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Time to task failure and muscle activation vary with load type for a submaximal fatiguing contraction with the lower leg

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Hunter SK, Yoon T, Farinella J, Griffith EE, Ng AV. Time to task failure and muscle activation vary with load type for a submaximal fatiguing contraction with the lower leg. *J Appl Physiol* 105: 463–472, 2008. First published June 5, 2008; doi:10.1152/japplphysiol.90398.2008.—The purpose was to compare the time to failure and muscle activation patterns for a sustained isometric submaximal contraction with the dorsiflexor muscles when the foot was restrained to a force transducer (force task) compared with supporting an equivalent inertial load and unrestrained (position task). Fifteen men and women (mean ± SD; 21.1 ± 1.4 yr) performed the force and position tasks at 20% maximal voluntary contraction force until task failure. Maximal voluntary contraction force performed before the force and position tasks was similar (333 ± 71 vs. 334 ± 65 N), but the time to task failure was briefer for the position task (10.0 ± 6.2 vs. 21.3 ± 17.8 min, $P < 0.05$). The rate of increase in agonist root-mean-square electromyogram (EMG), EMG bursting activity, rating of perceived exertion, fluctuations in motor output, mean arterial pressure, and heart rate during the fatiguing contraction was greater for the position task. EMG activity of the vastus lateralis (lower leg stabilizer) and medial gastrocnemius (antagonist) increased more rapidly during the position task, but coactivation ratios (agonist vs. antagonist) were similar during the two tasks. Thus the difference in time to failure for the two tasks with the dorsiflexor muscles involved a greater level of neural activity and rate of motor unit recruitment during the position task, but did not involve a difference in coactivation. These findings have implications for rehabilitation and ergonomics in minimizing fatigue during prolonged activation of the dorsiflexor muscles.

muscle fatigue; load compliance; coactivation; antagonist activation; tibialis anterior

MAINTENANCE OF A SUBMAXIMAL fatiguing contraction is accompanied by a gradual reduction in the force capacity of the muscle due to an impairment of neural and muscular processes that eventually cause task failure (11, 29, 42, 44). The rate of impairment in neural and muscular processes varies with the type of task performed, the involved muscle group, and the demands on accessory, antagonist, and synergist muscles (7). Healthy adults, for example, exhibit a longer time to task failure when performing a submaximal isometric contraction with upper arm and hand muscles by pushing against a force transducer (force task) compared with supporting an equivalent inertial load (position task) (17, 30). Despite a similar load torque for the two tasks, the briefer time to task failure for the position task involved greater central neural activity during the position task than the force task. Accordingly, for the first dorsal interosseous muscle of the hand and the elbow flexor muscles, there was a more rapid recruitment of the motor unit pool, indicated by a greater rate of increase in the amplitude of the surface electromyogram (EMG) and single motor units (31, 36, 41). Whether or not such differences between the force and position task exist for lower limb muscles is not known.

Time to task failure of a sustained contraction also depends on the posture of a limb and the involvement of antagonist and accessory muscles (7). The magnitude of difference between the force and position task, for example, was greater for the elbow flexor muscles when the position of the forearm was horizontal to the ground vs. vertical (21, 23, 39, 41). This greater difference between the two tasks when the postures differed was attributed to a greater demand on the shoulder muscles during the position task when the arm was horizontal to the ground (21, 39). Thus accessory muscles were able to limit the position task more than the force task and led to earlier failure of the position task for the elbow flexor muscles when the forearm was horizontal. Activation of antagonist muscles during a fatiguing contraction (coactivation) may also limit the time to task failure of a submaximal task (6, 28, 37). Evidence suggests a difference in coactivation probably does not explain the difference between the force and position tasks of the upper limb muscles (20, 21, 23, 31, 39, 41). Coactivation, however, has not been systematically examined during the force and position task.

The differences in the position and force task for upper limb muscles (first dorsal interosseous and elbow flexor muscles) and the likely mechanism involves greater activation of the stretch reflex during the position task when coactivation is limited (23). The cause of task failure of a submaximal contraction, however, is quite specific to a muscle group. The fiber-type composition, biomechanical considerations, such as the mechanical arrangement of muscle at a joint, the neural connections of a muscle group, and the recruitment range of a muscle will influence the ability of a muscle group to sustain the required contraction force (7, 31, 32). Limitations of performance and any differences between a force and position task in a lower leg muscle group, such as the dorsiflexor muscles, are not known. Based on findings from upper limb muscles, varying the support of the foot during the force and position task with the lower limb muscles will potentially influence fatigability and the mechanisms involved.

The purpose of the study was to compare the time to task failure and muscle activation patterns for a force task and position task during dorsiflexion. We hypothesized that the time to failure of the position task would be briefer than the force task, and this would be accompanied by an increased rate of agonist muscle activation during the position task, and an

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increased rate of other neural indexes during the position task, including fluctuations in motor output, mean arterial pressure (MAP), heart rate, and rating of perceived exertion (RPE). Because activation of antagonist muscles will increase joint stability, we also hypothesized that antagonist muscle activation would be greater during the position task compared with the force task performed with the dorsiflexor muscles.

METHODS

Fifteen healthy young adults (8 men and 7 women; mean ± SD; 21.1 ± 1.4 yr in age, 172 ± 8 cm in height, 65 ± 13 kg in mass) volunteered to participate in the study. All subjects were healthy with no known neurological or cardiovascular diseases and were naive to the protocol. Before participation, each subject provided informed consent, and the protocol was approved by the institutional review board at Marquette University.

Subjects reported to the laboratory on three separate occasions: once for a familiarization session, followed by two experimental sessions that involved the dorsiflexor muscles of the nondominant foot. Dominance was determined as the preferred kicking foot. At the familiarization session, each subject practiced maximal voluntary contractions (MVC) of the dorsiflexor muscles.

The two experimental sessions involved an isometric fatiguing contraction with the dorsiflexor muscles. In one session, the fatiguing contraction involved maintaining a force that was equivalent to 20% of MVC force for as long as possible; this is referred to as the force task. In the other session, the fatiguing contraction involved maintaining a constant angle at the ankle, while supporting an inertial load equivalent to 20% MVC force over the dorsal forefoot; this is referred to as the position task. The order of these two tasks was randomized across subjects, and the sessions were at least 5 days apart. The load torque applied at the foot for the two tasks was identical for each subject. The subject was provided with visual feedback of the force exerted by the foot during the force task and of the ankle angle during the position task. For both tasks, the subject was required to sustain the fatiguing contraction for as long as possible.

