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Mottram, Carol J., Katrina S. Maluf, Jennifer L. Stephenson, Melissa K. Anderson, and Roger M. Enoka. Prolonged vibration of the biceps brachii tendon reduces time to failure when maintaining arm position with a submaximal load. *J Neurophysiol* 95: 1185–1193, 2006. First published November 9, 2005; doi:10.1152/jn.00807.2005. Vibration reduces the amplitudes of the tendon jerk response and the Hoffmann and stretch reflexes in the muscle exposed to the vibration, yet does not alter the time to task failure when the task involves exerting a submaximal force against a rigid restraint. Because the amplitude of the stretch reflex is greater when a limb acts against a compliant load than a rigid restraint, the purpose was to determine the influence of prolonged tendon vibration on the time to failure when maintaining limb position with the elbow flexor muscles. Twenty-five healthy men performed the fatiguing contraction by maintaining elbow angle at 1.57 rad until failure while supporting a load equal to 20% of maximal voluntary contraction (MVC) force. The fatiguing contraction was performed on 3 separate days with different levels of vibration applied to the biceps brachii tendon: no vibration, subthreshold for a tonic vibration reflex (TVR), and suprathreshold for a TVR. MVC force before the fatiguing contraction was similar across the three sessions (mean of 3 sessions: 313 ± 54 N, $P = 0.83$). Despite a similar decline in MVC force after the fatiguing contraction across conditions ($-18.0 \pm 8.0\%$, $P > 0.05$), the time to task failure was 3.7 ± 1.4 min for the suprathreshold TVR condition, 4.3 ± 2.1 min for the subthreshold TVR condition, and 5.0 ± 2.2 min for the no-vibration condition ($P < 0.0001$). The average EMG of the elbow flexor muscles was similar ($P = 0.22$) during the fatiguing contractions. However, the fluctuations in limb acceleration at task onset were greater for the suprathreshold TVR condition ($P < 0.01$), but were not different between the subthreshold TVR and no-vibration conditions ($P \geq 0.22$). Furthermore, the difference in the SD of limb acceleration between the no-vibration and vibration conditions was correlated with the difference in time to failure for the no-vibration and subthreshold TVR conditions ($P = 0.03$; $r^2 = 0.22$), but not for the no-vibration and suprathreshold TVR conditions ($P = 0.90$; $r^2 = 0.001$). These findings indicate that prolonged vibration reduced the time to failure of a sustained contraction when subjects maintained limb position, suggesting that peripheral inputs to the motor neuron pool play a significant role in sustaining a contraction during tasks that require active control of limb position.

INTRODUCTION

It has been known for several decades (Echlin and Fessard 1938; Granit and Henatsch 1956) that vibration excites the primary spindle endings (Brown et al. 1967a,b; Burke et al. 1976a) and produces a tonic vibration reflex (Burke et al. 1976b; De Gail et al. 1966; Eklund and Hagbarth 1966; Lance 1966) in the muscle exposed to the vibration. Although

short-term vibration (2–20 s) augments muscle force (Bongiiovanni and Hagbarth 1990; Ribot-Ciscar et al. 2003) and the discharge rates of motor units (Griffin et al. 2001) and primary afferents (Burke et al. 1976b; Roll et al. 1989), prolonged vibration (1–30 min) reduces muscle force (Bongiiovanni et al. 1990; Kouzaki et al. 2000), the tendon jerk response (Lance et al. 1973), and the Hoffmann (Cresswell and Löscher 2000; Desmedt and Godaux 1978) and stretch (Bove et al. 2003; Rymer and Hasan 1981; Schieppati et al. 2001) reflexes in the vibrated muscle. Furthermore, prolonged vibration of a muscle reduces the discharge of its primary spindle endings (Burke et al. 1976a; Hagbarth et al. 1976; Ribot-Ciscar et al. 1998; Roll et al. 1989).

Despite its influence on the function of the Ia circuit, prolonged tendon vibration does not alter the time to failure when the task involves exerting a submaximal force against a rigid restraint (Cresswell and Löscher 2000). Because muscle spindle sensitivity is augmented during precision tasks and reinforcement maneuvers (Hulliger 1993; Kakuda and Nagaoka 1998; Kakuda et al. 1996, 1997) and the amplitude of the stretch reflex is greater when the limb acts against a compliant load than a rigid restraint (Akazawa et al. 1983; Stein et al. 1995), there is uncertainty about whether the inhibitory effects of prolonged vibration on reflex responsiveness would influence time to failure during a task that involved heightened activation of the stretch reflex.

The time to task failure during a submaximal contraction is influenced by the type of load supported by the limb (Hunter and Enoka 2003; Hunter et al. 2002, 2003; Rudroff et al. 2005). For example, the time to failure during a sustained contraction was greater when the wrist pushed against a rigid restraint (force task) compared with when the subject maintained a constant limb position while supporting an equivalent inertial load (position task), despite the two tasks requiring each subject to exert the same net muscle torque about the elbow joint (Hunter et al. 2003; Rudroff et al. 2005). The synaptic input received by the motor neuron pool differs during these two tasks, however, as indicated by differences in the change in the discharge characteristics of the same motor unit when the two tasks were performed for the same duration (Mottram et al. 2005a). These findings indicated that the motor unit pool was activated more rapidly during the position task compared with the force task (Maluf et al. 2005) and suggest differences in the control strategies used by the nervous system when performing these two tasks (Maluf and Enoka 2005).

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The purpose of this study was to determine the influence of prolonged tendon vibration on the time to failure when maintaining limb position with the elbow flexor muscles. Because prolonged vibration alters the magnitude of the force fluctuations during an isometric contraction (Cresswell and Löscher 2000; Shinohara et al. 2005; Yoshitake et al. 2004) and thereby the amount of mechanical work performed during the task, a secondary purpose was to quantify the extent to which differences in limb acceleration induced by three levels of vibration contributed to changes in the time to failure across conditions. It was expected that different levels of vibration would produce a larger range of changes in limb acceleration to allow examination of the role of mechanical work in contributing to differences in the time to failure of the fatiguing contractions.

