Eccentric Exercise

Muscle fascicle strains in human gastrocnemius during backward downhill walking

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Hoffman BW, Cresswell AG, Carroll TJ, Lichtwark GA. Muscle fascicle strains in human gastrocnemius during backward downhill walking. J Appl Physiol 116: 1455–1462, 2014. First published April 4, 2013; doi:10.1152/japplphysiol.01431.2012.—Extensive muscle damage can be induced in isolated muscle preparations by performing a small number of stretches during muscle activation. While typically these fiber strains are large and occur over long lengths, the extent of exercise-induced muscle damage (EIMD) observed in humans is normally less even when multiple high-force lengthening actions are performed. This apparent discrepancy may be due to differences in muscle and tendon dynamics in vivo; however, muscle and tendon strains have not been quantified during muscle-damaging exercise in humans. Ultrasound and an infrared motion analysis system were used to measure medial gastrocnemius fascicle length and lower limb kinematics while humans walked backward, downhill for 1 h (inducing muscle damage), and while they walked briefly forward on the flat (inducing no damage). Supramaximal tibial nerve stimulation, ultrasound, and an isokinetic dynamometer were used to quantify the fascicle length-torque relationship pre- and 2 h postexercise. Torque decreased ~23%, and optimal fascicle length shifted rightward ~10%, indicating that EIMD occurred during the damage protocol even though medial gastrocnemius fascicle stretch amplitude was relatively small (~18% of optimal fascicle length) and occurred predominantly within the ascending limb and plateau region of the length-torque curve. Furthermore, tendon contribution to overall muscle-tendon unit stretch was ~91%. The data suggest the compliant tendon plays a role in attenuating muscle fascicle strain during backward walking in humans, thus minimizing the extent of EIMD. As such, in situ or in vitro mechanisms of muscle damage may not be applicable to EIMD of the human gastrocnemius muscle.

While it is known that a single bout of unaccustomed, eccentric exercise can cause muscle damage (exercise-induced muscle damage (EIMD)), there are limited data on the muscle mechanics that lead to EIMD in humans under natural conditions. Much of our mechanistic understanding of EIMD has been established from nonhuman experiments, in which single muscle fibers in vitro, or isolated muscles in situ, were stretched under electrical activation (9, 10). Experiments of this kind usually involve a small number of fiber stretches (as few as 1–10), high muscle stimulation frequencies (producing up to 100% of maximal force), large stretch amplitudes (up to 60% of optimal length \((L_o)\), and a range of fiber lengths corresponding to the descending limb of the length-tension curve (up to ~70% longer than \(L_o\)). The literature indicates that the force production of fibers exposed to such protocols can be reduced by ~40–80% (3–7, 24, 31, 35, 36, 59), with immediate and extensive structural damage to the sarcomeres (4, 7, 51).

Although most current ideas regarding the mechanisms of EIMD (such as the “popping sarcomere hypothesis”; Ref. 40) have been derived from, or supported by, in situ or in vitro experiments, it is not clear whether the nature or mechanisms of damage in these contexts are comparable to muscle damage that occurs in vivo (10). For example, the force decrements observed in vivo are typically less than those observed in situ or in vitro, even when the level of muscle activation is maximal (9, 41), when long muscle-tendon unit (MTU) lengths are used (9, 41), or when thousands of contractions are performed (26). Nonhuman in vivo studies have shown that multiple lengthening contractions (~20–70) produce immediate reductions in force in the range of 25–55% (9, 14, 18, 57). In humans, the decrease in maximum force production due to EIMD is similarly less, ranging between ~10 and 50%, with the decrements in force typically peaking 24 to 48 h postexercise (26, 37–39, 41, 42). The smaller magnitude and the delay in peak force decrement occurs even when thousands of contractions are performed, or if the lengthening contractions are performed at maximal intensities (26, 41). Furthermore, the appearance of extensive structural damage to muscle fibers in vivo appears to occur ~1–4 days postexercise rather than immediately after as observed in situ or in vitro (11, 27, 50). Thus the characteristics of muscle damage experienced in vivo may be different from those experienced in situ or in vitro.