Mechanical Recording

Subjects were seated in an adjustable chair (Biodex Medical Systems) with the hip and knee at 90° of flexion. The nondominant foot was assessed with the ankle in a neutral position (0° dorsiflexion). During the MVCs and the force task, isometric force of the dorsiflexor muscles was measured using a force transducer (Transducer Techniques, Temecula, CA) mounted at right angles under a footplate that was adjustable for height and was rigidly secured to the floor. The forefoot was secured to the footplate via a strap placed 1–2 cm proximal to the metatarsophalangeal joint of the toes (Fig. 1*A*). The force signal was amplified and displayed on a monitor placed 2 m in front of the subject. The forces detected by the transducer were recorded on line at 500 Hz using a Power 1401 analog-to-digital (A/D) converter and Spike 2 software [Cambridge Electronics Design (CED), Cambridge, UK].

Ankle angle during the position task was measured with an electrogoniometer (XM110 and K100, Penny and Giles, Cwmfelinfach, Gwent, UK) that was taped to the lateral side of the foot, using the fifth metatarsal and fibular head as references for placement (Fig. 1*B*). The output was recorded online (Power 1401 and Spike 2 software, CED) and displayed on the oscilloscope for subject feedback. A custom-fitted brace, similar in width to the force transducer strap, was strapped over the dorsal forefoot, and an inertial load equivalent to 20% of MVC force was suspended from the foot, at the same location that contacted the force transducer strap. During the position task, a uniaxial accelerometer (Endevco 7265A-HS, San Juan Capistrano, CA) was mounted on a right-angled aluminum platform that was secured on the medial forefoot on the brace during the fatiguing contraction. The accelerometer was aligned to record acceleration in the vertical direction. Acceleration was recorded online using a Power 1401 A/D converter and Spike 2 software (CED). The position and acceleration signals were digitized at 500 samples/s.

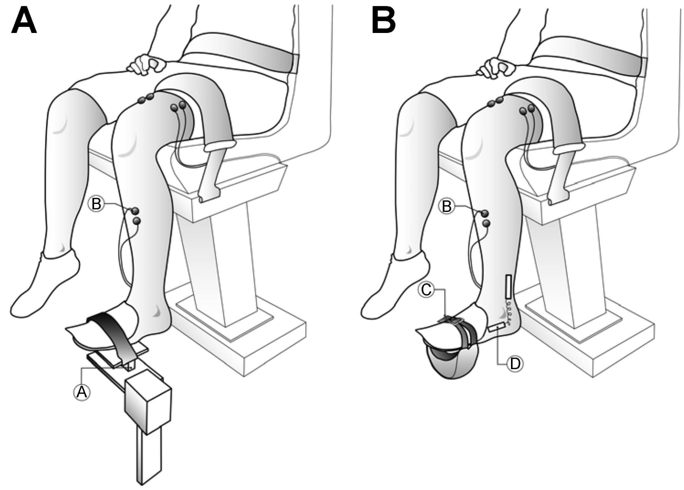

Fig. 1. Schematic drawing of the experimental setup for the force task (*A*) and position task (*B*). Each subject was seated upright with knee at 90° and faced an oscilloscope for visual feedback. The foot was attached to a force transducer for the force task (*B*). The position task involved supporting an inertial load that was suspended from the foot (*A*). Measurements at the leg were made with a force transducer (A), electromyogram (EMG) electrodes (B), accelerometer (C), and goniometer (D).

Electrical Recordings

Whole muscle activity of the tibialis anterior, medial head of the gastrocnemius, vastus lateralis, and femoris was monitored via surface electrodes. EMG of the soleus was not recorded because it was difficult to achieve reasonable surface EMG recordings. Also, pilot data showed that the gastrocnemius muscle was quite active during the position task when stabilizing the load. Sintered pellet AgCl electrodes (8-mm diameter), taped to the skin over the bellies of each muscle, were used for the bipolar surface EMG recordings. The recording electrodes on each muscle were placed in line with the muscle fibers and in locations, according to the European Recommendations for Surface Electromyography (16). The center-to-center distance between each electrode pair was 20 mm. Reference electrodes were placed on the medial maleolus for the tibialis anterior and gastrocnemius muscles and on the patella for the vastus lateralis and rectus femoris. All EMG signals were amplified (1,000–10,000 times), band-pass filtered (10–1,000 Hz), and recorded to PC via a Power 1401 and Spike 2 software (CED). The EMG was sampled at 2,000 samples/s and analyzed offline using Spike 2 (CED).

Cardiovascular Measurements

Heart rate and blood pressure were monitored throughout the fatiguing contraction with an automated beat-by-beat blood pressure monitor (Finapress 2300, Ohmeda, Louisville, CO). The blood pressure cuff was placed around the middle finger of the left hand, and the arm was placed with the hand at heart level. The blood pressure was sampled at 500 samples/s and collected online to PC using Spike 2 (CED).

Experimental Protocol

Each of the two experimental sessions involved the same core procedures. They included performance of *1*) MVCs of the knee extensor muscles and plantar flexor muscles to obtain peak EMG values; *2*) MVCs of the dorsiflexor muscles to obtain maximal isometric strength and peak EMG values; *3*) submaximal contractions of the dorsiflexor muscles while attached to the force transducer (force task) to assess the EMG-force relationship on each day; and *4*) a fatiguing contraction of the dorsiflexor muscles sustained at 20% of MVC (either the force task or position task); followed by *5*) an MVC with the dorsiflexor muscles (within 10 s of task termination).

MVC of the knee extensors and plantar flexor muscles. MVCs of the knee extensor muscles and plantar flexor muscles were obtained at the beginning of each experimental session to obtain peak EMG. Two MVCs were performed with the knee extensor muscle followed by two MVCs with the plantar flexors. Subjects rested for 60 s between each trial. For both muscle groups, the MVCs were performed in the same posture and leg position as described above for the fatiguing contraction with the dorsiflexor muscles. Knee extension and plantar flexion forces were not recorded during these contractions. Each subject, however, was asked to push as hard as he or she could against the immovable restraint for 3–4 s. For the knee extensor muscles, an inflexible strap was attached between the chair and the leg (just above the lateral malleolus) so that the lower leg was restrained at 90° flexion when the subject performed maximal knee extension. For the plantar flexor muscles, the foot of each subject was placed on an immovable block, and vertical movement of their knee was minimized with a rigid restraint during the MVCs. The largest EMG activity from these MVCs was used to normalize the EMG recordings during the fatiguing contractions of the vastus lateralis, rectus femoris, and medial gastrocnemius muscles.