The hypothesis was that prolonged vibration applied to the biceps brachii tendon during the fatiguing contraction would reduce the time to failure but that this reduction would not be attributable to differences in limb acceleration across the three vibration conditions. The hypothesis was derived from a model that purports to explain differences in the time for failure of sustained contractions when the limb is restrained compared with when the task is to maintain limb position (Maluf and Enoka 2005). The findings indicated that, although the decline in maximal voluntary contraction (MVC) force was similar at task failure with and without vibration, the time to failure was less when vibration was applied to the biceps brachii tendon during the fatiguing contraction. Furthermore, the association between the difference in the fluctuations in limb acceleration and the difference in time to failure suggested that more mechanical work was performed during the application of submaximal vibration compared with the no-vibration condition, but not during the delivery of suprathreshold vibration. Some of these data have been presented in a preliminary report (Mottram et al. 2005b).

METHODS

Twenty-five healthy men (22 ± 4 yr; range, 18–39 yr) participated in the study. All subjects were moderately active and were right-handed (average laterality quotient score was 0.70 ± 0.21 ; range: 0.33–1.0), as identified by the Edinburgh Handedness Inventory (Oldfield 1971). None of the subjects had any known neurological disorder or cardiovascular disease and all were naive to the purpose of the experiment. The Human Research Committee at the University of Colorado approved the procedures, and the experiments were performed in accordance with the Declaration of Helsinki. Before participation in the study, all subjects gave written informed consent.

Experimental arrangement

Subjects were seated upright in an adjustable chair with the non-dominant arm abducted ~ 0.26 rad and the elbow resting on a padded support. The elbow joint was flexed to 1.57 rad and positioned midway between pronation and supination with the forearm parallel to the ground. One strap was placed around the subject's waist and chair, and two nylon straps were placed vertically over each shoulder to restrain the subject and to minimize shoulder movement. The hand and forearm were secured in a modified wrist-hand-thumb orthosis (Orthomerica, Newport Beach, CA).

Before performing the fatiguing contraction, the MVC force of the elbow flexor muscles was measured with a force transducer (900-N range, 89.7 N/V; JR-3, Woodland, CA) that was mounted on a custom-designed, adjustable support. The orthosis was rigidly at-

tached to the force transducer. The force detected by the transducer was recorded on-line using a Power 1401 A/D converter and Spike2 (Version 5.02) software (Cambridge Electronics Design, Cambridge, UK), and was displayed on a 17-in monitor that was located at eye level ~ 1.2 m in front of the subject. In addition, the compressive force under the elbow joint was recorded with an Entran transducer (ELW-D1-100L, 273.37-mV range) that was placed under a padded elbow support. The compressive force under the elbow was displayed on an oscilloscope and monitored on-line to ensure similar task performance across sessions.

Elbow angle during the position task was measured with an electrogoniometer (SG110 and K100, Biometrics, Cwmfelinfach, Gwent, UK) that was secured to the lateral side of the left elbow joint. A uniaxial, piezoresistive accelerometer (linear range of acceleration response ± 100 m/s²; model 7265A-HS, Endevco, San Juan Capistrano, CA) was mounted on an aluminum platform that was secured to the orthosis near the thumb to record acceleration in the vertical direction. Output from the electrogoniometer and accelerometer was recorded on-line. Elbow angle was displayed for the subject on a 17-in monitor.

The EMGs of the short and long heads of the biceps brachii, brachioradialis, upper trapezius, posterior deltoid, and triceps brachii muscles were recorded with bipolar surface electrodes (8 mm diam; silver-silver chloride) that were placed 16 mm apart (center-to-center) on the skin overlying the respective muscles. Electrodes were placed on one side of the innervation zone to minimize signal cancellation (Merletti et al. 2001). Reference electrodes were placed over the dorsal surface of the ulna at the elbow and over the superior surface of the acromion. The EMG of the brachialis muscle was measured with an intramuscular bipolar electrode inserted 3–4 cm proximal to the antecubital fold. The electrode comprised two stainless-steel wires (100 μ m diam) that were insulated with Formvar (California Fine Wire Company, Grover Beach, CA). One wire in each pair had the insulation removed for ~ 2 mm to increase the recording volume of the electrode. A surface electrode (8 mm diam) placed on the lateral epicondyle of the humerus served as the reference electrode. Surface and intramuscular EMG signals were amplified (500–2,000 times) and band-pass filtered (13–1,000 Hz) with Coulbourn modules (Coulbourn Instruments, Allentown, PA) before being displayed on an oscilloscope and collected on-line.

Experimental procedures

Each subject participated in one familiarization and three experimental sessions that were separated by at least 1 wk. In the experimental sessions, subjects performed the fatiguing contraction at 20% of maximum with the elbow flexor muscles of the left arm by holding a load suspended from the wrist until failure. In two of the three sessions, subjects performed the fatiguing contraction while receiving vibration to the common tendon of the biceps brachii at an intensity that was either below or above the threshold to evoke a tonic vibration reflex (TVR) (Eklund and Hagbarth 1966; Hagbarth and Eklund 1966; Lance 1966). In the other session, subjects performed the fatiguing contraction without vibration (no-vibration condition). The gain of the feedback signal for elbow angle was 1.5°/cm for all sessions, which is a value that has previously been shown not to influence either the time to failure or the rates of increase in perceived exertion, the pressor response, or the SD of limb acceleration across three separate sessions (Hunter et al. 2003).

Before the experimental sessions, each subject visited the laboratory for an introductory session to become familiar with the equipment and the procedures and to perform several trials of the isometric MVC task. The three experimental sessions consisted of 1) an assessment of the MVC force for the elbow flexor and extensor muscles, 2) measurement of the EMG-force relation with 5-s isometric contractions at 20, 40, and 60% MVC, 3) determination of the amplitude of vibration that induced a TVR, and 4) performance of the fatiguing

contraction to failure either with or without vibration and a subsequent MVC. The order of the three experimental sessions (no-vibration, subthreshold TVR vibration, or suprathreshold TVR vibration) was counterbalanced across subjects.

