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J Neurophysiol 94:2878-2887, 2005. First published Jul 6, 2005; doi:10.1152/jn.00390.2005

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Frequency Modulation of Motor Unit Discharge Has Task-Dependent Effects on Fluctuations in Motor Output

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Submitted 18 April 2005; accepted in final form 27 June 2005

Mottram, Carol J., Evangelos A. Christou, François G. Meyer, and Roger M. Enoka. Frequency modulation of motor unit discharge has task-dependent effects on fluctuations in motor output. *J Neurophysiol* 94: 2878–2887, 2005. First published July 6, 2005; doi:10.1152/jn.00390.2005. The rate of change in the fluctuations in motor output differs during the performance of fatiguing contractions that involve different types of loads. The purpose of this study was to examine the contribution of frequency modulation of motor unit discharge to the fluctuations in the motor output during sustained contractions with the force and position tasks. In separate tests with the upper arm vertical and the elbow flexed to 1.57 rad, the seated subjects maintained either a constant upward force at the wrist (force task) or a constant elbow angle (position task). The force and position tasks were performed in random order at a target force equal to $3.6 \pm 2.1\%$ (mean \pm SD) of the maximal voluntary contraction (MVC) force above the recruitment threshold of an isolated motor unit from the biceps brachii. Each subject maintained the two tasks for an identical duration (161 ± 93 s) at a mean target force of $22.4 \pm 13.6\%$ MVC. As expected, the rate of increase in the fluctuations in motor output (force task: SD for detrended force; position task: SD for vertical acceleration) was greater for the position task than the force task ($P < 0.001$). The amplitude of the coefficient of variation (CV) and the power spectra for motor unit discharge were similar between tasks ($P > 0.1$) and did not change with time ($P > 0.1$), and could not explain the different rates of increase in motor output fluctuations for the two tasks. Nonetheless, frequency modulation of motor unit discharge differed during the two tasks and predicted ($P < 0.001$) both the CV for discharge rate (force task: 1–3, 12–13, and 14–15 Hz; position task: 0–1, and 1–2 Hz) and the fluctuations in motor output (force task: 5–6, 9–10, 12–13, and 14–15 Hz; position task: 6–7, 14–15, 17–19, 20–21, and 23–24 Hz). Frequency modulation of motor unit discharge rate differed for the force and position tasks and influenced the ability to sustain steady contractions.

INTRODUCTION

The variability in motor output during a submaximal contraction depends on the type of load supported by the limb (Hunter et al. 2002, 2003; Maluf et al. 2005; Rudroff et al. 2005). The rate of increase in the fluctuations in motor output during a sustained contraction, for example, has been found to be less when the wrist pushed against a rigid restraint (force task) compared with when the limb supported an equivalent inertial load (position task), despite the two tasks requiring a similar net muscle torque about the elbow joint (Hunter et al. 2002; Mottram et al. 2005).

The different rates of increase in the fluctuations of motor output during the two tasks have been associated with the

normalized variability (coefficient of variation, CV) in motor unit discharge rate (Mottram et al. 2005). Nonetheless, the CV for motor unit discharge is not always a strong predictor of the motor output variability (Semmler et al. 1998, 2000) for at least three reasons: first, the amplitude of the CV for motor unit discharge provides only an *average* measure of the variability in discharge, which is modulated both by inputs to the motor neuron pool (De Luca et al. 1982; Farmer et al. 1993; McAuley and Marsden 2000) and by synaptic noise (Calvin and Stevens 1968; Jones et al. 2002; Matthews 1996). Second, the fluctuations in motor output are associated with the oscillatory activity of *multiple* active motor units (De Luca et al. 1985), whereas the CV for discharge rate reflects the characteristics of a single motor unit. Third, the strength of the association between the variability in motor unit discharge and motor output depends on the difference between the target force and the recruitment threshold of the recorded motor unit (Moritz et al. 2005; Person and Kudina 1972).

An alternative approach to identify the origin of the fluctuations in motor output is to compare the frequency content of the rate at which motor units discharge action potentials with the frequency content of the motor output. Accordingly, studies have demonstrated that slow (0–3 Hz) and fast (16–32 Hz) oscillations in discharge rate during submaximal contractions (De Luca et al. 1982, 1985; Farmer et al. 1993) can cause fluctuations in motor output at similar frequencies (Erimaki and Christakos 1999; Halliday et al. 1999; Kakuda et al. 1999; Vaillancourt et al. 2002).

One limitation of these coherence analyses, however, is that they only identify common frequencies in both signals. Such an analysis does not detect the influence of frequency modulation in dissimilar bands; for example, the contribution of motor unit discharge at 13–22 Hz to the 8- to 12-Hz oscillations in force observed during isometric contractions (Elble and Randall 1976). Furthermore, changes in the resonant frequency of the limb arising from variation in its inertia will affect the load-dependent component of the fluctuations in motor output (Halliday et al. 1999; Mayston et al. 2001; Stiles and Randall 1967) and cause the frequency modulation of motor unit discharge to influence the motor output differently during the force and position tasks.

The purpose of the study was to examine the contribution of frequency modulation of motor unit discharge to the fluctuations in the motor output during sustained contractions with the force and position tasks. A multiple-regression analysis was

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used to compare the modulation of discharge rate and motor output during the two tasks. The hypothesis was that different frequencies in the motor unit discharge would contribute to the fluctuations in the motor output for the force and position tasks. Preliminary data have been presented previously in abstract form (Christou et al. 2004a).