MVC force of the dorsiflexor muscles. Subjects performed four MVC trials with the ankle dorsiflexors, while their foot was attached to the force transducer. Each subject was asked to increase the force exerted from zero to maximum over 1–2 s, with the maximal force held for 2–3 s. Subjects were given visual feedback on a monitor and were given strong verbal encouragement to achieve and maintain maximal force. Subjects rested for 60 s between each trial. If the peak force achieved for two of the four trials was not within 5% of each other, additional trials were performed until this criteria was met. The greatest force achieved over the trials was taken as the MVC and used for calculations of the submaximal target forces and the inertial load for the position task.

EMG activity during submaximal tasks. The EMG activity of the involved muscles was recorded in standardized tasks so that the force-EMG relation could be compared across experimental days. For the dorsiflexor muscles, the subject performed an isometric contraction for 6 s at target forces of 20, 40, and 60% MVC force. The subject was given a 60-s rest between each contraction. The order of the contractions was randomized across subjects, but remained constant for each subject on the 2 experimental days.

Fatiguing contractions. The subject was required to match the vertical target force as displayed on the monitor for the force task and was verbally encouraged to sustain the force for as long as possible. The fatiguing contraction was terminated when the force declined by 5% of the target torque, despite strong verbal encouragement to maintain the task. This time was recorded as the time to task failure for the force task. The position task was terminated when the ankle angle declined by 18° from a right angle, despite strong verbal encouragement. Subjects were required to keep the lower leg vertical at all times during the tasks, with no eversion or inversion of the foot permitted. Therefore, during the task position task, in particular, each subject was corrected for any movement of the lower leg, including inversion and eversion of the foot. In most circumstances, the position task was ended with the subject dropping the load abruptly at task failure. This time of termination was recorded as the time to task failure for the position task. Based on a static biomechanical analysis, the two criteria for task termination represented similar changes in the load torque about the ankle joint for the two tasks. To minimize the influence of transient fluctuations in motor output on the criteria for task failure, the task was terminated only after torque fell below the predetermined threshold for 4 consecutive s. Neither the subject nor the investigator who terminated the task knew the time during the tasks. Subjects were not informed of the time to task failure until completion of their final experimental session.

An index of perceived effort, the RPE, was assessed with the modified Borg 10-point scale (2). The subject was instructed to focus the rating of exertion on the dorsiflexor muscles. The scale is anchored so that 0 represents the resting state and 10 represents the strongest contraction that the muscles can perform. RPE was recorded at 60-s intervals during the fatiguing contraction.

Data Analysis

All data collected during the experiments were recorded online using a Power 1401 A/D converter and analyzed offline using Spike 2 (CED).

The MVC force was quantified as the average value over a 0.5-s interval that was centered about the peak. The maximal EMG for each muscle was determined as the root-mean-square (RMS) value over a 0.5-s interval about the peak EMG during the MVC. The RMS EMG value of the 6-s submaximal contractions for the tibialis anterior performed at 20, 40, and 60% of MVC torque was averaged over the middle 2 s during the 6-s contraction. RMS EMG of the tibialis anterior, medial gastrocnemius, vastus lateralis, and rectus femoris were quantified during the fatiguing contraction performed at 20% of MVC at the following time intervals: the first 30 s; 15 s on both sides of 25, 50, and 75% of time to task failure; and the last 30 s of the task duration. The EMG activity of each muscle was normalized to the RMS EMG value obtained during the MVC for each respective muscle. The level of coactivation was quantified by calculating the ratio between the RMS EMG (%peak) of the agonist muscle (tibialis anterior) and antagonist muscle (medial gastrocnemius) (28).

To quantify the bursts of EMG activity of the tibialis anterior, the EMG signal was first rectified, smoothed (averages of 1-s duration, 500 data points), and then differentiated over 0.25-s averages (Fig. 2). The differentiated signal represents the rate of change and was used to identify rapid changes in the rectified and smoothed EMG signal. A threshold for establishing if a burst of EMG had occurred was determined by first finding the minimum SD of the differentiated EMG during the fatiguing contraction using a 30-s moving window.

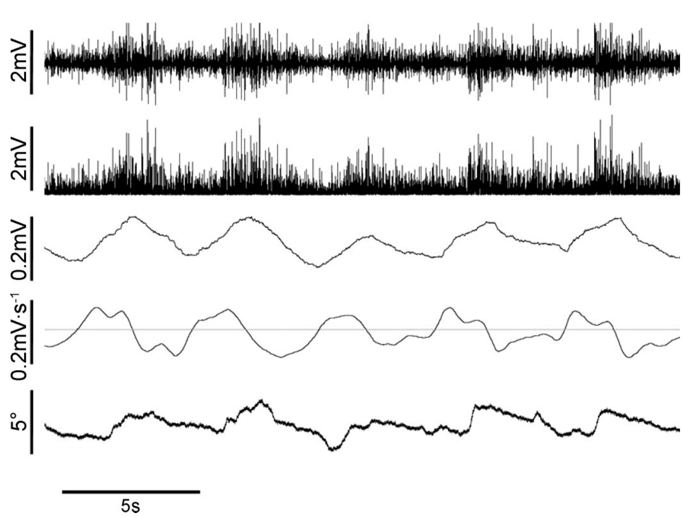

Fig. 2. Identification of bursting activity in the interference EMG for tibialis anterior muscle during a fatiguing contraction (position task shown). Records show the interference EMG (1st trace), the rectified EMG (2nd trace), the rectified EMG after it was smoothed using a moving average (3rd trace), the differentiated EMG after being rectified and smoothed (4th trace), and the position signal (5th trace). A burst was identified when the differentiated EMG crossed the threshold value (mean + 3 SD). In this example, the analysis identified 5 bursts of EMG activity, because the threshold is crossed on 5 occasions on the differentiated signal as it rises (4th trace).