MVC FORCE. The protocol began with the subject performing three isometric MVC trials with the elbow extensor muscles and three trials with the elbow flexor muscles. The MVC task consisted of a gradual increase in force from zero to maximum over 3 s, with the maximal force held for 3 s. Efforts that the subject did not regard as maximal were rejected, and the visual gain of the force feedback was varied across trials to minimize the subject's awareness of differences in performance (Gandevia 2001). Subjects were given a 60- to 90-s rest between trials. When the peak forces from two of the three trials were not within 5% of each other, additional trials were performed until this was accomplished. The greatest force achieved by the subject was defined as the MVC force and was used as the reference for determining the 20% MVC contraction intensity for the fatiguing contraction.

EMG-FORCE RELATION. Subjects performed isometric contractions for 5 s at target forces of 20, 40, and 60% of MVC force. Subjects were given a 60-s rest between each contraction. The order of the contractions was randomized across subjects but remained constant for each individual subject on the 3 experimental days. These data were used to evaluate the reliability of the EMG measurements across sessions for each subject.

VIBRATION AMPLITUDE. Before performing the fatiguing contraction, vibration at 100 Hz was applied to the common biceps brachii tendon of the relaxed muscle using an electromagnetic mechanical stimulator (model V203, Ling Dynamic Systems, Yalesville, CT) with a 1.5-cm-diam probe. The arm was supported during this measurement. The probe was cupped around the tendon to minimize displacement. The force applied by the probe on the tendon was measured with a force transducer (model MLP-10, Transducer Techniques, Temecula, CA) that was attached in series with the vibrator and probe. This force was maintained at 2.5 N during each experiment. Peak-to-peak vibration was monitored with an accelerometer (model 7265A-HS, Endevco; linear range of acceleration response $\pm 100 \text{ m/s}^2$) that was mounted on a platform connected to the vibration probe. Vibration began at a level that was below sensory perception and the peak-to-peak amplitude of the vibration was slowly increased until a stable tonic vibration reflex was observed in EMG amplitude ($< 5\%$ MVC for at least 1 elbow flexor muscle). Subjects were instructed to count backward from 100 in multiples of 7 to distract them from the vibration. Once a TVR in any of the elbow flexor muscles was noted, the peak-to-peak amplitude of the vibration was recorded and the vibrator was turned off. Subjects rested for ≥ 5 min until MVC force was within 5% of the initial value. The peak-to-peak amplitude of the vibration was set at approximately one-half of that for the TVR for the subthreshold TVR condition and twice for the suprathreshold TVR condition. Vibration amplitude at task onset was adjusted as necessary to ensure that the required condition (presence or absence of a TVR) was met, as indicated by the EMG activity. For the no-vibration condition, the vibrator was placed on the subject's tendon in the same manner as the two vibration conditions and subjects received the same instructions; they were not told that the vibrator was turned off.

FATIGUING CONTRACTION. The fatiguing contraction was performed at a target force of 20% MVC as determined from the MVC performed during the first experimental session. The subject was required to maintain a right angle at the elbow joint while supporting an inertial load suspended from the wrist. Subjects were provided with visual feedback of elbow angle during each experimental session. For all sessions, the vibrator was placed over the common biceps brachii tendon, and vibration began at the start of the fatiguing contraction at the predetermined level. Subjects were not told that they received

different levels of vibration over the three sessions. Subjects were verbally encouraged and were offered a monetary incentive to sustain the task for as long as possible. The fatiguing contraction was terminated when the elbow angle declined by 0.17 rad from a right angle for > 3 s, as detected by custom software that continuously monitored the position signal. In addition, the fatiguing contraction was terminated when the subject was unable to maintain the forearm in a neutral position in the transverse plane (no internal rotation about the shoulder was allowed) for > 3 s, despite strong verbal encouragement. The time from the beginning to the end of the fatiguing contraction was recorded as the time to failure.

CARDIOVASCULAR MEASURES. Heart rate and blood pressure were monitored during the fatiguing contraction with an automated beat-by-beat, blood pressure monitor (Finapres 2300, Ohmeda, Madison, WI). The blood pressure cuff was placed around the middle finger of the dominant hand, the arm was supported on a table at heart level with both the shoulder abducted, and the elbow flexed to a right angle.

MEASURE OF EXERTION. The rating of perceived exertion (RPE) was assessed with the modified Borg 10-point scale (Borg 1982). Subjects were instructed to focus the assessment of effort on the arm muscles performing the task. The scale was anchored so that 0 represented the resting state and 10 corresponded to the strongest effort that the elbow flexor muscles could sustain. It was assumed that the rating scale had equivalent intervals for the purpose of conducting the ANOVA on ratio data.

Data analysis

Force, acceleration, elbow angle, mean arterial pressure, heart rate, and EMG were collected on-line and subsequently digitized (A/D converter, 16-bit resolution) and analyzed off-line using the Spike2 (version 5.02) data analysis system. The surface and intramuscular (brachialis) EMGs were digitized at 2,083 samples/s. The force, position, acceleration, and blood pressure signals were digitized at 200 samples/s.

MVC force was quantified as the peak force obtained during the MVC task. The maximal EMG for each muscle was determined as the average value over a 0.5-s interval that was centered about the peak of the rectified EMG during the MVC.

Acceleration in the vertical direction was recorded during the fatiguing contraction and was compared for the first 20 s, 10 s on either side of 25, 50, and 75% of the time to failure, and the last 20 s of the contraction. The SD of acceleration was also determined for the same duration within a subject for each task. The difference in the SD of acceleration between tasks was determined by subtracting the average SD during each vibration condition from the average SD during the no-vibration condition.