METHODS

The data used for the present investigation were obtained from a previous study that examined the discharge characteristics of the same motor unit in biceps brachii during the performance of two types of fatiguing contractions (Mottram et al. 2005). The analysis differed in two ways between studies: First, four motor units from the previous study [$n = 32$, recruitment threshold mean \pm SD: $18.9 \pm 11.2\%$ maximum voluntary contraction (MVC)] were not used in the current study ($n = 28$, recruitment threshold mean \pm SD: $18.9 \pm 12.0\%$ MVC) because there were insufficient data points in the motor unit discharge to perform the power spectral analyses. The recruitment thresholds of the removed motor units were 7, 11, 26, and 31% MVC. For both studies, the range of recruitment thresholds was 3–44% MVC. Second, 20-s periods at the start, middle, and end of each task were analyzed in the current study, whereas 20- to 30-s periods were analyzed in the prior study by Mottram et al.

Fifteen healthy adult men (25.5 ± 5.9 yr; range, 20–39 yr) participated in the study. All subjects were moderately active and were right-handed (average laterality quotient score was 0.73 ± 0.22 ; range: 0.18–1.0), as identified by the Edinburgh Handedness Inventory (Oldfield 1971). None of the subjects had any known neurological disorder or cardiovascular disease and all subjects 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.

Each subject participated in one to three experimental sessions that were at least 1 wk apart. Each experiment involved recording the discharge of a single motor unit ($n = 28$) in the biceps brachii of the left arm. Single motor unit recordings were obtained from the same motor unit during two isometric contractions (force and position tasks) performed with the elbow flexor muscles by each subject.

Experimental arrangement

Details of the experimental setup, the preparation of the subjects, and the equipment used have been described previously (Mottram et al. 2005). Briefly, subjects were seated upright in an adjustable chair with the nondominant arm abducted approximately 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. The hand and forearm were secured in a modified wrist–hand–thumb orthosis (Orthomerica, Newport Beach, CA).

The force applied at the wrist in the vertical direction was measured with a force transducer that was mounted on a custom-designed, adjustable support. The orthosis was rigidly attached to the force transducer. The MVC force of the elbow flexor muscles was measured at the wrist with the JR-3 Force-Moment Sensor (900-N range, 90.0 N/V JR-3, Woodland, CA) before performance of the force task, and with a Baldwin SR-4 load cell (2700-N range, 177 N/V; Baldwin-Lima-Hamilton, Philadelphia, PA) before performance of the position task. The force exerted in the vertical direction was displayed on a 17-in. monitor that was located at eye level approximately 1.2 m in front of the subject.

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 (model 7265A-HS, Endevco; linear range of acceleration response ± 100 m/s², San Juan Capistrano, CA) was mounted on the orthosis near the thumb to record acceleration in the vertical direction. Output from the electrogoniometer and accelerometer was recorded on digital tape. Elbow angle was displayed on the same 17-in. monitor as the force trace.

The compressive force under the elbow joint was recorded with an Entran transducer (ELW-D1-100L, 273.37 mV range, Fairfield, NJ) that was placed under the padded elbow support. The compression force under the elbow was displayed on an oscilloscope and stored on digital tape.

Muscle fiber action potentials from single motor units in the biceps brachii were recorded with branched bipolar electrodes (stainless steel, 50- μ m diameter; California Fine Wire, Grover Beach, CA). A disposable 25-gauge hypodermic needle was used to insert the branched bipolar electrode under the skin (not penetrating the fascia) and over the belly of the biceps brachii muscle for a distance of 3–8 cm, and was removed before recording motor unit activity. The electrode was inserted perpendicular to the direction of the muscle fibers and moved to optimize the detection of action potentials from a single motor unit. Once a motor unit was isolated, the electrode was not moved again until the experiment was completed. Single motor unit recordings were amplified (1,000–2,000 \times), bandpass filtered (20–8,000 Hz), displayed on an oscilloscope, and stored on digital tape.

Experimental procedures

Subjects performed two submaximal isometric contractions (force and position tasks) with the elbow flexor muscles of the left arm. These two tasks were performed for identical durations on the same day in random order. Before the experimental session, 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 MVC task. The experimental session consisted of 1) an assessment of the MVC force for the elbow flexor muscles, 2) isolation and determination of the recruitment threshold of a single motor unit in the biceps brachii, 3) performance of the force task and a subsequent MVC, 4) performance of the position task and a subsequent MVC, and 5) repeat assessment of the recruitment threshold of the isolated motor unit. Steps 3 and 4 were performed in random order. Before initiating the second task (force or position), subjects rested until the MVC force was within 5% of the value recorded at the beginning of the protocol.

MVC FORCE. The protocol began with the subject performing three isometric MVC trials with the elbow flexor muscles. The MVC task consisted of a gradual increase in force from zero to maximum in ~ 3 s, with the maximal force held for 3 s. The greatest force achieved by the subject was defined as the MVC force and was used as the reference for determining the recruitment threshold of the isolated motor unit and the contraction intensity for the force and position tasks.