The threshold for a burst was then defined as the mean + 3 SD of the minimum differentiated signal. The minimal burst duration was 0.1 s. The EMG bursting activity (bursts/min) was quantified for five continuous intervals of 20% of the time to task failure.

The fluctuations in force during the force task and in acceleration during the position task were quantified for the first 30 s; 15 s on both sides of 25, 50, and 75% of time to task failure; and the last 30 s of the task duration. The amplitude of the force fluctuations was quantified as the coefficient of variation (SD/mean × 100), and the fluctuations of acceleration for the position task were characterized as the SD of acceleration.

Heart rate and MAP recorded during the fatiguing contraction were analyzed by comparing ~15-s averages at 25% intervals throughout the fatiguing contractions. For each interval, the blood pressure signal was analyzed for the mean peaks [systolic blood pressure (SBP)], mean troughs [diastolic blood pressure (DBP)], and the number of pulses per second (multiplied by 60 to determine heart rate). MAP was calculated for each epoch with the following equation: MAP = DBP + ⅓(SBP − DBP).

Statistical Analysis

Data are reported as means (±SD) within the text, and displayed as means (±SE) in Figs. 3–7. Time to task failure was compared across sessions using repeated-measures ANOVA with sex as a between-group factor. ANOVAs with repeated measures on time and task were used to compare the dependent variables of MVC force, heart rate, MAP, RPE, fluctuations in motor output, EMG-force relation for the 6-s constant-force contractions, and EMG burst rate and RMS EMG activity during the fatiguing contraction of the various muscles. Post hoc analyses (Tukey-Kramer) were used to test for differences among pairs when appropriate. Paired *t*-tests (one-tailed) were used to compare the percent decline in MVC force across the fatiguing tasks and the rates of increase in various dependent variables as a function of absolute time. A significance level of $P < 0.05$ was used to identify statistical significance.

The contribution of several variables to the time to task failure was analyzed using multiple linear regressions and the associated partial correlations (*r*). These variables included the rate of change in RMS EMG activity of each muscle, EMG bursting activity of the tibialis anterior, MAP, heart rate, RPE, fluctuations in force or acceleration, and MVC force. The associated partial correlation coefficients were used to identify the contribution of each independent variable to the time to task failure. The strength of an association is reported as the squared Pearson product-moment correlation coefficient (r^2).

RESULTS

This study involved the comparison of the time to task failure, patterns of muscle activation, fluctuations in force and acceleration, and the pressor response during two types of fatiguing contractions performed with the dorsiflexor muscles that varied in support of the foot. The isometric fatiguing contractions for the force and position tasks involved a similar net muscle torque about the ankle joint. However, the force task required the subject to match a target force of 20% MVC force when the foot was attached to a force transducer, whereas the position task required the subject to maintain the ankle joint at a right angle while supporting an inertial load equivalent to the 20% MVC force.

MVC Torque and Time to Task Failure

MVC force performed before the force task (333 ± 71 N) was similar to that before the position task (334 ± 65 N, $P = 0.46$), which meant that similar net torques were exerted at the foot during the two fatiguing contractions. There was no interaction of session and time ($P = 0.54$), because the absolute and relative decline in MVC force performed after the fatiguing contraction for the force task (30 ± 18%) and position task (28 ± 12%, $P = 0.57$) did not differ.

Despite the similar net muscle torque exerted by the subject for each task, comparable criteria for termination of the tasks, and equivalent reductions in MVC force after the fatiguing contraction, the time to failure for the force task (21.3 ± 17.8 min) was twice as long as that for the position task (10.0 ± 6.2 min, $P = 0.03$). There was no main effect of sex ($P = 0.18$) and no interaction between task and sex ($P = 0.37$).

EMG-Force Relation

The EMG activity (RMS; %peak EMG) for the tibialis anterior muscle was determined during brief isometric contractions held at 20, 40, and 60% of MVC for both testing sessions before the fatiguing contraction. EMG activity increased with contraction intensity (effect of contraction intensity, $P < 0.001$) similarly for both testing sessions (interaction of intensity and session, $P = 0.72$). The EMG activity for the tibialis anterior muscle during the force and position task sessions was 30.9 ± 9.3 and 28.2 ± 8.4%, respectively, for the 20% contraction, 49.2 ± 12.9 and 49.5 ± 13.6% for the 40% contraction, and 71.1 ± 12.1 and 73.0 ± 14.4%, respectively, for the 60% contraction.

EMG Activity During the Fatiguing Contraction

EMG activity of the tibialis anterior. EMG activity (RMS; %peak EMG) for the tibialis anterior muscle increased during the fatiguing contraction for both tasks ($P = 0.03$). The EMG was similar in the first 30 s of the force and position task (30 ± 7 vs. 27 ± 10%), but there was an interaction of time and task ($P = 0.04$) because the position task had a more rapid increase in EMG activity (1.1 ± 0.8%/min) than the force task (0.03 ± 1.3%/min, $P = 0.01$) when normalized to the absolute contraction time. Similarly, the rate of change in EMG activity relative to the initial values (%initial EMG) was greater for the position task (5.7 ± 5.0%/min) than the force task (1.0 ± 3.5%/min, $P = 0.01$) when normalized to absolute contraction time. Thus the results were consistent when the EMG was expressed relative to the peak EMG during the MVC and also when expressed relative to the EMG at start of each contraction (Fig. 3, *A* and *B*).

EMG bursting of the tibialis anterior. There was a progressive increase in the number of bursts in EMG activity during both tasks (effect of time, $P < 0.001$, Fig. 3*C*). There was no effect of task ($P = 0.80$) and no interaction of time and task ($P = 0.19$). However, the rate of increase in the bursting activity normalized to absolute contraction time for the tibialis anterior muscle was greater for the position task (1.9 ± 0.6 bursts·min^{-1}·min^{-1}) compared with the force task (1.4 ± 1.0 bursts·min^{-1}·min^{-1}, $P = 0.024$) (Fig. 3*C*).

EMG activity antagonist, synergist, and accessory muscles. We examined the EMG activity of various other muscles that act either as an antagonist (medial gastrocnemius), stabilizer of the lower leg (vastus lateralis and rectus femoris), or a potential contributor to vertical force during the fatiguing contraction via hip flexion (rectus femoris).