In addition to differences in the nature of muscle damage between isolated muscle preparations and in vivo human exercise, there may be fundamental differences in the muscle fiber dynamics during active lengthening in these contexts (10). The amplitude and rate of changes in muscle fiber length produced in situ and in vitro closely mimic the externally imposed stretches, as either the fibers have been completely removed from the muscle or the tendon has been cut. In contrast, during exercise such as walking, changes in muscle fiber length do not necessarily follow changes in MTU length \((L_{MTU})\) due to the compliance of the in-series tendinous tissue (16, 19, 22, 29). As a consequence, it is possible that, under natural conditions, both the amplitude and rate of stretch of fibers will differ from the amplitude and rate of stretch of the MTU. While it has been established that tendon plays a role in

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regulating muscle fiber length in vivo (13, 30, 47), the relationship between muscle fiber and tendon length changes during a bout of EIMD in humans is unknown.

A classic EIMD experimental design used to damage the human triceps surae is backward downhill walking (26, 27, 55). Compared with forward walking, where little or no muscle damage is experienced, prolonged backward, downhill walking causes substantial damage to the triceps surae, highlighted by a drop in maximal plantar flexion torque production, changes in the plantar flexion torque-angle curve, and muscle soreness occurring 24 to 48 h postexercise (21, 26, 27, 55, 56). This damage is presumably caused by active stretch of the triceps surae muscle fibers. Interestingly, the lower limb kinematics and kinetics of backward walking are remarkably similar to those of forward walking; however, the order of events occurs in a reverse time sequence (25, 53). Hence, it could be hypothesized that muscles that generate positive work during forward walking generate negative work in backward walking and vice versa. This claim has recently been supported by simulations examining the role of the lower limb muscles during backward walking (25). Given that the soleus muscle fascicles work over the ascending limb of the length-tension curve during forward walking, it seems likely that triceps surae fascicle shortening also occurs within the ascending limb during backward walking (48). However, length changes in the muscle fascicles and tendon of the triceps surae have never been examined in humans during backward downhill walking in vivo, nor has it been determined over which range of the length-tension relationship fascicle strain occurs.

The aim of this study was to quantify muscle fascicle and tendon dynamics of the human gastrocnemius during prolonged backward downhill walking. We hypothesized that backward downhill walking would result in muscle damage through repeated stretch of the muscle fascicles during the stance phase. We further postulated that the strains experienced by muscle fascicles would be much lower than those typical for in vitro and in situ EIMD preparations, due to the compliance by muscle fascicles that generate positive work during forward walking and generate negative work during backward walking. The role of the lower limb muscles during backward walking; however, the order of events occurs in a reverse time sequence (25, 53). Hence, it could be hypothesized that muscles that generate positive work during forward walking generate negative work in backward walking and vice versa. This claim has recently been supported by simulations examining the role of the lower limb muscles during backward walking (25). Given that the soleus muscle fascicles work over the ascending limb of the length-tension curve during forward walking, it seems likely that triceps surae fascicle shortening also occurs within the ascending limb during backward walking (48). However, length changes in the muscle fascicles and tendon of the triceps surae have never been examined in humans during backward downhill walking in vivo, nor has it been determined over which range of the length-tension relationship fascicle strain occurs.

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**METHODS**

*Subjects.* Ten male subjects (21.5 ± 1.5 yr, 82 ± 27 kg, 1.84 ± 0.14 m), who provided written, informed consent, volunteered to participate in this study. All subjects were healthy, had no history of neuromuscular disease or illness, and were not participating in regular, strenuous exercise. The protocol was approved by a local university ethics committee and conducted according to the Declaration of Helsinki.