MOTOR UNIT RECRUITMENT THRESHOLD. With the left wrist attached to the force transducer, the subject gradually increased the force exerted by the elbow flexor muscles to a level that was sufficient to sustain a minimal, repetitive discharge of an isolated motor unit. Subjects were given audio feedback of action potential discharge and visual feedback of elbow flexor force to assist in achieving and maintaining a minimal repetitive discharge rate. The force at which the discharge rate of the isolated motor unit was minimal and repetitive was defined as the recruitment threshold (Spiegel et al. 1996). In two of 28 experiments, the isolated motor unit was lost between tasks.

FORCE AND POSITION TASKS. The position and force tasks were performed at a similar target force above the recruitment threshold of

the isolated motor unit. For the force task, the subject was required to exert a force in the upward direction by contracting the elbow flexor muscles and matching the target force displayed on a monitor. For the position task, the subject was required to maintain the elbow joint angle at 1.57 rad while supporting an inertial load that was equivalent to the target force achieved during the force task. This was accomplished by hanging a weight from the wrist at the same point on the orthosis as the point of application for the force that was exerted during the force task. Thus the load torque about the elbow joint was identical within subjects for the two tasks. Subjects were provided with visual feedback of the force (0.3% MVC/cm) exerted at the wrist during the force task, and of the elbow angle (2.0°/cm) during the position task.

The durations of the two tasks, which were not performed to failure, were identical within subjects and were based on target force. The duration of each task decreased linearly with target force: contraction duration was 300 s for target forces that were 0–5% MVC force and declined to 60 s for target forces that were 35–50% MVC force.

Data analysis

Force, acceleration, and elbow angle were recorded on digital tape and subsequently digitized (A/D converter, 12-bit resolution) and analyzed off-line using the Spike2 (version 5.02) data-analysis system (Cambridge Electronic Design, Cambridge, UK). The single motor

unit recordings were digitized at 18.5k samples/s, and the force, position, and acceleration signals were digitized at 200 samples/s.

The MVC force was quantified as the peak force obtained during the MVC task. Fluctuations in the vertical direction were quantified during the position and force tasks by calculating the SD of acceleration and detrended force, respectively, at the start, middle, and end (20-s intervals) of each contraction.

Action potentials discharged by single motor units in biceps brachii were discriminated using a computerized, spike-sorting algorithm (Spike2, version 5.02; Cambridge Electronic Design), which identified the potentials belonging to a single motor unit based on waveform amplitude, duration, and shape. The recruitment threshold of the isolated motor units ranged from 3 to 44% of MVC. The CV for discharge rate was determined for the first, middle, and last 20 s of contraction time (Fig. 1); for one subject the first, middle, and last 15 s were analyzed because the contraction lasted only 45 s. To ensure discrimination accuracy, the interspike intervals (ISIs) of identified motor units were manually examined for every trial. Trials that contained abnormally long or short ISIs (force task: 29% of trials, position task: 47% of trials) were visually discriminated on a spike-by-spike basis. Mean discharge rate was determined from the ISIs using custom-designed software written in Matlab (The MathWorks, Natick, MA). The ISIs were detrended before determining the SD and CV for the discharge rate, and then converted to instantaneous frequencies. For each subject, discharge times that were <4 pps or