For the medial gastrocnemius, there was an interaction of time and task ($P = 0.049$) in EMG activity (%peak), because

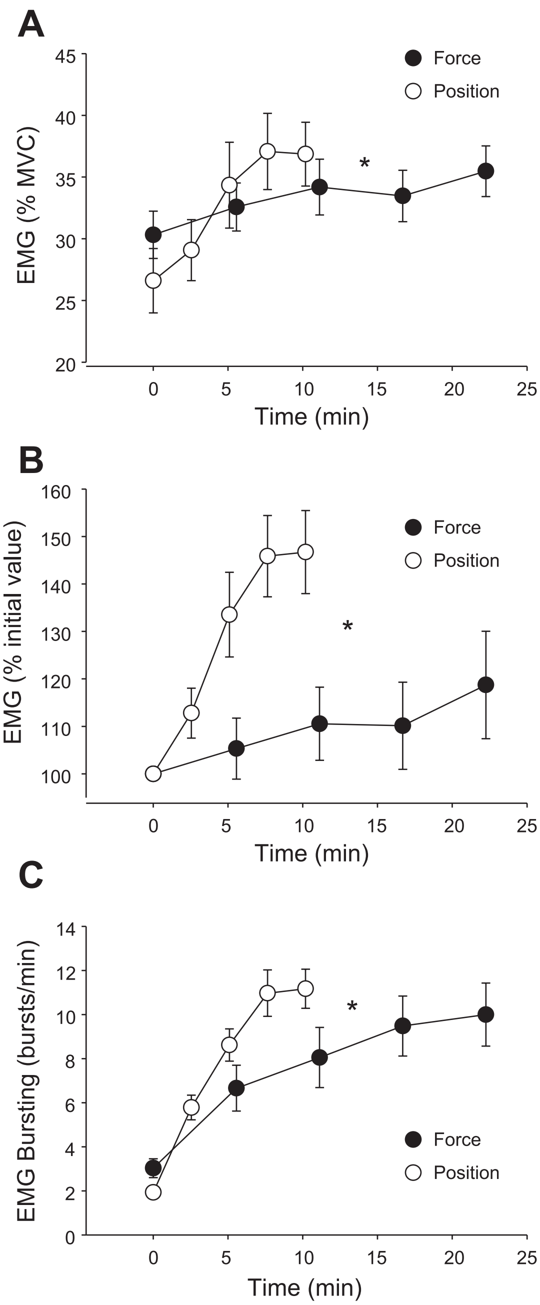

Fig. 3. EMG activity of the tibialis anterior during the fatiguing contraction for the position and force tasks. *A*: root-mean-square (RMS) EMG [%maximal voluntary contraction (MVC) peak] for the force and position task. *B*: RMS EMG (%initial 30 s of EMG). Each data point represents means ± SE at 25% increments of the time to task failure for a 30-s interval for *A* and *B*. The rate of increase in EMG activity was greater for the position task than the force task for both graphs (*A* and *B*) (*$P < 0.05$). *C*: burst rate of the EMG signal for the tibialis anterior for the fatiguing contractions. Values are means ± SE for 20% intervals of time to task failure. The increase in the burst rate was greater for the position than the force task. *Different rates of increase (slopes) ($P < 0.05$).

the rate of increase for the position task (0.35 ± 0.51%/min) was greater than for the force task (0.05 ± 0.07%/min, P = 0.024, Fig. 4*A*) when normalized to absolute contraction time. Although, gastrocnemius activity increased more during the position task than the force task, the coactivation ratio did not differ between tasks (effect of task, P = 0.16, Fig. 4*B*) and did not increase with time (effect of time, P = 0.086). There was also no interaction of task and time (P = 0.48).

The EMG activity of the vastus lateralis increased during the fatiguing contractions (effect of time, $P < 0.001$), with no main effect of task (P = 0.22) and no interaction of time and task (P = 0.10) when compared at the same relative time. The rate of increase in EMG activity, however, was greater for the position task (3.8 ± 4.7%/min) compared with the force task (2.1 ± 3.1%/min, P = 0.025, Fig. 5*A*) when normalized to absolute contraction time.

In contrast to other muscles, the EMG activity of the rectus femoris was greater during the force task (7.4 ± 4.1%) than the position task (5.8 ± 2.8%, main effect of task, P = 0.002) (Fig. 5*B*). The EMG activity of the rectus femoris also increased with time for both tasks (P = 0.046); however, there was no interaction of task and time (P = 0.055). There was also no difference in the rate of change in rectus femoris EMG activity (normalized to the absolute contraction time) between the force and position task (P = 0.23).

Fluctuations in Force and Acceleration During the Fatiguing Contraction

The amplitude of the vertical fluctuations in force and acceleration increased progressively during the two tasks (effect of fatigue, $P < 0.001$). The increase in vertical fluctuations

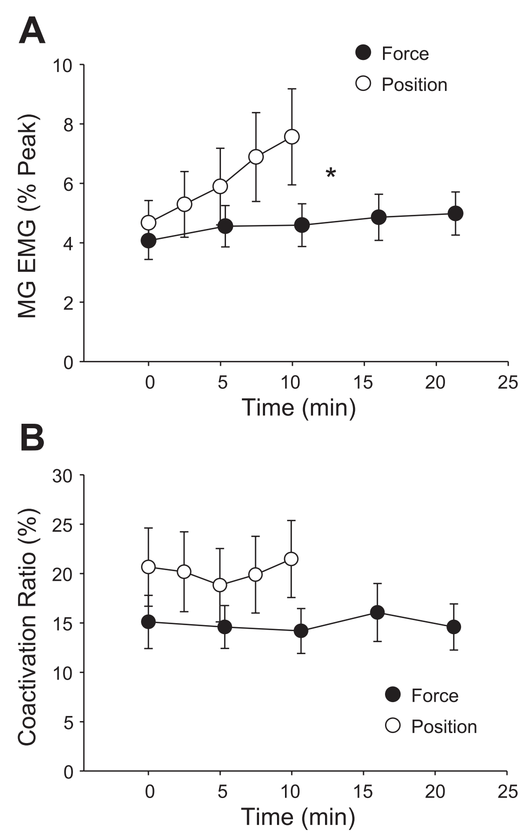

Fig. 4. EMG activity of the medial gastrocnemius (MG) during the fatiguing contraction for the position task and force task. Values are means ± SE at 25% increments of the time to task failure for a 30-s interval. *A*: RMS EMG (%peak) of the MG increased at a greater rate for the position task than the force task. *Different rates of increase (slopes) ($P < 0.05$). *B*: coactivation ratios of the MG relative to the tibialis anterior did not differ between tasks and over time ($P > 0.05$).