The EMG activity of the elbow flexor muscles, upper trapezius, posterior deltoid, and triceps brachii muscles during the fatiguing contraction were quantified in two ways: 1) for statistical purposes, as averages of the rectified EMG (aEMG) over the first 20 s, 15 s on either side of 25, 50, and 75 of time to failure, and the last 20 s of the contraction; and 2) for graphic presentation, as averages of the rectified EMG (aEMG) for every 1% of the contraction time. The EMG was normalized to the peak EMG obtained during the MVC for the elbow flexor and extensor muscles and to the aEMG at the start of the task for the upper trapezius and posterior deltoid. The mean arterial pressure, heart rate, and perceived exertion were quantified at the same 25% interval time-points as the other variables.

Statistical analysis

A repeated-measures ANOVA (SPSS version 13.0) was used to compare the time to failure for the three sessions. A two-factor ANOVA (3 tasks \times 2 times) and one-way, repeated-measures ANOVAs were used to compare the MVC force before and after each

task. Two-factor, repeated-measures ANOVAs (3 tasks \times 5 time-points) were used to compare the dependent variables at 25% intervals of task duration for elbow force, perceived exertion, mean arterial pressure, heart rate, aEMG for the upper trapezius, posterior deltoid, and triceps brachii, and the SD for acceleration across the three conditions. The SD for acceleration was also compared at absolute time-points that corresponded to 25% intervals of the shortest task within a subject. Three-factor, repeated-measures ANOVAs were used to compare aEMG of the elbow flexor muscles (4 muscles \times 3 tasks \times 5 time-points) and the EMG-force relation for the isometric contractions of the elbow flexor muscles at three contraction intensities (20, 40, 60%; 4 muscles \times 3 sessions \times 3 intensities). A two-factor, repeated-measures ANOVA was used to compare the rate of increase in the aEMG of the elbow flexor and extensor muscles across sessions. The corresponding EMG-force relation of the antagonist triceps brachii muscle was assessed with a two-factor ANOVA (3 sessions \times 3 intensities).

Linear and nonlinear (SD for acceleration) slope analyses were conducted for the three conditions at absolute time-points to determine the rate of change in the dependent variables. A linear regression analysis was used to quantify the association between the difference in time to task failure and the difference in the average SD for acceleration across tasks.

When ANOVAs yielded significant interactions, post hoc comparisons were performed using the Bonferroni adjustment for multiple comparisons and dependent *t*-test to identify the source of differences between tasks. The alpha level for all statistical tests was 0.05, except for paired comparisons, when the alpha level was adjusted with a Bonferroni correction. Data are reported as means \pm SD within the text and displayed as means \pm SE in the figures.

RESULTS

MVC force before the fatiguing contractions was similar ($P = 0.83$; Fig. 1A) in the no-vibration (314 ± 55 N), the subthreshold TVR (311 ± 53 N), and the suprathreshold TVR (313 ± 56 N) sessions. Furthermore, MVC force after determining vibration amplitude for the TVR and before beginning the fatiguing contraction was within $1.5 \pm 5.0\%$ of the initial MVC force and did not differ across sessions ($P = 0.37$). The percent decline in MVC force after the fatiguing contraction was similar for the no-vibration ($-19 \pm 9\%$), subthreshold TVR ($-19 \pm 9\%$), and suprathreshold TVR ($-16 \pm 7\%$; $P = 0.09$) sessions.

Pilot experiments confirmed that short-term vibration excited muscle spindle primary endings, because a tonic vibration reflex was observed in the biceps brachii after 10 s of vibration was applied to the relaxed muscle. Prolonged vibration, however, reduced the efficacy of the spindle-induced facilitation of the motor neuron pool. Despite exerting similar net muscle torques during the fatiguing contractions and constant criteria for task termination, the time to task failure was briefest for the suprathreshold TVR condition (3.7 ± 1.4 min), intermediate for the subthreshold TVR condition (4.3 ± 2.1 min), and longest for the no-vibration condition (5.0 ± 2.2 ; $P < 0.001$; Fig. 1B). Vibration of the biceps brachii tendon that did not induce a TVR reduced the time to failure by 13% compared with the no-vibration condition ($P < 0.001$), whereas vibration of the biceps brachii tendon that did induce a tonic vibration reflex reduced the time to failure by 22% compared with the no-vibration condition ($P < 0.001$).

The similarity in the net muscle torque for the three sessions was underscored by comparable values for the mean vertical force exerted under the elbow joint during the no-vibration

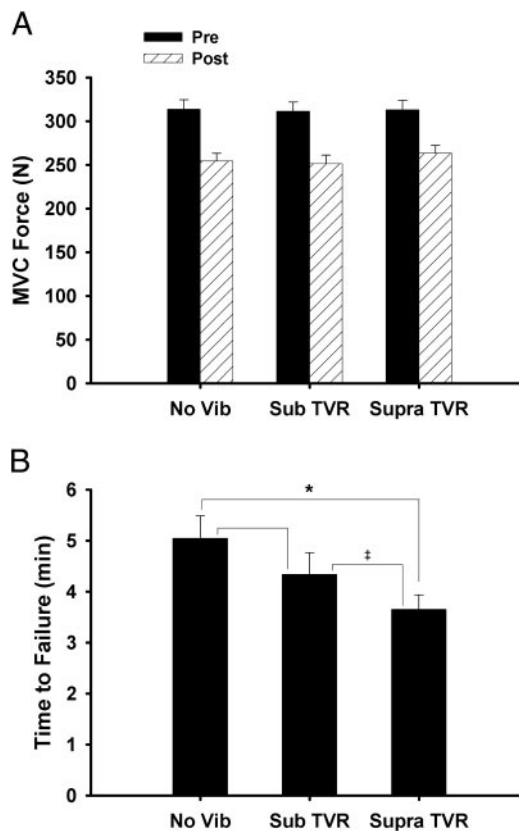


FIG. 1. Maximal voluntary contraction (MVC) force (A) and time to task failure (B) for the 3 vibration conditions. Initial MVC forces (313 ± 54 N) and values recorded after fatiguing contractions (256 ± 47 N) were similar across the 3 conditions ($P = 0.09$). Time to task failure was 3.7 ± 1.4 min for the suprathreshold tonic vibration reflex (TVR) condition, 4.3 ± 2.1 min for the subthreshold TVR condition, and 5.0 ± 2.2 min for the no-vibration condition ($P < 0.001$). * $P < 0.001$, † $P = 0.002$, ‡ $P = 0.015$.