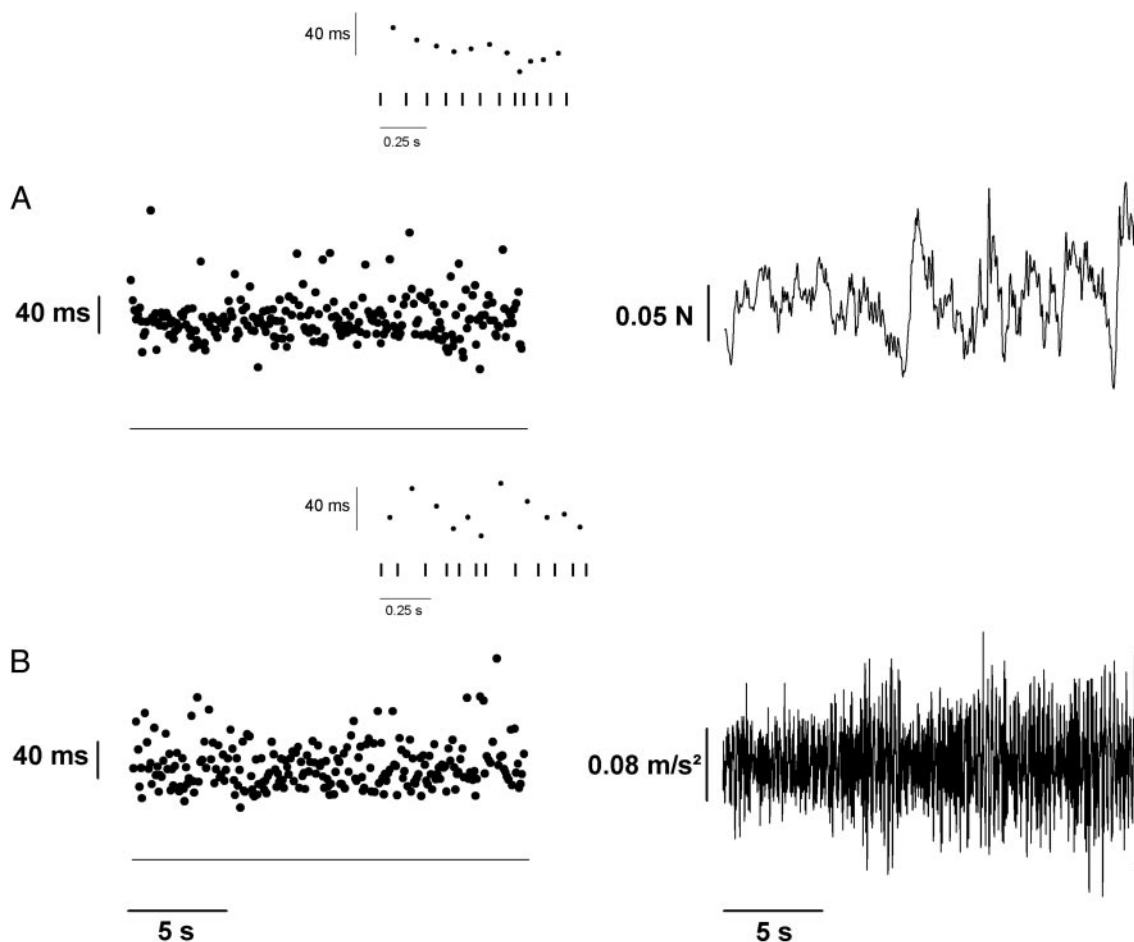


FIG. 1. Representative interspike intervals (ISIs) of the same motor unit at the start (20-s interval) of the force task (A) and position task (B). Horizontal line beneath the ISIs denotes baseline. Scatter indicates the variability in discharge rate (CV for discharge), which was similar for the force (30.4%) and position (30.3%) tasks. Corresponding fluctuations in force during the force task (A, top right) and acceleration during the position task (B, bottom right) are shown. Inset above A portrays the first second of instantaneous discharges and corresponding ISIs for the force task. Similarly, the inset above B portrays the first second of instantaneous discharges and corresponding ISIs for the position task. Recruitment threshold of the motor unit was 35% maximal voluntary contraction (MVC) force and the target force was 40% MVC force. Force signal was low-pass filtered at 10 Hz.

>50 pps ($1.6 \pm 4.4\%$ of discharges) were considered outliers as a result of discrimination error and were not included in subsequent analyses. The incidence of double discharges that were removed for this purpose was similar between the force and position tasks.

Because the goal was to examine the contribution of fluctuations in the motor unit discharge rate to the variations in the acceleration or force, a standard spectral analysis of the discharge train $N(t)$ of a motor unit (Halliday et al. 1995; Rosenberg et al. 1989) was not appropriate because it would produce a large peak at the mean discharge rate of the motor unit (ν) and might not reveal the presence of the slow modulation of the discharge rate around the frequency ν . Rather, the analysis estimated the instantaneous discharge rate of the motor unit as the intensity of the point process (Brown et al. 2002; Daley and Vere-Jones 2003), where the intensity $\lambda(t|H_t)$ measures the probability that a discharge occurs over the interval $(t, t + dt)$ given the prior history H_t of the point process. The discharge rate of the motor unit was estimated with a kernel approach (Gerstner and Kistler 2002; Lánský et al. 2004; Nawrot et al. 1999; Paulius and Baker 2000). The ISIs were first computed from the discharge times (Fig. 2, A and B) and then smoothed (Fig. 2C) before calculating the inverse of the smoothed ISI function (Fig. 2D). Accordingly, preliminary analyses indicated that the standard spectral analysis of the discharge train (Halliday et al. 1995; Rosenberg et al. 1989) does not produce the same results as those obtained with the approach used in the current study.

Because the estimation procedure did not take into account the past history of the process H_t , the point process was modeled as an inhomogeneous point process (Brown et al. 2001; Daley and Vere-Jones 2003). The power spectrum of motor unit discharge rate $\lambda(t|H_t)$ was then quantified using spectral analysis based on the Welch method (Brillinger 2001) after the mean discharge rate had been subtracted from the smoothed ISI function. The duration of the motor

unit discharge sample was 20 s and the frequency resolution was 0.39 Hz (sampling frequency = 200 Hz; window size = 512). The estimation of the power spectrum of the force and acceleration time series was also performed with the Welch method after the linear trends had been removed. Adjacent time windows (512 points) were overlapped by 256 time samples to reduce the variance in the estimated power spectrum (Brillinger 2001).

Statistical analysis

The dependent variables for the motor output were the SDs of acceleration (position task) and detrended force (force task) in the vertical direction. The dependent variables for the motor unit discharge were the CV for motor unit discharge ($\text{CV} = (\text{SD}/\text{mean motor unit discharge}) \times 100$). The statistical comparisons of the power spectra for motor unit discharge during the force and position tasks (absolute and % change), and for the SD of the force or acceleration (% total power) were performed with a 1-Hz resolution from 0.5 to 25.5 Hz (26 frequency bins). The dependent variables for the frequency modulation of motor unit discharge were the absolute power (s^2), and total power (% change) for the motor unit discharge during the force and position tasks (spectrum from 0 to 26 Hz). The dependent variable for the frequency modulation of the SD for force or acceleration was the power from 0 to 26 Hz, expressed as a percentage of the total power from 0 to 100 Hz.