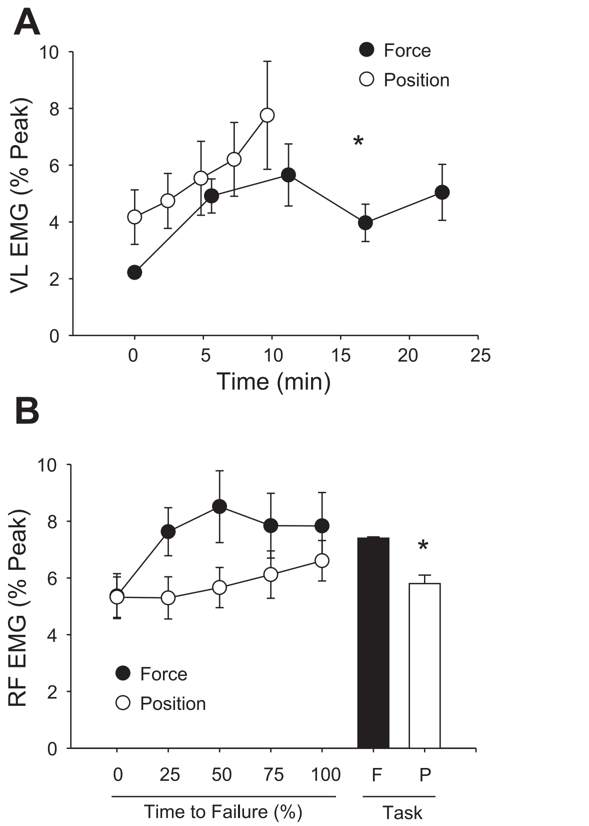

Fig. 5. EMG activity of the vastus lateralis (VL; *A*) and rectus femoris (RF; *B*) during the fatiguing contraction for the position and force tasks. Values are means ± SE of the RMS EMG (%peak) at 25% increments of the time to task failure for a 30-s interval. The rate of increase in EMG activity VL (*A*) was greater for the position task than the force task (*$P = 0.025$). In contrast, EMG activity of the RF muscle (*B*) was greater during the force task (F) than the position task (P) (main effect of task: *$P = 0.002$) and is shown with the vertical bars. There was also a main effect of time ($P = 0.046$) but no interaction of time and task ($P = 0.06$).

at task failure was 439 ± 241% for the position task and 218 ± 87% for the force task (effect of task, $P = 0.007$). The relative increase in the acceleration fluctuations during the position task, however, was greater than the increase in force fluctuations during the force task (interaction of task and time, $P = 0.004$, Fig. 6).

MAP and Heart Rate

MAP increased during both tasks ($P < 0.001$, Fig. 7*A*). When compared at the same relative time, the MAP was similar. MAP was similar at the beginning of the fatiguing contractions for the force and position tasks (96 ± 15 and 94 ± 13 mmHg, respectively) and at task failure (121 ± 24 and 128 ± 26 mmHg, respectively). The increase in MAP was described by a quadratic trend ($P < 0.001$), and the interaction of task and time was $P = 0.06$. The rate of change in MAP (normalized to the absolute contraction time), however, was greater during the position task than the force task ($P = 0.018$). The rate of change in MAP was negatively correlated with the time to task failure ($r = -0.54$, $r^2 = 0.29$, $P = 0.003$), indicating that a greater rate of change in MAP was associated with a briefer time to task failure.

Heart rate also increased during the fatiguing contraction ($P < 0.001$, Fig. 7*B*). Heart rate was similar at the beginning of the force and position task (83 ± 11 and 88 ± 16 beats/min, respectively) and at task failure (105 ± 12 and 107 ± 12 beats/min, respectively). There was an interaction of task and time ($P = 0.002$), because heart rate increased more gradually during the force task compared with the position task. Accordingly, the rate of change in heart rate (normalized to the absolute contraction time) was greater during the position task than the force task ($P = 0.014$). The rate of change in heart rate was negatively correlated with the time to task failure ($r = -0.44$, $r^2 = 0.19$, $P = 0.02$), indicating that a greater rate of change in heart rate was associated with a briefer time to task failure.

Perceived Exertion During the Fatiguing Tasks

The RPE increased during the fatiguing contraction ($P < 0.001$, Fig. 7*C*). RPE was similar at the beginning and end of the fatiguing contraction for the force (1.0 ± 0 and 9.9 ± 0.4) and position (1.0 ± 0 and 9.7 ± 0.7) tasks. However, the rate of increase in the RPE was more gradual during the force task in absolute time ($P = 0.006$). The rate of change in RPE was negatively correlated with the time to task failure ($r = -0.75$, $r^2 = 0.56$, $P < 0.001$), indicating that a greater rate of change in RPE was associated with a briefer time to task failure.

Factors that Contributed to Time to Failure: Regression Analysis

Regression analysis showed the rate of change in RPE and the increase in EMG burst rate of the tibialis anterior were the two significant predictors of time to failure for the force and position tasks combined. These variables explained 77% of the variance in the time to task failure ($r = 0.88$, $r^2 = 0.77$, $P < 0.01$).

DISCUSSION

The new findings of this study are that *1*) leg muscles exhibit a difference in the time to task failure for a position and force task; *2*) the difference in task duration for the dorsiflexor muscles was accompanied by more rapid rates of increase in neural indexes during the position task, including EMG agonist and antagonist activity, EMG bursting activity, perceived effort, fluctuations in motor output, and cardiovascular measures;

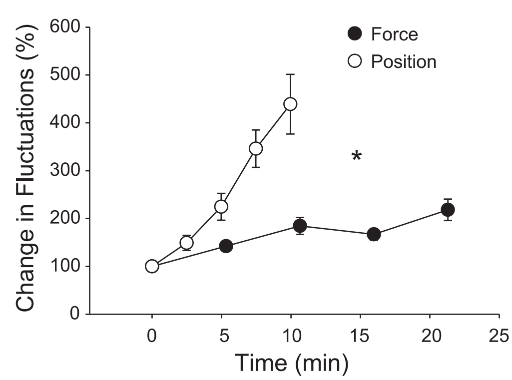

Fig. 6. Percent changes (mean ± SE) in the SD of fluctuations in the vertical direction for the force and position tasks. The values are means ± SE at 25% increments of the time to task failure for 30-s intervals. The change is expressed as a percentage of the value measured during the first 30-s interval at the start of the fatiguing contraction. The rate of change in the fluctuations was greater for the position task than the force task (*$P = 0.004$).