Length-tension relationship experimental setup. Length-tension data were collected immediately before the walking tasks, as well as 2-h after the completion of the 1-h backward walking protocol. The 2-h wait before retesting the length-tension relationship was imposed to avoid the effects of muscle fatigue (54). The data were collected according to a protocol similar to that detailed in Hoffman et al. (23). In brief, subjects had their foot attached to an isokinetic dynamometer (Biodex System 3 Pro, Biodex Medical Systems, Shirley, NY) that rotated the ankle from the neutral ankle position to maximum dorsiflexion. Ankle joint angle position was recorded from the dynamometer, and the signal was low-pass filtered at 9 Hz and converted using a 16-bit analog-to-digital converter at 1 kHz (Power 1401, Cambridge Electronic Design). Plantar flexion torque was also measured from the dynamometer with the signal low-pass filtered at 5 Hz and analog-to-digital converted at 1 kHz (Power 1401, Cambridge Electronic Design).

Simultaneously, MG muscle fascicle length was measured using a 96-element, multifrequency ultrasound transducer (LV7.5/60/96, Telemed, Vilnius, Lithuania) attached to a PC-based ultrasound system (EchoBlast 128, UAB, Telemed). The location of the transducer on the leg was determined such that it provided the clearest image of continuous MG muscle fascicles, and the location on the skin was marked with indelible pen. The images were captured at a mean frequency of 6 MHz, a field of view of 60 × 65 mm, a focus range of 18–26 mm in B-mode, and at a frame rate of 80 frames/s using software (EchoWave II, Telemed). After the images were captured, a tracking algorithm implemented in Matlab (Mathworks) was used to measure muscle fascicle length during each peripheral nerve stimulation (17). 

Peripheral nerve stimulation. To determine the torque produced at each muscle length or joint angle, supramaximal peripheral nerve stimulation (pulse width = 500 µs) was applied using a double-pulse stimulation technique (interstimulus interval = 20 ms) to the tibial nerve with the subject at rest. Using a constant-current stimulator (DSTAH, Digitimer), current was passed from a cathode (Ag-AgCl electrode, 24 mm diameter; Tyco Healthcare Group) placed on the optimal site of stimulation within the popliteal fossa to an anode (Ag-AgCl electrode, 24 mm diameter; Tyco Healthcare Group) positioned proximal to the cathode on the midline of the popliteal fossa. The stimulation-evoked resting torque twitches were measured as the difference between the peak value of the twitch and the torque directly preceding the twitch. The current value used for each subject was set at 50% greater than the minimum current required to evoke the maximum torque (T max) twitch at rest.

Length-tension data collection protocol. Length-tension data were collected by applying stimulations at 12–16 preselected joint angles across the subject’s range of motion. To minimize any thixotropic effects, the subject performed a small, brief plantar flexion contraction before each stimulation (46). This process was repeated three times randomly at each joint angle for a total of 36–48 stimulations.

Length-tension curve construction. To quantify the length-tension relationship before and after the eccentric exercise bout, we used the same based method outlined in Hoffman et al. (23) that assumes that the parallel elastic component lies in parallel only with the contractile element (23, 32). The protocol and method for constructing the length tension curve in this way has been shown to be consistent and reliable across different sessions (23). As such, active torque was calculated as the difference between the total torque during the stimulation (i.e., the peak of the twitch) and the passive torque during the contraction. To determine this passive torque, the passive length-torque (L-T) curve was first determined, and then the passive value was estimated that corresponded to the shortest fascicle length to which the muscle contracts during each contraction. Once active torque was calculated and then plotted against fascicle length, second-order exponential curves were fit for each subject according to previous physiologically appropriate models (2, 43):

\[ T_{active} = e^{-\left(\frac{L-a}{b}\right)^k} \]  

(1)

where \( T \) is torque, \( L \) is fascicle length, \( a \) is roundness, \( b \) is skewness, and \( s \) is width. Passive L-T curves were also constructed by fitting a standard exponential expression:

\[ T_{passive} = A e^{(L-L_0)} \]  

(2)

where \( A \) is curvature, \( k \) is stiffness of the curve, and \( L_0 \) is the slack length (or slack angle when angle-torque data is fit). To determine the
Eccentric exercise experimental setup. A four-camera, infrared motion analysis system (Qualysis AB, Gothenburg, Sweden) was used to measure the kinematics of the left leg during walking. Single reflective spherical markers (diameter = 1 cm) were placed on the greater trochanter, medial and lateral femoral epicondyles, medial and lateral malleoli, and the head of the first and fifth metatarsals, while marker clusters (groups of 3–4 markers) were attached to the lateral aspect of the thigh and shank and on the dorsal aspect of the foot. The position of the markers was sampled at 200 Hz using computer software (Qualysis Track Manager, Qualysis, Gothenburg, Sweden) and analyzed offline (Visual 3D, C-Motion). At the same time, MG fascicle length was measured using the same equipment and process detailed above.