(38 ± 53 N), subthreshold TVR (45 ± 48 N), and suprathreshold-TV (30 \pm 47 N; $P = 0.13$) sessions.

Vibration amplitude

The vibration amplitude necessary to evoke a TVR was consistent within subjects across the two vibration conditions ($P = 0.30$): subthreshold TVR session = 0.19 ± 0.13 mm (range, 0.06–0.60 mm) and suprathreshold TVR session = 0.22 ± 0.17 mm (range, 0.05–0.70 mm). Peak-to-peak amplitude of the vibration during the fatiguing contraction was 0.09 ± 0.10 mm (range, 0.01–0.41 mm) for the subthreshold TVR session and 0.43 ± 0.23 mm (range, 0.10–0.75 mm) for the suprathreshold TVR session. These values corresponded to peak-to-peak vibration amplitudes of $37 \pm 17\%$ of that necessary to evoke a TVR during the subthreshold TVR session compared with $219 \pm 75\%$ during the suprathreshold TVR session.

Perceived exertion and cardiovascular measures

Perceived exertion was similar at the start of the fatiguing contractions (1.1, 1.3, and 1.0 for the no-vibration, subthreshold TVR, and suprathreshold TVR sessions, respectively), but increased more rapidly to a value of 10 during the subthreshold and suprathreshold TVR sessions compared with the no-vibra-

tion session (task \times time $P < 0.001$; 1-way ANOVA slope comparison $P < 0.001$). In contrast, heart rate was similar at the start of the three fatiguing contractions, and it increased at a similar rate ($P = 0.75$). Mean arterial pressure was also similar at the start of the three contractions ($P = 0.96$), but achieved a lower final value ($P = 0.004$) during the suprathreshold TVR session (117 ± 16 mmHg) compared with the no-vibration session (130 ± 15 mmHg).

EMG-force relation

The aEMG for the elbow flexor muscles was recorded in each of the three sessions during 5-s isometric contractions at 20, 40, and 60% of maximum. Average EMG increased with contraction intensity ($P < 0.001$) and was similar across sessions ($P = 0.96$), indicating a consistent relation between aEMG and force for the elbow flexor muscles across sessions.

Adjustments in average EMG

Representative EMG data for a typical subject performing the fatiguing contraction during two of the vibration conditions are shown in Fig. 2. The aEMG of the elbow flexor muscles was similar within muscles for the three conditions ($P = 0.22$; Fig. 3). Slope analyses revealed that the rate of increase in the elbow flexor and extensor EMG was also similar across conditions for the short head of biceps brachii ($P = 0.95$), long head of biceps brachii ($P = 0.17$), brachialis ($P = 0.12$), brachioradialis ($P = 0.09$), and triceps brachii ($P = 0.33$). The mean aEMG of triceps brachii increased with time ($P < 0.001$) by similar amounts during the no-vibration ($2.6 \pm 2.2\%$), subthreshold TVR ($2.6 \pm 3.4\%$), and suprathreshold TVR ($2.7 \pm 2.2\%$, $P = 0.92$) sessions. The aEMG of the brachialis muscle was greater than that for the other elbow flexor muscles ($P < 0.001$). The mean aEMG for the brachialis muscle collapsed across sessions ($21.5 \pm 16.5\%$) was significantly greater ($P \leq 0.002$) than that for the short head of biceps brachii ($12.0 \pm 12.5\%$), long head of biceps brachii ($13.0 \pm 16.5\%$), and brachioradialis ($13.5 \pm 8.0\%$).

The amplitude of two accessory muscles (upper trapezius and posterior deltoid) was normalized to the value recorded at the onset of each fatiguing contraction. The amplitude of the normalized aEMG for the posterior deltoid was similar ($P < 0.001$) at all time-points from the start through 75% of task duration for the no-vibration ($251 \pm 547\%$), subthreshold TVR ($145 \pm 297\%$), and suprathreshold TVR ($128 \pm 338\%$) conditions. However, it was lower at task termination for the suprathreshold TVR condition ($676 \pm 745\%$) compared with the no-vibration condition ($11,175 \pm 1,071\%$, $P = 0.04$). The amplitude of the normalized aEMG for upper trapezius increased at the same rate and reached similar values at task termination for the no-vibration ($239 \pm 251\%$), subthreshold TVR ($178 \pm 215\%$), and suprathreshold TVR ($229 \pm 634\%$) conditions ($P = 0.72$).

Fluctuations in acceleration across conditions

The SD of vertical limb acceleration increased progressively ($P < 0.001$; Fig. 4) at a rate that was similar for the three conditions ($P = 0.15$). The SD of acceleration was significantly greater for the suprathreshold TVR condition compared

with the subthreshold TVR and no-vibration conditions at the start and during the first 25% of the task duration ($P \leq 0.005$) and was greater for the suprathreshold TVR compared with the subthreshold TVR condition at 50% of task duration ($P =$

