examination. *J Electromyogr Kinesiol*. 2003;13:519-532.
4. Butler DL, Grood ES, Noyes FR, Zernicke RF. Biomechanics of ligaments and tendons. In: Hutton RS, ed. *Exercise and Sports Science Reviews*. Philadelphia, PA: The Franklin Institute Press; 1978.
5. Chleboun GS, France AR, Crill MT, Braddock HK, Howell JN. In vivo measurement of fascicle

- length and pennation angle of the human biceps femoris muscle. *Cells Tissues Organs*. 2001;169:401-409.
6. De Zee M, Voigt M. Assessment of functional series elastic stiffness of human dorsiflexors with fast controlled releases. *J Appl Physiol*. 2002;93:324-329.
  7. den Otter AR, Geurts AC, Mulder T, Duysens J. Speed related changes in muscle activity from normal to very slow walking speeds. *Gait Posture*. 2004;19:270-278.
  8. Dubo HI, Peat M, Winter DA, et al. Electromyographic temporal analysis of gait: normal human locomotion. *Arch Phys Med Rehabil*. 1976;57:415-420.
  9. Finni T, Ikegawa S, Lepola V, Komi PV. Comparison of force-velocity relationships of vastus lateralis muscle in isokinetic and in stretch-shortening cycle exercises. *Acta Physiol Scand*. 2003;177:483-491.
  10. Fukunaga T, Kubo K, Kawakami Y, Fukashiro S, Kanehisa H, Maganaris CN. In vivo behaviour of human muscle tendon during walking. *Proc Biol Sci*. 2001;268:229-233.
  11. Granzier H, Labeit S. Cardiac titin: an adjustable multi-functional spring. *J Physiol*. 2002;541:335-342.
  12. Griffiths RI. Shortening of muscle fibres during stretch of the active cat medial gastrocnemius muscle: the role of tendon compliance. *J Physiol*. 1991;436:219-236.
  13. Ichinose Y, Kawakami Y, Ito M, Kanehisa H, Fukunaga T. In vivo estimation of contraction velocity of human vastus lateralis muscle during "isokinetic" action. *J Appl Physiol*. 2000;88:851-856.
  14. Ishikawa M, Finni T, Komi PV. Behaviour of vastus lateralis muscle-tendon during high intensity SSC exercises in vivo. *Acta Physiol Scand*. 2003;178:205-213.
  15. Ishikawa M, Komi PV. Effects of different dropping intensities on fascicle and tendinous tissue behavior during stretch-shortening cycle exercise. *J Appl Physiol*. 2004;96:848-852.
  16. Ishikawa M, Komi PV, Grey MJ, Lepola V, Bruggermann GP. Muscle-tendon interaction and elastic energy usage in human walking. *J Appl Physiol*. 2005;99:603-608.
  17. Ito M, Kawakami Y, Ichinose Y, Fukashiro S, Fukunaga T. Nonisometric behavior of fascicles during isometric contractions of a human muscle. *J Appl Physiol*. 1998;85:1230-1235.
  18. Kawakami Y, Muraoka T, Ito S, Kanehisa H, Fukunaga T. In vivo muscle fibre behaviour during counter-movement exercise in humans reveals a significant role for tendon elasticity. *J Physiol*. 2002;540:635-646.
  19. Kubo K, Kawakami Y, Fukunaga T. Influence of elastic properties of tendon structures on jump performance in humans. *J Appl Physiol*. 1999;87:2090-2096.
  20. Kurokawa S, Fukunaga T, Fukashiro S. Behavior of fascicles and tendinous structures of human gastrocnemius during vertical jumping. *J Appl Physiol*. 2001;90:1349-1358.
  21. Kurokawa S, Fukunaga T, Nagano A, Fukashiro S. Interaction between fascicles and tendinous structures during counter movement jumping investigated in vivo. *J Appl Physiol*. 2003;95:2306-2314.
  22. Lieber RL. *Skeletal Muscle Structure, Function, and Plasticity*. Baltimore, MD: Lippincott, Williams & Wilkins; 2002.
  23. Lieber RL, Friden J. Muscle damage is not a function of muscle force but active muscle strain. *J Appl Physiol*. 1993;74:520-526.
  24. Lindstedt SL, Reich TE, Keim P, LaStayo PC. Do muscles function as adaptable locomotor springs? *J Exp Biol*. 2002;205:2211-2216.
  25. Maganaris CN, Baltzopoulos V. Predictability of in vivo changes in pennation angle of human tibialis anterior muscle from rest to maximum isometric dorsiflexion. *Eur J Appl Physiol Occup Physiol*. 1999;79:294-297.
  26. Maganaris CN, Baltzopoulos V, Sargeant AJ. Changes in the tibialis anterior tendon moment arm from rest to maximum isometric dorsiflexion: in vivo observations in man. *Clin Biomech (Bristol, Avon)*. 1999;14:661-666.
  27. Maganaris CN, Paul JP. In vivo human tendinous tissue stretch upon maximum muscle force generation. *J Biomech*. 2000;33:1453-1459.
  28. Maganaris CN, Paul JP. In vivo human tendon mechanical properties. *J Physiol*. 1999;521 Pt 1:307-313.
  29. Maganaris CN, Paul JP. Load-elongation characteristics of in vivo human tendon and aponeurosis. *J Exp Biol*. 2000;203:751-756.
  30. Magnusson SP, Aagaard P, Dyhre-Poulsen P, Kjaer M. Load-displacement properties of the human triceps surae aponeurosis in vivo. *J Physiol*. 2001;531:277-288.
  31. Milner M, Basmajian JV, Quanbury AO. Multifactorial analysis of walking by electromyography and computer. *Am J Phys Med*. 1971;50:235-258.
  32. Muramatsu T, Muraoka T, Takeshita D, Kawakami Y, Fukunaga T. In vivo mechanical properties of proximal and distal aponeuroses in human tibialis anterior muscle. *Cells Tissues Organs*. 2002;170:162-169.
  33. Muramatsu T, Muraoka T, Takeshita D, Kawakami Y, Hirano Y, Fukunaga T. Mechanical properties of tendon and aponeurosis of human gastrocnemius muscle in vivo. *J Appl Physiol*. 2001;90:1671-1678.
  34. Murray MP. Gait as a total pattern of movement. *Am J Phys Med*. 1967;46:290-333.
  35. Perry J. *Gait Analysis: Normal and Pathological Function*. Thorofare, NJ: Slack; 1992.
  36. Reeves ND, Narici MV. Behavior of human muscle fascicles during shortening and lengthening contractions in vivo. *J Appl Physiol*. 2003;95:1090-1096.
  37. Stanish WD, Rubinovich RM, Curwin S. Eccentric exercise in chronic tendinitis. *Clin Orthop Relat Res*. 1986;65-68.
  38. Whittle M. *Gait Analysis: An Introduction*. Oxford, UK: Butterworth-Heinemann; 2002.