Two-factor ANOVAs [two tasks \times three time points (start, middle, end)] with repeated measures on task and time were used to compare the CV for discharge rate, elbow force, absolute power for motor unit discharge rate, and the change in the SDs of acceleration and detrended force (SPSS version 11.5). A three-factor ANOVA (two tasks \times two time points (start and end) \times 26 frequency bins) with repeated measures on task, time, and frequency bin was used to compare the absolute power for the motor unit discharge rate and the % total power for the SD for force and acceleration. Two-factor ANOVAs (two tasks \times 26 frequency bins) with repeated measures on task and frequency bin were performed at each time point (start, middle, and end) to compare the absolute power and power (% change) between tasks at the respective time points. Bivariate linear regression analyses examined the association between the CV for discharge and fluctuations in motor output (SDs of force or acceleration) and stepwise, multiple-regression analyses evaluated the contribution of each frequency bin from the motor unit discharge (26 frequency bins) to the CV for discharge and fluctuations in motor output for the two tasks. For these analyses, the 84 rows consisted of the 28 motor units at each of the three time points, whereas the columns consisted of the independent variables (26 columns for the power of the signal in 0 to 1-Hz frequency bins at each of the three time points) and the dependent variables (four columns for the SD of force or acceleration, and the CV for discharge rate for the force or position task at each of the three time points). Dependent t -tests were used to compare the MVC force before and after task performance.

When ANOVAs yielded significant interactions, post hoc comparisons (dependent t -tests or Bonferroni adjustment for multiple comparisons) were performed to locate differences between and within tasks at the appropriate time points. The alpha level for all statistical tests was 0.05, except for paired comparisons when the alpha level was adjusted with a Bonferroni correction, and for post hoc analyses, when values of $P \leq 0.11$ were considered significant. Our criteria for post hoc comparisons were less strict for two reasons: First, the statistical power was much lower for paired t -tests compared with interactions among multiple levels. Second, even within a subject, there is a large amount of variability in the frequency that the peaks occur in the power spectrum. The 1-Hz-bin resolution used in this study for statistical comparisons may thus have significantly influenced the statistical power for post hoc comparisons across individual bins. Data are reported as means \pm SD within the text and displayed as means \pm SE in the figures.

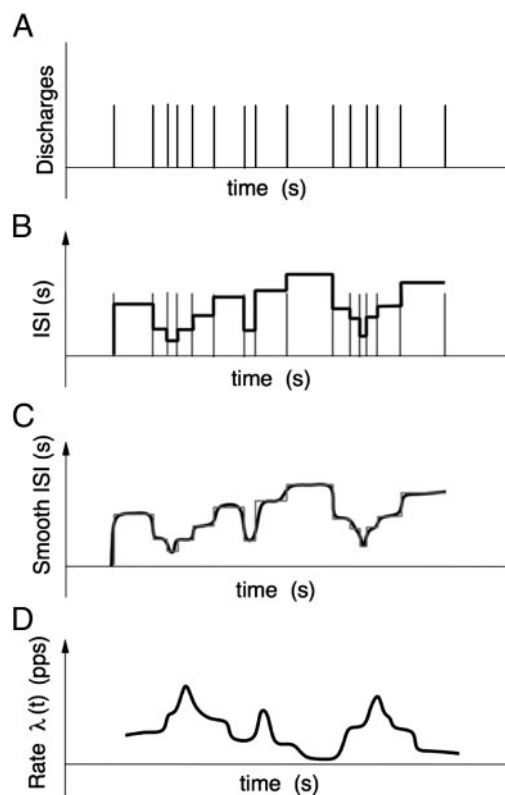


FIG. 2. Method for estimating the instantaneous discharge rate of the motor units. From a set of discharge times (A), the ISIs were computed (B) and smoothed with a kernel approach (C) before calculating the inverse of the smoothed ISI (D).

RESULTS

The two tasks were performed one after the other, in a randomized order, at a target force equal to $3.6 \pm 2.1\%$ of the MVC force above the recruitment threshold of the isolated motor unit. The target force was $22.4 \pm 13.6\%$ MVC force (range: 3–49% MVC force). The mean contraction duration, which was identical between tasks for each motor unit, was 161 ± 93 s (range 45–300 s). The average decline in MVC force after the completion of all tasks was similar: $10.2 \pm 11.4\%$ for the force task and $6.1 \pm 12.1\%$ for the position task (paired *t*-test, $P = 0.09$) for an average value of $8.2 \pm 12.0\%$ ($P < 0.001$). Subjects rested for 15–20 min between the two tasks, which was sufficient to ensure that the MVC forces were similar ($P = 0.4$) before the start of the first and second tasks (first task: 267 ± 48 N; second task: 262 ± 52 N). The similarity in the net muscle torque about the elbow joint for the two tasks was underscored by comparable values for the mean vertical force exerted under the elbow joint during the position (66 ± 40 N) and force tasks (70 ± 48 N, $P = 0.30$), and at the start (73 ± 34 N and 70 ± 45 N, $P = 0.34$) and end (62 ± 40 N and 63 ± 62 N) of the two tasks, respectively (task \times time, $P = 0.93$).

Despite the similarity in the forces exerted during the two tasks, there were differences in the rates of change in the fluctuations in motor output (force and acceleration). The SD for force and acceleration increased progressively during the two tasks (main effect for time $P < 0.001$; Fig. 3). The relative increase in the fluctuations in acceleration during the position task ($90 \pm 72\%$ at task termination) was greater than that for the fluctuations in force during the force task ($19 \pm 41\%$ at task termination, task \times time interaction, $P < 0.001$).