Eccentric exercise protocol. Before performing the muscle-damaging walking protocol, subjects were required to perform a 1-min bout of forward flat walking on a motorized treadmill (Austredex, Melbourne, Australia). After this short bout, subjects walked backward at 6 km/h, downhill at an angle of 13°, for 1 h while they carried 10% of their body mass in a backpack. Prolonged backward downhill walking has been shown to induce muscle damage within the triceps surae (26, 27). The high speed and inclination of the treadmill were chosen to ensure that triceps surae muscles underwent high-force eccentric contractions while walking backward.

For the 1-min forward-walking bout, muscle fascicle length and kinematic data were collected over a 10-s period during the middle of the bout. This ensured that subjects were walking comfortably on the treadmill before data were collected, and that six to eight complete stride cycles were sampled. For the 1-h backward downhill walking bout, data were collected similarly during the 1st and 60th min of the task. Measurements were also taken at 15, 30, and 45 min into the 1-h walking task; however, these measurements did not provide any additional insights into MG fascicle behavior during this task, and thus, for clarity, they were subsequently removed from RESULTS.

Data analysis. For every 10-s window of ultrasound data that was collected during the walking tasks, the MG fascicle length, pennation angle, and the knee and ankle joint angles were determined from the average of the six to eight strides captured during that window. Muscle fascicle length and pennation angle were measured from the ultrasound recording using a semiautomated algorithm that has been shown to reliably track muscle fascicle length changes during gait (12). Fascicle length data were then converted and accessed by Visual 3D to allow analysis between muscle parameters and kinematic variables.

Normative $L_{MTU}$ was determined using the following regression equation from previous literature:

$$L_{MTU} = C_0 + C_2 \beta + C_4 \phi$$  \hspace{1cm} (3)

where $C_0$, $C_2$, and $C_4$ are correlation coefficients (0.9, -0.00062, and 0.00214, respectively) determined by Hawkins and Hull (20), and $\beta$ and $\phi$ are the measured flexion joint angles of the knee and ankle, respectively. To determine the estimated MG $L_{MTU}$, the normative $L_{MTU}$ was then multiplied by the shank length of each subject (20).

Series elastic element (SEE) length, which represents all elastic tissue in series with the muscle fascicles, including tendon and aponeurosis, was calculated according to a previously published model (16):

$$L_{SEE} = L_{MTU} - L_{FAS} \times \cos \theta$$  \hspace{1cm} (4)

where $L_{MTU}$ is the MG $L_{MTU}$ calculated from Eq. 1 above, $L_{FAS}$ is the measured fascicle length, and $\theta$ is the measured pennation angle relative to the line of action of the force (horizontal to the image plane).

In RESULTS, fascicle, MTU, and SEE length are sometimes presented relative to the passive $L_s$. The $L_s$ values were determined from the length-tension data collected at baseline. For fascicle $L_s$, this value was determined from the baseline passive fascicle L-T curve (see Eq. 2 above), $MTU L_s$ was calculated using Eq. 3 above, where $\beta$ is the slack angle of the knee (5° flexion), and $\phi$ was the slack angle of the ankle determined from the baseline passive angle-torque curve (see Eq. 2 above). $SEE L_s$ was calculated using Eq. 4 above, where $\theta$ is the slack pennation angle determined from the linear fit between pennation angle and fascicle length. For each walking condition, fascicle, SEE, and MTU stretch amplitude were calculated as the difference between maximum length and minimum length while the SEE was lengthening during the stance phase (i.e., while tendon force was increasing). For backward walking, this typically occurred from approximately toe strike to ~30% of the stride cycle. For forward walking, this typically occurred between ~10% and ~50% of the stride cycle.