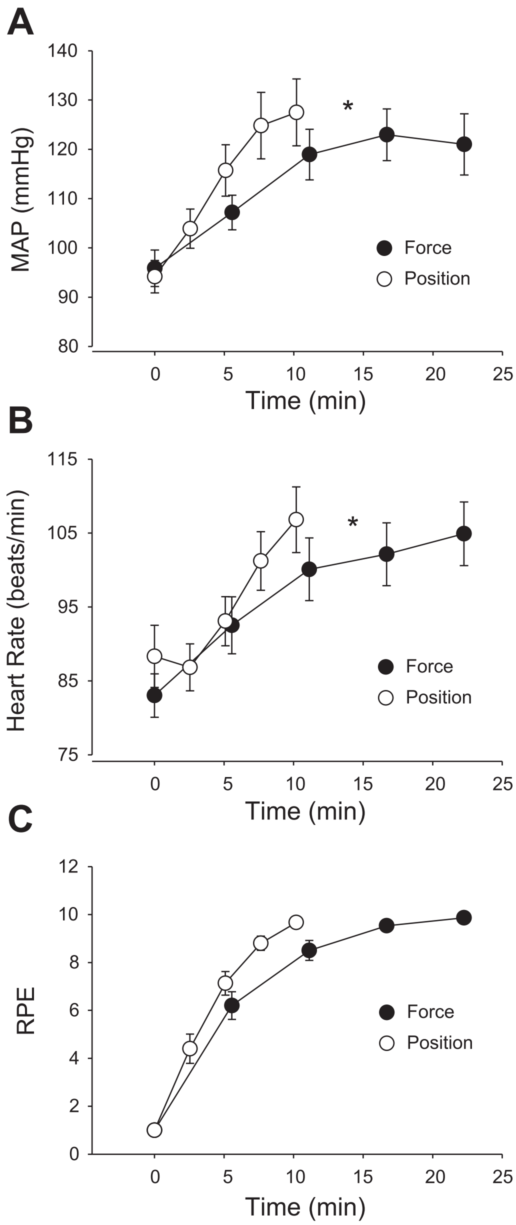

Fig. 7. The mean arterial pressure (MAP; *A*), heart rate (*B*), and ratings of perceived exertion (RPE; *C*) during the force and position tasks. Values are means ± SE at 25% increments of the time to task failure. Averages of 15-s intervals were used for the MAP and heart rate. The rates of increase in MAP and heart rate were greater during the position task compared with the force task (*$P < 0.05$).

3) coactivation levels were similar for the force and position task and did not explain the task difference in time to failure; and *4*) some of the difference in time to task failure may be attributed to activation of the quadriceps muscles that stabilized the lower leg (vastus lateralis) more during the position task or muscles that facilitated a longer task duration for the force task (rectus femoris).

The time to task failure was briefer for the position than the force task performed with the dorisflexor muscles, despite each subject exerting a similar load torque for the two tasks. MVC force was similar before the tasks and reduced to similar levels at termination of the tasks (~28–30%), indicating that performance was similar for each of the tasks. Accordingly, motivation and effort were similar between tasks, and RPE exerted at the same relative time and at the start and end of the two tasks were the same.

The difference in time to failure between the force and position task with the lower leg muscles was 53%. This difference is much greater than for the elbow flexor muscles when the forearm is in the vertical position (40, 41), but is similar to that for contractions performed at 20% MVC with the elbow flexor muscles when the arm was held horizontal (20, 21, 23, 39) and the first dorsal interosseous muscle (31). A comparison of the studies for the upper limb and this present study are shown in Fig. 8. The mechanism for the difference between the force and position task when maintaining a low force or load, therefore, appears independent of the muscle group and depends more on other factors, such as posture and involvement of accessory or synergist muscles. Muscle properties, such as fiber-type composition and the subsequent contractile properties, also appear to have little influence on the difference between the force and position task. The proportion of fiber types varies between the primary agonists of the elbow flexors and dorsiflexors: the biceps brachii is estimated to have 26% type I fiber area (24), and the tibialis anterior 63% type I area (15). Recruitment range of a muscle, however, will likely influence the magnitude of difference between the force and position task (31). The recruitment range of the tibialis anterior and elbow flexor muscles is similar (~90%) (26, 47), and so the difference between the force and position task at different contraction intensities should be similar for the two muscle groups. Thus comparison of the difference in the time to task failure of various muscles groups confirm that the mechanism is not mediated by muscular mechanisms.

One of the key findings in this study was that the physiological adjustments during the position task performed with the dorsiflexor muscles indicated a greater rate of increase in central neural activity and descending drive during the position task compared with the force task. This was indicated foremost by the increased rate of EMG activity and bursting activity of the agonist muscle, tibialis anterior, and an increased rate of

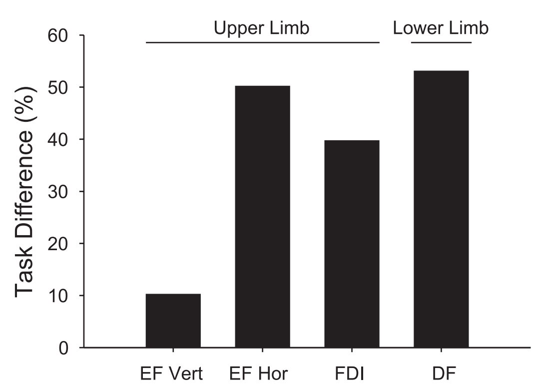

Fig. 8. The relative difference between the force task and position task performed at 20% of MVC for various muscle groups in 7 different studies. The percent difference (%) shown on the *y*-axis indicates the force task was longer in duration than the position task. Shown on the *x*-axis from *left* to *right*: the elbow flexor muscles when the forearm was held vertical [EF Vert, average of 2 studies (40, 41) and range of −1–22%]; the elbow flexor muscles when the forearm was held horizontal [EF Hor, average of 4 studies (20, 21, 23, 39) and range of 41–56%]; the first dorsal interosseous [FDI, data from one study (31)]; and the dorsiflexor muscles [DF, data from present study].

increase in effort (RPE). Accordingly, the most significant predictors of the variability in the time to task failure was RPE and bursting activity of the EMG of the tibialis anterior. Perceived effort is modulated by descending drive (4, 33). The mismatch between perceived effort and the sustained contraction at a submaximal force or load (21, 44) strongly suggests that central processes are important in impairing performance (46). Perceived effort of the lower leg during exercise differed between the tasks, despite the similar load torque, and provides evidence that the difference between the two tasks was centrally mediated.