Variability in discharge rate and fluctuations in motor output

The CV for discharge rate was similar at the start (23.3 ± 7.9 and $21.8 \pm 10.2\%$) and end (23.1 ± 8.1 and $26.5 \pm 9.8\%$) of the force and position tasks, respectively (task \times time interaction, $P = 0.10$), and did not change during either task (main effect time, $P = 0.13$). Nonetheless, there was a modest association between the CV for discharge rate and the absolute fluctuations (SD) in motor output (force or acceleration) across the three time points for both the force task ($P = 0.001$, $r^2 = 0.18$) and the position task ($P < 0.001$, $r^2 = 0.31$; Fig 4).

Power spectra of motor unit discharge

The spectra for motor unit discharge rate were similar across time (start and end) for the force and position tasks [time main effect ($P = 0.13$), time \times frequency ($P = 0.74$), task \times time ($P = 0.51$), task \times time \times frequency ($P = 0.08$); Fig. 5; A and B], and were also similar when the ANOVA was performed at all three time points. However, a significant task \times frequency interaction ($P < 0.001$) indicated that the frequency modulation differed between the force and position tasks when collapsed across all time points. Post hoc analyses indicated that 0 to 1- and 18 to 26-Hz frequencies had a trend toward being significantly different ($P < 0.08$). Because of a borderline task \times time \times frequency interaction ($P = 0.08$), the task \times frequency interaction was examined independently at each point of time (start and end). There was a significant task \times

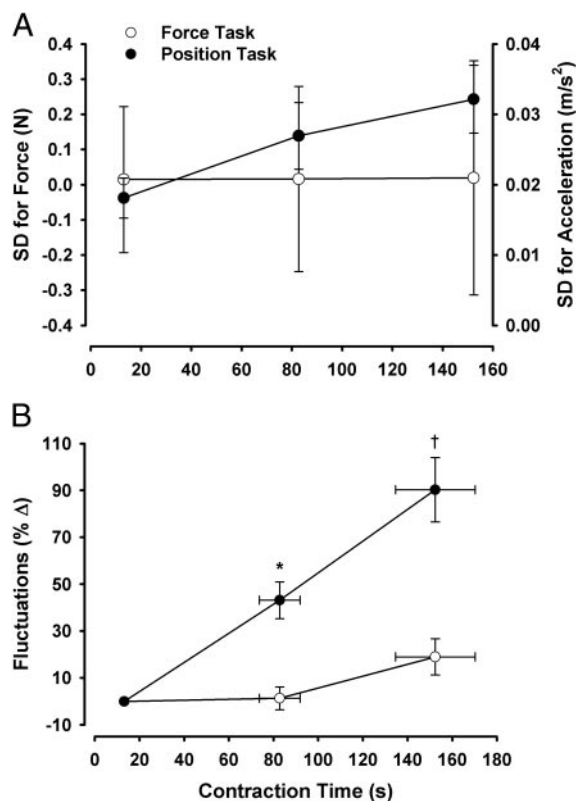


FIG. 3. Fluctuations in motor output at the start, middle, and end of the 2 tasks. A: fluctuations in motor output (mean \pm SE) were quantified as the SD of the detrended force during the force task and the SD of acceleration during the position task. Large SE bars for force SD are attributed to the increase in SD with target force: mean SD for force was 0.03 ± 0.004 N for the contractions at higher target forces (recruitment threshold range 26–44% MVC), whereas the mean SD for force was 0.007 ± 0.001 N for contractions at lower target forces (recruitment threshold range 3–21% MVC). B: percentage increase from the beginning of the task to the middle and end of the task (20-s intervals). Change in SD with time was significantly greater for the position task (task \times time interaction, $P < 0.001$). * $P = 0.003$, † $P < 0.001$ between the 2 tasks (post hoc paired *t*-test).

frequency interaction at the start ($P = 0.005$), but not at the end ($P > 0.98$) of the tasks. The differences at the start of the task were attributed to a significant difference at the 0 to 1-Hz frequency bin ($P = 0.05$; Fig. 5A).

Additionally, frequency modulation of motor unit discharge rate appeared to differ across time for the force and position tasks. The differential modulation with time was more evident when the % change in power from the start to the end was compared for the two tasks (task \times frequency, $P = 0.03$; Fig. 5C). Post hoc analyses indicated that the differences between the two tasks were most likely attributable to differences at 0–1 Hz ($P = 0.07$), 1–2 Hz ($P = 0.06$), 16–17 Hz ($P = 0.09$), 17–18 Hz ($P = 0.11$), and 18–19 Hz ($P = 0.10$).

Power spectra of SD for force or acceleration

The spectra for motor output (SD for force or acceleration), expressed as a percentage of the total power from 0 to 100 Hz, were similar across time (start and end) for the force and position tasks [time main effect ($P = 0.29$), time \times frequency ($P = 0.24$), task \times time ($P = 0.26$), task \times time \times frequency ($P = 0.34$)], and were also similar when the ANOVA was performed at all three time points. However, a significant