Statistical analysis. From the fitted L-T curves, the $T_{max}$, the muscle fascicle length at which $T_{max}$ occurs (i.e., $L_0$), $L_s$, and passive curvature ($k$ and $A$) were determined. Dependent t-tests were used to compare these variables between baseline and 2 h postexercise and were also used to compare muscle and tendon stretch parameters (e.g., fascicle, MTU, SEE stretch amplitude, and velocity) in forward and backward flat walking. From the ultrasound length data, dependent t-tests were performed to examine how fascicle, MTU, and SEE peak length during stretch changed during the 1-h backward walking exercise. The Spearman ranked correlation coefficient was calculated to determine the relationship between the drop in $T_{max}$ 2 h postexercise and the maximum fascicle stretch length during the beginning of 1-h backward, downhill walking. All group data presented in RESULTS are presented as means ± SD. The shaded area in Figs. 3 and 5 indicates the SE of the mean. Significant differences were established at $P \leq 0.05$.

RESULTS

Identifying the presence of EIMD. To determine whether EIMD occurred, the shape of the active and passive L-T curves was compared between pre- and 2 h postexercise (Fig. 1). Significant differences were found for $T_{max}$ ($P \leq 0.05$ and $L_0$ ($P \leq 0.05$), where $T_{max}$ decreased ~23% and $L_0$ increased ~10% between pre- and 2 h post-backward downhill walking (Table 1). However, there was no change in the shape of the passive L-T curve with no significant differences detected in passive stiffness ($P = 0.54$), passive curvature ($P = 0.19$), or $L_s$ ($P = 0.92$; Table 1). While there was little change in the passive L-T curve, changes in the active L-T curve are consistent with the presence of EIMD.

![Fig. 1. Mean active and passive length-torque (L-T) curves before (solid line) and 2 h after (dashed line) 1-h backward downhill walking. Indications of the standard deviations can be found in Table 1.](http://jap.physiology.org/doi/10.1152/japplphysiol.01431.2012)
Fascicle length working ranges relative to the L-T curve. Figure 2A provides an example of how the calculated group mean active and passive L-T curves were fit through individual L-T data points. Also shown is the average fascicle length working range while the MTU is lengthening for both backward downhill walking and forward flat walking, along with horizontal error bars (SE) indicating the variance in the minimum and maximum fascicle lengths during the stretch of the fascicles in early stance. Figure 2B shows group mean active and passive L-T curves and working fascicle ranges for backward and forward walking before damage occurring. For backward downhill walking, the fascicle stretched from the ascending limb to the plateau region, and in some cases to the descending limb. For forward flat walking, the fascicle shortened from the descending limb to the plateau region. This shows that the fascicle operated at lengths primarily over the ascending limb and plateau region for backward downhill walking. Furthermore, when the working ranges of backward downhill walking at the end of the 1-h exercise bout and forward flat walking postexercise are superimposed onto the 2-h postexercise L-T curve, it can be seen that the fascicles now work over a range that is at a shorter length compared with before the 1-h exercise bout (Fig. 2C).

Over the period of the 1-h backward, downhill walking task, changes in peak length during stretch were analyzed to determine whether the extent of fascicle stretch was altered during the muscle damage protocol (Fig. 3). There was no significant change in peak length during stretch found for fascicle ($P = 0.52$), MTU ($P = 0.54$), or SEE ($P = 0.25$) between the 1st and 60th min of the backward, downhill walking task (Table 2). This suggests that the fascicles were not stretched to longer lengths over the duration of the muscle damage task.

To determine whether there was a length dependency of the muscle damage incurred by the subjects, the drop in $T_{\text{max}}$ experienced by each subject 2-h postexercise was plotted against the maximum fascicle stretch length during the start of 1-h backward, downhill walking (Fig. 4). There was no significant correlation found between the two variables ($r = 0.13, P = 0.74$). As such, this suggests that the fascicle working length range had no effect on the presence and amount of muscle damage experienced by the subjects.