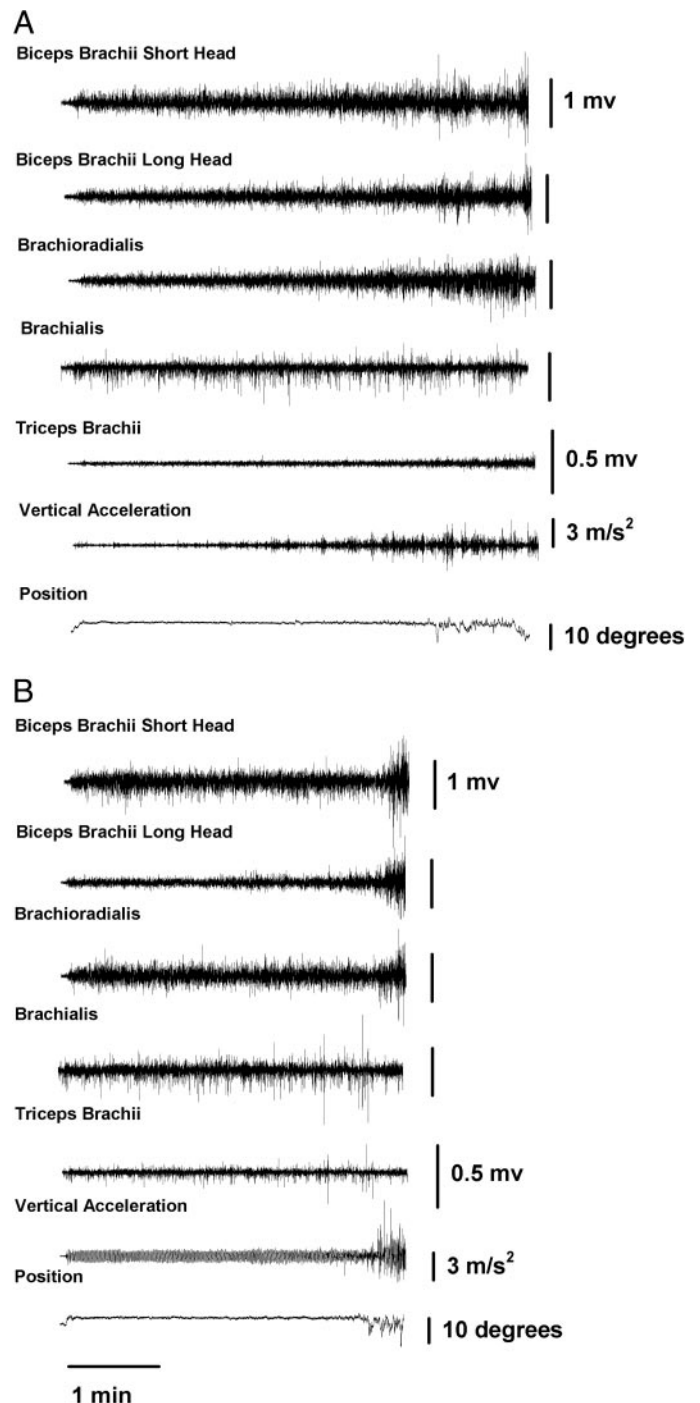


FIG. 2. Representative data from 1 subject for 2 of the vibration conditions: (A) no-vibration condition and (B) suprathreshold TVR condition. Time to failure was 3.8 min for the suprathreshold TVR condition, 4.6 min for the subthreshold TVR condition, and 5.2 min for the no-vibration condition. Rate of increase in the interference EMG for the brachialis, long head of biceps brachii, short head of biceps brachii, brachioradialis, and triceps brachii was similar for the 3 conditions. Rate of increase in SD of vertical acceleration was similar across the 3 conditions, and average elbow angle (bottom trace) remained constant during the 3 conditions.

0.002). However, fluctuations in limb acceleration were not significantly different for subsequent time-points and were similar at task termination for the no-vibration (0.94 ± 0.69 m/s²), subthreshold TVR (0.73 ± 0.40 m/s²), and supra-threshold TVR (0.83 ± 0.33 m/s²) conditions, respectively ($P \geq 0.12$).

Linear regression analyses revealed that the difference in the acceleration SD between conditions was correlated with the difference in time to failure between the no-vibration and

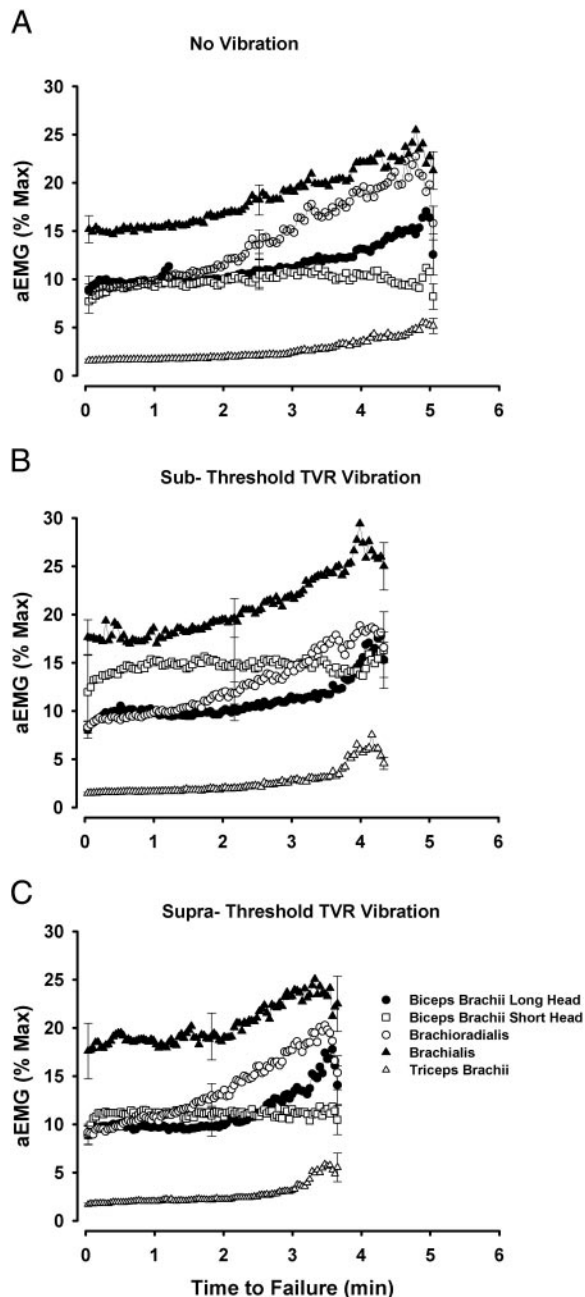


FIG. 3. Average EMG activity (aEMG) of elbow flexor muscles was similar across the 3 conditions ($P = 0.22$). aEMG was normalized to maximal values recorded during MVC trials. Each data point corresponds to an average value for 1% of task duration. SE bars are indicated at start, middle, and end of each aEMG. Brachialis muscle had up to twice the normalized aEMG compared with brachioradialis muscle and short and long heads of biceps brachii ($P < 0.001$). Triceps brachii aEMG increased similarly with time during the 3 conditions ($P = 0.92$).