EMG activity of the tibialis anterior, which is the primary agonist during dorsiflexion, increased more rapidly during the position task compared with the force task. The task difference in the amplitude of EMG activity was not due to recording conditions, because EMG activity was similar for the brief, nonfatiguing submaximal contractions at varying intensities performed on each experimental day before the fatiguing contraction. The more rapid increase in the tibialis anterior EMG activity during the position task was also reported for a low-force contraction with the first dorsal interosseous (31) and the elbow flexor muscles when the forearm was positioned vertically (41). The increase in EMG amplitude during a submaximal contraction is attributed to increased descending drive to the motoneuron pool (10, 23, 44), despite the nonlinear summation of motor unit action potentials in the EMG signal (8, 22). Consequently, motor unit recruitment increases, and there is modulation of discharge rates as the active motor units become fatigued and the required torque is maintained (3, 14). The difference between the tasks, therefore, represents a greater rate of motor unit recruitment during the position task. For the elbow flexor muscles, this was confirmed with single motor unit experiments (36), and our study suggests that this is probably similar for the dorsiflexor muscles. The increased rate of tibialis anterior EMG activity during the position task compared with the force task provides evidence that the net excitation output of the motor unit pool was greater during the position task, resulting in a greater rate of motor unit recruitment. Consistent with these findings, the fluctuations in motor output increased more rapidly during the position task than force task, as observed for the elbow flexor muscles (20, 21). Because the amplitude of the fluctuations increases with contraction intensity (5, 35), the greater rate of increase in the fluctuations in motor output during the position task likely indicated a more rapid recruitment of the motor unit pool.

Antagonist EMG (medial gastrocnemius) also increased more rapidly during the position task compared with the force task. Although antagonist EMG typically increases during submaximal fatiguing contractions with the dorsiflexor muscles (28) and upper limb muscles during the force and position task (18, 19, 21, 23, 31, 41), coactivation ratios have not been previously quantified for these tasks. Increased activation of antagonist muscles during a fatiguing contraction relative to the agonist activation (coactivation) may limit the time to task failure of a submaximal task (6, 37). Alternatively, a decrease in the coactivation ratio during the contractions would prolong the time to failure, but joint stability would be compromised. Our study substantiates that, although antagonist activation levels increase during the force and position task, coactivation ratios did not differ between tasks. Levels of coactivation were 15–20% during the fatiguing contractions and also did not alter during the sustained contraction (Fig. 4*B*), because the increase in agonist activation was paralleled by the antagonist activity. Differences in task failure between the force and position task with the lower leg muscles, therefore, cannot be attributed to greater activation of the one of the antagonist muscles compared with the agonist. We did not, however, record EMG from the soleus muscle and lateral gastrocnemius, which are also antagonists and may contribute to task failure. Nevertheless, because coactivation regulation is suprapsinal (27, 28) and coactivation of the medial gastrochemius did not differ between the tasks, our results provide evidence that the cause for the briefer time to task failure for the position task compared with the force task in the lower leg could be spinal in origin.

In this present study, the vastus lateralis muscle activation stabilized the lower leg at 90° of flexion and increased more rapidly for the position task compared with the force task during dorsiflexion. Thus increasingly greater activation of muscle was required to stabilize the lower leg during the position task while holding the inertial load. Synergist and accessory muscles are able to enhance or limit time to task failure of a low-force task (25, 39, 43, 45, 48). In contrast to the vastus lateralis, the average activation of the rectus femoris muscle, which is biarticulate and a hip flexor, was greater during the force task than the position task. While seated, hip flexion potentially increased force in the vertical direction and may have facilitated a longer time to failure during the force task compared with the position task. The difference in rectus femoris activation between tasks was significant but not large (Fig. 5*B*), and rectus femoris activation was not a significant predictor of the time to task failure. Nevertheless, the longer time to task failure during the force task may be, in part, attributed to involvement of the rectus femoris muscle.

Other variables that we measured provided evidence for a greater rate of increase in descending drive during the position task than the force task. This included the rate of the bursts of EMG activity, heart rate, and MAP. EMG bursting activity corresponds to the transient recruitment of motor units (17, 25). The increase in heart rate is modulated by central command (9, 12, 13), and MAP is driven by central command and peripheral reflexes (metaboreflex) during isometric fatiguing contractions (group III and IV afferent feedback to the spinal cord) (1, 34, 38). A greater metaboreflex during the position task leads to greater inhibition via presynaptic mechanisms. Consequently, we have indirect evidence that the position task likely involved a greater rate of increase in a broad range of neural processes compared with the force task, despite a similar load torque for the two tasks. These neural processes probably involved a reduction in peripheral excitatory input and greater descending drive to the motorneuron pool during the position task.

In conclusion, this is the first study to show the time to task failure is briefer for a position task compared with a force task, despite a similar load torque for a muscle group in the legs (dorsiflexor muscles). This study also highlighted that the difference in time to failure between the force and position tasks for the leg was influenced by synergist and accessory muscle activation, but not by coactivation of an antagonist muscle. Importantly, comparison with various muscle groups of the arm and dorsiflexor muscles suggests muscular mechanisms that determine contractile properties have limited influence on the difference between the force and position task. The briefer time to task failure for the position task during dorsiflexion involved greater rates of increase in neural processes that suggested an increased rate of descending drive and motor unit recruitment during the position task compared with the force task. These findings have implications for rehabilitation and ergonomics in minimizing fatigue during prolonged activation of the dorsiflexor muscles.

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