Muscle fiber and tendon dynamics before EIMD. Mean fascicle length during the gait cycle is shown in Fig. 5 for forward flat walking and backward flat walking before the muscle damage protocol, as well as for during the first minute of backward downhill walking (i.e., before damage has occurred). The forward walking trace has been reversed in time to allow for comparison of reverse muscle function (53). Although the fascicle length traces appear to show a greater strain experienced by the fascicle during the initial part of the stance phase during backward downhill walking compared with backward flat walking, this difference was not significant ($P = 0.21$; Table 2). Furthermore, there were no significant differences between backward downhill walking and backward flat walking during the stance phase for MTU and SEE strain ($P = 0.96$ and 0.6, respectively). Similarly, there was no difference in the rate of stretch during the stance phase for fascicle, MTU, or SEE between backward downhill walking and backward flat walking ($P = 0.66, 0.67, 0.94$, respectively; Table 2).

The amplitude of SEE stretch during the initial stance phase of backward, downhill walking was compared with fascicle stretch to identify their relative contribution to total MTU stretch (Fig. 3, A–C). The amplitude of fascicle stretch was 10.77 $\pm$ 4.18 mm ($\sim 18\% L_o$), while for the SEE the stretch amplitude was 38.74 $\pm$ 9.41 mm. Compared with the stretch amplitude of the MTU (42.56 $\pm$ 9.56 mm), and accounting for the pennation angle of the muscle fascicles, the tendon contributed 91.02% to the stretch of the MTU at the beginning of backward, downhill walking. Further to this, the time at which maximum fascicle length occurs during the stride cycle was compared with MTU to identify changes in the rate of stretch (Fig. 3). For MTU, peak stretch length occurred at 26 $\pm$ 3% of stride time, which was significantly less than fascicle peak stretch length that occurred at 37 $\pm$ 3% of stride time ($P \leq 0.05$). This indicates that the muscle fascicles continued to absorb mechanical work, while the MTU and SEE were shortening.

**DISCUSSION**

The present study investigated human in vivo muscle mechanics of the MG before, during, and after 1 h of backward, downhill walking. The 23% drop in $T_{\text{max}}$ and 10% increase in the $L_o$ for torque production observed 2 h postexercise indicate that the task induced muscle damage, since most, if not all, fatigue-related force decrements typically recover within this time frame (15, 49, 54). We believe that this is the first documentation of muscle fascicle length changes during exercise that induces muscle damage in humans. Importantly, damage occurred in response to low-amplitude muscle fascicle stretches ($\sim 18\%$), and fascicle lengths appeared to operate predominantly on the ascending limb and plateau region. While some participants reached a peak stretch on the descending limb of the L-T curve, there was no relationship between the maximum stretch length and the amount or presence of EIMD. In contrast, the SEE experienced much larger strains ($\sim 90\%$ of total MTU strain), which suggests that compliant tendons play a major role in minimizing damage to the muscle by buffering much of the overall MTU stretch (2). This mechanism may be critical in allowing muscles to absorb mechanical work effectively without adverse muscle strains. These conditions contrast markedly with those in typical reduced muscle preparations, which suggests that mechanisms of damage revealed in vitro or in situ may not be applicable to...
intact human muscles with compliant tendons. This may explain why multiple stretches are required to induce substantial muscle damage in vivo.

Strains and strain rates responsible for muscle damage in vivo. To our knowledge, this is the first time that muscle fascicle length has been measured during a classic muscle-damaging exercise. The measurement of muscle fascicle length and its relationship to muscle torque and strain rate during exercise can provide new insights into the mechanisms of muscle injury. This information can be used to design more effective muscle-damaging exercises and to develop preventive strategies to reduce the risk of muscle injury.