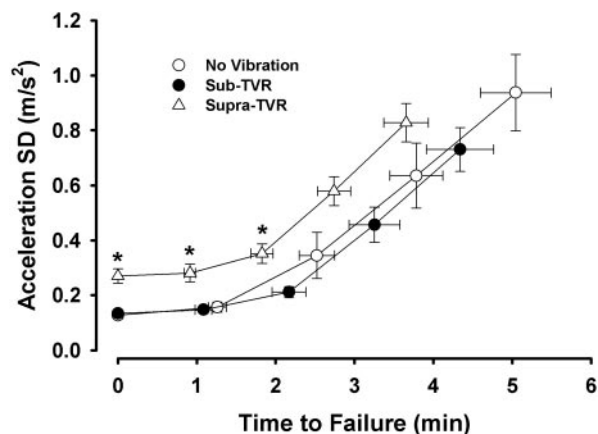


FIG. 4. Rate of increase in SD of limb acceleration was similar for the 3 vibration conditions ($P < 0.001$). Data (mean \pm SE) are shown at start and at times that corresponded to 25, 50, 75, and 100% of task duration. SD for vertical limb acceleration was greater at the start and at 25% of task duration for suprathreshold TVR condition compared with no-vibration and subthreshold TVR conditions and at 50% of task duration for subthreshold TVR condition compared with suprathreshold TVR condition ($P = 0.03$). SD of acceleration at task failure was similar for the 3 gain conditions ($P \geq 0.12$). * $P \leq 0.005$ compared with subthreshold TVR condition. † $P \leq 0.005$ compared with no-vibration condition.

subthreshold TVR conditions ($P = 0.03$; $r^2 = 0.22$; Fig. 5A), whereas there was no relation between these variables for the no-vibration and suprathreshold TVR conditions ($P = 0.90$; $r^2 = 0.001$; Fig. 5B).

DISCUSSION

The purpose of this study was to determine the influence of prolonged tendon vibration on the time to failure when maintaining limb position with the elbow flexor muscles. Vibration reduced the duration that the fatiguing contraction could be sustained. The reduction in time to task failure was associated with the difference in the SD of limb acceleration between the no-vibration and subthreshold TVR conditions but not between the no-vibration and suprathreshold TVR conditions. Furthermore, there was no difference in the rate of change in EMG activity of the elbow flexor muscles across the three vibration conditions. These findings suggest that different mechanisms were responsible for the reduction in the time to failure for the subthreshold and suprathreshold TVR conditions.

Prolonged vibration and the time to task failure

Although prolonged vibration does not influence the time to failure when the task involves exerting a submaximal force against a rigid restraint (Cresswell and Löscher 2000), these results indicate that it does have an effect on the duration that limb position can be maintained. The difference in the influence of vibration during the two tasks is consistent with a greater level of activity in the stretch reflex pathway during the performance of tasks that involve the control of limb position (Maluf and Enoka 2005). Presumably, the inhibitory effects of prolonged vibration on reflex responsiveness (Shinohara et al. 2005) are greater when maintaining limb position compared with exerting a constant force.

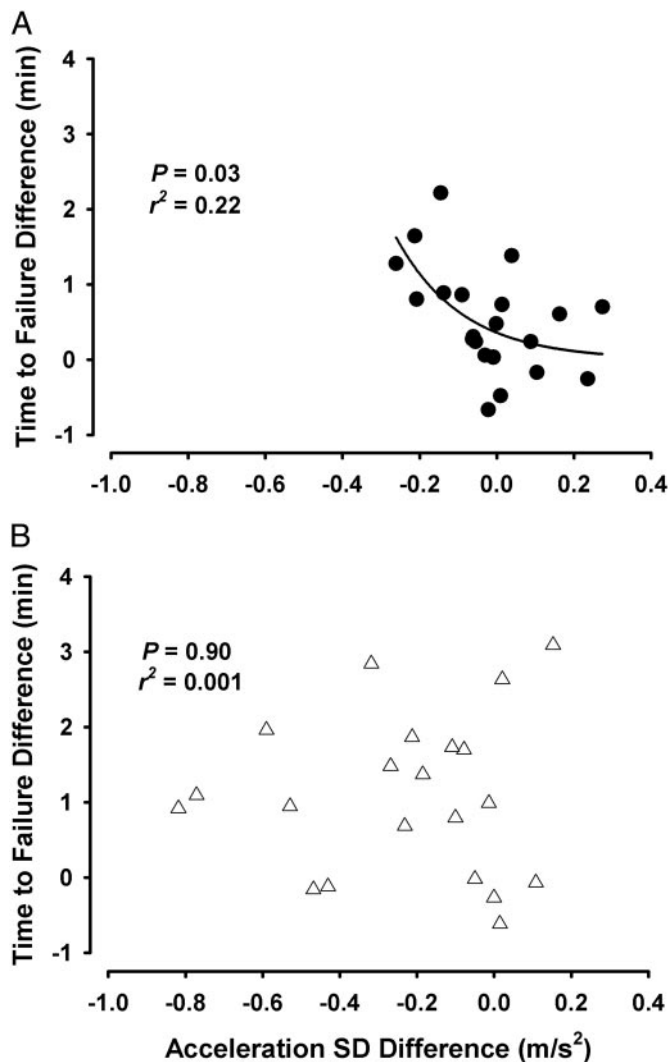


FIG. 5. Association between difference in time to failure and difference in acceleration SD for the 3 conditions. A: no-vibration and subthreshold TVR conditions. B: no-vibration and suprathreshold TVR conditions. Each data point corresponds to value for 1 subject. Average SD of acceleration was determined at the same absolute time within subjects based on duration of the briefest contraction. Difference in SD of acceleration was associated with difference in time to failure between no-vibration and subthreshold TVR conditions ($P = 0.03$; $r^2 = 0.22$; A), but not between no-vibration and suprathreshold TVR conditions ($P = 0.90$, $r^2 = 0.001$; B). One outlier was removed, and 3 other subjects were discarded because their acceleration signals were pulsed by the vibrator.