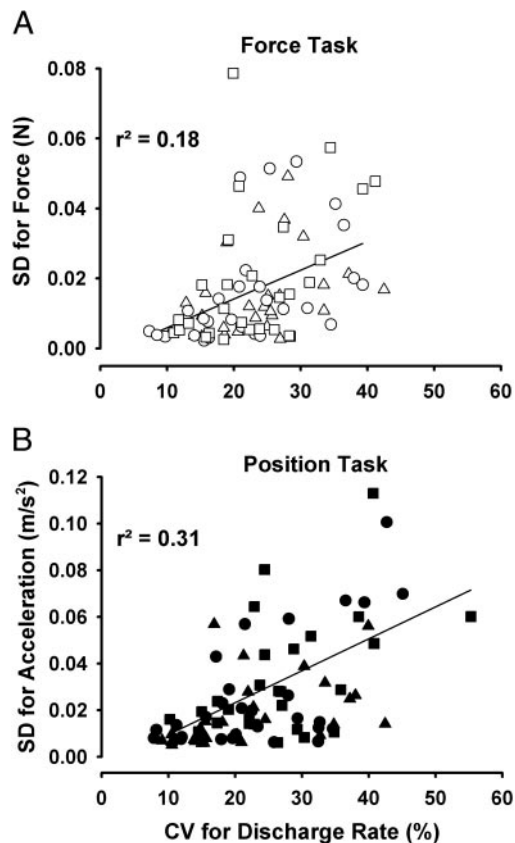


FIG. 4. CV for discharge rate was associated with the absolute fluctuations (SD) in motor output for the force (A) and position (B) tasks. Each symbol represents the SD in force or acceleration vs. the CV for discharge rate for the same 28 motor units at the start (▲), middle (●), and end (■) of the respective tasks. Overlap of the different symbols underscores that absence of a change in the CV for discharge rate during each task. Linear equations were $SD = 0.0008 (\text{Discharge CV}) - 0.0022$ for the force task and $SD = 0.0013 (\text{Discharge CV}) - 0.0046$ for the position task.

task \times frequency interaction ($P < 0.001$) indicated that the frequency modulation differed between the force and position tasks when collapsed across all time points. Post hoc analyses indicated that the power was different at all 26 frequencies ($P \leq 0.01$). Most of the power in the force spectra occurred at 0–3 Hz, whereas the majority of the power in the acceleration spectra occurred at 3–7 Hz.

Association between modulation of motor unit discharge and motor output

Although the CV for discharge rate was similar and did not change with time for the two tasks, different frequencies from the power spectra of the motor unit discharge predicted the CV for discharge rate during the force and position tasks. The best predictor of the CV for discharge rate during the force task ($R^2 = 0.72$, $P < 0.001$; Fig. 6) was modulation of the motor unit discharge at 1–2 Hz ($r = 0.17$, $P = 0.005$), 2–3 Hz ($r = 0.12$, $P = 0.05$), 12–13 Hz ($r = 0.13$, $P = 0.03$), and 14–15 Hz ($r = -0.20$, $P = 0.001$). In contrast, the best predictor of the CV for discharge rate during the position task ($R^2 = 0.68$, $P < 0.001$) was modulation of the motor unit discharge at 0–1 Hz ($r = 0.22$, $P = 0.001$) and 1–2 Hz ($r = 0.23$, $P < 0.001$).

Similarly, although the power spectrum of motor unit discharge rate was similar between tasks with time, different

frequencies from the power spectra of motor unit discharge predicted the fluctuations in motor output for the force and position tasks. The best predictor of the SD for force ($R^2 = 0.54$, $P < 0.001$; Fig. 7) was modulation of the motor unit discharge rate at 5–6 Hz ($r = 0.43$, $P < 0.001$), 9–10 Hz ($r = -0.18$, $P = 0.02$), 12–13 Hz ($r = 0.24$, $P = 0.003$), and 14–15 Hz ($r = -0.25$, $P = 0.001$), whereas the best predictor of the SD for acceleration ($R^2 = 0.51$, $P < 0.001$) was modulation of the motor unit discharge rate at 6–7 Hz ($r = -0.38$, $P < 0.001$), 14–15 Hz ($r = 0.47$, $P < 0.001$), 17–18 Hz ($r = 0.21$, $P = 0.009$), 18–19 Hz ($r = -0.29$, $P = 0.001$), 20–21 Hz ($r = 0.15$, $P = 0.07$), and 23–24 Hz ($r = -0.19$, $P = 0.02$).

DISCUSSION

The purpose of this study was to examine the contribution of frequency modulation of motor unit discharge to the fluctua-