Fig. 2. Group mean active and passive L-T curves with working fascicle length ranges. A: an example of how the calculated group mean L-T curves were fit through individual subject L-T data points (each color represents an individual subject). Fascicle length is normalized to the calculated optimum length (L_o), and torque is normalized to the calculated maximum torque (T_max). Superimposed onto the L-T curves are the fascicle length ranges during the initial part of the stance phase during forward flat walking before the muscle-damaging exercise (diagonal striped shading) and during the first minute of backward downhill walking (solid shading). The horizontal error bars indicate the SE of the group mean minimum or maximum fascicle length. Before (B) and 2-h after (C) 1-h backward downhill walking L-T curves with working fascicle length ranges are shown. Arrows indicate the direction of stretch (backward downhill walking; solid arrow) or shortening (forward walking; dashed arrow) that occurs relative to the L-T curve.

Fig. 3. Group mean stride traces of fascicle (A), muscle-tendon unit (MTU; B), and series elastic element (SEE; C) length at the beginning (solid line) and at the end of 1-h backward downhill walking (dashed line). Shading indicates the SE for the stride length trace at the beginning of 1-h backward downhill walking. As the variability is similar across both conditions, only one SE is displayed for reader clarity. The vertical line indicates the stance phase (left) and swing phase (right) for the stride cycle.
damaging exercise in humans in vivo. We observed the MG muscle fascicle to stretch over an amplitude of 18% of \(L_o\) at the beginning of 1-h backward downhill walking at lengths corresponding to the ascending limb and plateau region of the L-T curve. While EIMD occurred during this exercise protocol, the strain experienced by the fascicles was much smaller than is typically produced in situ and in vitro (4, 24, 58). It is likely that this factor contributed to the modest, 23% reduction in \(T_{\text{max}}\) 2 h postexercise compared with the large force decrements (up to \(\sim60-80\%\)) reported in situ and in vitro with as few as 1–10 active stretches (3–7, 58). We suggest that the extensive damage that occur in situ and in vitro is the result of muscle fiber stretches that are of an amplitude, or occur at lengths, that are unlikely to occur under natural conditions in human lower limb muscles with significant series compliance, such as the gastrocnemius muscles (8, 10).

The amplitude of stretch measured here is quite similar to an animal in vivo study by Butterfield & Herzog (9), who found that the stretch of rabbit hind limb muscle fibers was no greater than 16% of \(L_o\). In the present study, we observed that the tendon contributed \(\sim90\%\) to overall \(L_{\text{MTU}}\) change during stretch, suggesting that the compliant tendon minimized the amplitude of stretch of the fascicle. This indicates that Achilles tendon and gastrocnemius muscle compliance is important beyond its capacity for storage and return of elastic energy for efficient locomotion (13, 16, 30, 47), and that it also has an important role in attenuating muscle stretch during eccentric contractions, as has recently been demonstrated in running turkeys (47). The current experiment is not able to determine which part of the tendinous tissue is undergoing the most stretch; however, high strain compared with the muscle fascicles is likely to occur in both the aponeurosis and Achilles tendon, similar to hopping or running (28, 29).

In addition to reducing the extent of fascicle stretch, the tendon took up most of the initial high-velocity stretch, and then, as it shortened, the fascicles lengthened to absorb energy. This effectively reduced the peak strain rate of the fascicles (47). The velocity of stretch is thought to play some role in the magnitude of EIMD, especially at large stretch amplitudes (6, 52). However, strain rates reported in reduced animal preparations are typically much higher (3–16 \(L/s\)) (6, 52) than those observed in our current experiment (\(\sim1 L/s\)). As such, our results suggest that the compliance of the tendon has an effect on buffering both the magnitude and the rate of muscle fascicle length changes during EIMD in humans.

Muscle fascicle length ranges during EIMD in vivo. We have shown here for the first time in humans that EIMD can occur when exercising at lengths corresponding to the ascending limb or plateau region of L-T curves constructed from muscle fascicle measurements. We also found no relationship between the final length to which the muscle fascicle stretches and the presence or amount of muscle damage incurred. This appears inconsistent with the mechanisms of EIMD proposed

### Table 2. Medial gastrocnemius fascicle, muscle-tendon unit, and series elastic element stretch amplitude, maximum stretch velocity, and peak length during stretch during backward flat walking, the start of, or the end of 1-h backward downhill walking