Time to failure and limb acceleration

Vibration simultaneously influences both Ia function (Schieppati et al. 2001) and force fluctuations (Cresswell and Löscher 2000; Shinohara et al. 2005; Yoshitake et al. 2004). Because the net muscle torque and limb position remained constant across the three vibration conditions, comparison of the SD of acceleration provides a measure of the relative mechanical work performed during the three conditions. Although there was no association between the difference in the SD of acceleration and the difference in time to failure for the no-vibration and suprathreshold TVR conditions, 22% of the variability in the time to failure during the subthreshold TVR conditions could be explained by the difference in the SD of acceleration. Thus the briefer duration for the suprathreshold TVR condition was not caused by the perfor-

mance of more mechanical work compared with the no-vibration condition. In contrast, the difference in work during the subthreshold TVR and no-vibration conditions did contribute to the briefer duration for the TVR condition. Nonetheless, these results suggest that the effects of vibration on the time to failure of a position task are more likely caused by adaptations within the CNS and that mechanical work did not contribute to the reduced time to failure for the suprathreshold TVR condition.

Average EMG of the elbow flexor muscles across conditions

Despite the differences in time to failure for the three conditions, the amplitude of the aEMG for the short and long heads of biceps brachii, brachioradialis, and brachialis was similar for all three conditions. Furthermore, there were no differences in the rates of increase in the aEMG across sessions. These results suggest that subjects maintained the same net muscle torque across the three vibration conditions. Furthermore, the rates of increase in aEMG for two accessory muscles (upper trapezius and posterior deltoid) were similar across the three vibration conditions. Because the time to task failure varied across the vibration conditions, the similarity in the amplitude and the rate of change in aEMG indicates that the input to the motor neuron pool varied across these conditions and required adjustments so that the motor output remained constant for as long as possible.

Cardiovascular measures

There were no differences across the three vibration conditions in the initial or final values of the heart rate or in its rate of increase, which suggests that those features of the motor command (Gandevia and Hobbs 1990; Gandevia et al. 1993; Ogoh et al. 2002) that control heart rate were not influenced by the level of vibration. Although the rate of increase in the mean arterial pressure was similar across the three conditions, mean arterial pressure was lower at task failure for the suprathreshold TVR condition compared with the no-vibration condition, whereas mean arterial pressure reached similar scores for the subthreshold TVR and no-vibration conditions. This result indicates that the peripheral and central regulatory mechanisms (Kaufman et al. 1988; Rowell and O’Leary 1990) that help maintain muscle perfusion during a sustained contraction responded differently during suprathreshold vibration compared with the no-vibration and subthreshold TVR conditions.

Potential mechanisms responsible for the effect of vibration

The reason for applying prolonged vibration to the biceps brachii tendon during a fatiguing contraction was to reduce the afferent input to the alpha motor neuron pool. Previous research provides convincing evidence that prolonged vibration depresses the Ia reflex pathway either by presynaptic inhibition of input to the alpha motor neuron pool (Hultborn et al. 1987), by refractoriness of Ia afferents (Hagbarth 1973), or by depletion of neurotransmitter in the group Ia afferents (Abbruzzese et al. 2001; Bongiovanni et al. 1990; Curtis and Eccles 1960). The net effect of these mechanisms is to remove the support for a voluntary contraction that is provided by the gamma motor neurons.

A number of reports have established that afferent input facilitates the motor neuron pool during voluntary contractions

(Macefield et al. 1993; Schieppati et al. 2001; Sinkjær et al. 1996). For example, acute deafferentation of the tibialis anterior muscle, which removes the muscle spindle support of a voluntary contraction, reduces the discharge rate of motor neurons during maximal and submaximal voluntary contractions (Macefield et al. 1993). Furthermore, afferent input is critical for adjustment of muscle activity during finely controlled movements (Kakuda et al. 1996; Nafati et al. 2005; Ribot-Ciscar et al. 2000), and the gain of the reflex response is heightened during tasks requiring the control of limb position (Akazawa et al. 1983). Thus the vibration-induced reduction in afferent input likely contributed to the briefer time to failure during a task that required the maintenance of limb position.

Although vibration may influence other receptors, such as the Golgi tendon organ, these potential effects did not influence time to failure in a previous study when the limb was restrained (Cresswell and Löscher 2000). It seems likely therefore that the effects of vibration were most pronounced in those receptors involved in maintaining limb position and that feedback from these peripheral afferents have a significant influence on the duration that a contraction can be sustained when the goal of the task is to maintain a constant limb position. This finding contrasts with previous observations when the limb was restrained, and therefore provides the basis for further study of the potential compensatory interactions between changes in afferent input and corticospinal drive during sustained contractions.

In summary, this report provides the first evidence that prolonged vibration applied to the biceps brachii tendon while maintaining arm position reduces the time to task failure. The reduction in time to failure was proportional to the amplitude of the vibration. The reduction in time to failure could be explained partially by the performance of greater mechanical work when the vibration was subthreshold for a TVR, but not when it was suprathreshold for a TVR. Nonetheless, these findings suggest that peripheral inputs to the motor neuron pool play a significant role in sustaining a contraction when performing tasks that require active control of limb position while supporting an inertial load.

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