<table>
<thead>
<tr>
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<th>Stretch Amplitude, mm</th>
<th>Maximum Stretch Velocity, L/s</th>
<th>Peak Length During Stretch, mm</th>
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<tbody>
<tr>
<td></td>
<td>BFW</td>
<td>Start BDW</td>
<td>BFW</td>
</tr>
<tr>
<td>Fas</td>
<td>9.61</td>
<td>4.05</td>
<td>1.30</td>
</tr>
<tr>
<td>MTU</td>
<td>42.32</td>
<td>10.14</td>
<td>6.73</td>
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<tr>
<td>SEE</td>
<td>38.30</td>
<td>10.56</td>
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Values are means ± SD. Fas, fascicle; MTU, muscle-tendon unit; SEE, series elastic element; BFW, backward flat walking; BDW, backward downhill walking; L/s, fascicle slack lengths/s.
in the “popping sarcomere hypothesis,” according to which, the production of EIMD requires sarcomeres to be stretched to muscle lengths that correspond to the descending limb of the length-tension curve (40). However, the present findings do not discount the possibility that stretching sarcomeres to very long lengths exacerbates reductions in muscle force and muscle fiber structural damage. In fact, because the lengths of sarcomeres along muscle fibers may be heterogeneous (1, 44, 45), it remains possible that some sarcomeres were stretched to sufficiently long lengths during our backward walking protocol to be consistent with the popping sarcomere hypothesis.

Because the triceps surae L-T relationship was developed from MG fascicle length and total plantar flexor torque, this L-T relationship may misrepresent the mechanical properties of the soleus or lateral gastrocnemius if their muscle properties were substantially different from those of the MG (i.e., if soleus or lateral gastrocnemius acted on a different part of the L-T curve). However, a recent study has shown that soleus fascicles shorten over the ascending limb of the soleus length-tension curve during forwards walking (48). As the kinematics and pattern of activation of muscles are similar, but in reverse, for forward and backward walking (25, 53), it seems likely that soleus fascicles also lengthen over the ascending limb during backward, downhill walking. Furthermore, it has been shown that all three triceps surae muscles operate along the ascending limb and plateau region of their length-tension curves for isometric MVCs performed across the ankle range of motion (33, 34). Thus we believe that the MG-constructed L-T curves described here provide an accurate representation of the triceps surae length-tension relationship.

Although the prolonged backward walking protocol we employed probably caused both progressive damage and fatigue within the gastrocnemius muscle, the muscle mechanics remained largely similar across the 1-h walking period (Fig. 3). There was no change in peak fascicle length during stretch, indicating no lengthening of the fascicle during the muscle damage protocol. The lack of change in mechanical behavior could be considered surprising given that we did find a significant shift in the Lₐ and maximum force-generating capacity assessed after the effects of fatigue had subsided (Fig. 2C). However, given that the forces required to walk backward remained the same across time (as the walking speed did not change), and that LATU changes were dominated by SEE rather than fascicle length changes at the beginning of the muscle damage protocol, it is not surprising that the extent of fascicle stretch remained similar across time. In fact, the rightward shift in the length-tension relationship ensured that the fascicle operated on the ascending limb of the L-T relationship throughout the task and did not stretch to longer lengths that might result in more damage.

Conclusion. We have shown here for the first time that human gastrocnemius muscle fascicles experience relatively small strains during prolonged backward downhill walking that causes muscle damage. However, the level of EIMD produced was much less than typically observed for in situ or in vitro preparations that involve larger stretch amplitudes. We also showed that eccentric exercise does not have to be performed at fascicle lengths corresponding to the descending limb of the length-tension curve to induce muscle damage. Investigations are required to determine whether sarcomere heterogeneity can lead to some sarcomeres being stretched to long lengths when the fascicles operate at such short lengths. As the tendon contributed a large amount of the stretch during the backward walking protocol, we attribute the attenuation of MG fascicle stretch to tendon compliance, which obviously plays an important role in protecting such muscles from stretch during energy absorbing activities. Future studies should measure fascicle length changes during different eccentric exercise protocols in humans, to better understand how fascicle and tendon dynamics influence EIMD under natural conditions.

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DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the author(s).

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