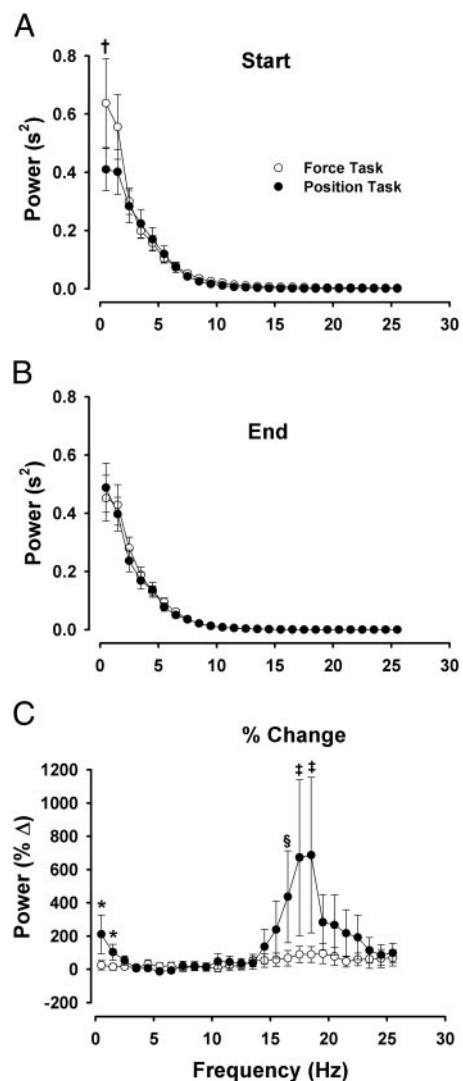


FIG. 5. Frequency modulation of motor unit discharge rate for the 2 tasks. A: power spectral density (PSD) at the start of the force and position tasks. B: power spectral density at the end of the force and position tasks. C: percentage change in the PSD from the start to the end of each task. Spectra were derived from the discharge times of the 28 motor units. † $P = 0.05$, * $P \leq 0.07$, § $P = 0.09$, ‡ $P \leq 0.11$ between the 2 tasks (post hoc paired t -test with Bonferroni correction). SE bars are shown for each frequency bin.

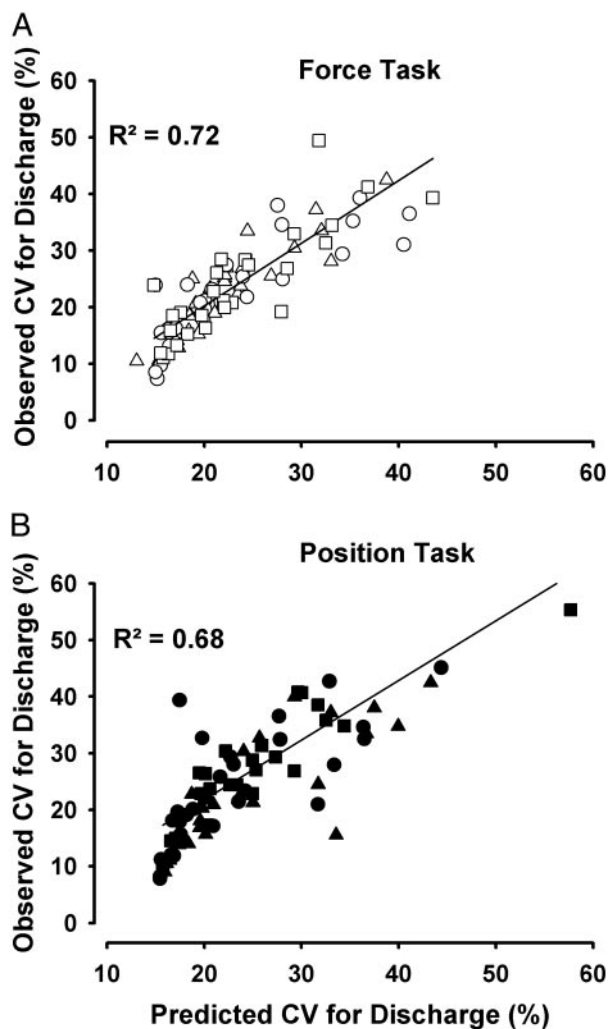


FIG. 6. Relations between the observed and predicted CV for discharge rate for the force (A) and position (B) tasks. Each symbol represents the predicted vs. observed CV for discharge rate for the 28 motor units at the start (\blacktriangle), middle (\bullet), and end (\blacksquare) of the respective tasks. Four frequencies (1–2, 2–3, 12–13, and 14–15 Hz) were used to predict the CV for discharge during the force task, whereas 2 frequencies (0–1 and 1–2 Hz) were used for the position task. CV for discharge rate during the force task was predicted with the equation: $14.41 + (15.09 \times 2.5 \text{ Hz}) - (1113.77 \times 14.5 \text{ Hz}) + (9.86 \times 1.5 \text{ Hz}) + (639.55 \times 12.5 \text{ Hz})$. CV for discharge rate during the position task was predicted with the equation: $14.5 + (10.37 \times 0.5 \text{ Hz}) + (13.77 \times 1.5 \text{ Hz})$.

tions in the motor output during sustained contractions with the force and position tasks. The results indicated that the power spectra for motor unit discharge rate and the *amplitude* of the variability in discharge rate did not change with time during either task. However, modulation of motor unit discharge at different frequencies contributed to the CV for motor unit discharge rate and to the fluctuations in motor output (SDs in force and acceleration) for the two tasks. Furthermore, the CV for discharge rate and the fluctuations in motor output for the two tasks were predicted by the modulation of *different* frequencies in motor unit discharge rate.

Relation between discharge rate variability and fluctuations in motor output

In agreement with other studies (Enoka et al. 2003; Knight and Kamen 2004; Komatz et al. 2005; Laidlaw et al. 2000;

Moritz et al. 2005; Taylor et al. 2003), the current results demonstrated a modest, but significant, association between the CV for discharge rate and the absolute fluctuations in motor output for both tasks. The CV for discharge rate, however, could not explain the greater rate of increase in the fluctuations in the motor output during the position task. Although the CV for discharge rate was greater when the subjects performed the position task, especially at the end of the task, this difference was not statistically significant. Furthermore, although this result contrasts with the findings of the previous study (Mottram et al. 2005), the data differed for the two studies in two ways: first, four motor units used in the previous study were excluded as a result of insufficient discharges at the end of the task for performing spectral analyses. Second, the current study analyzed 20-s periods, whereas the previous study examined 20- to 30-s periods. Because the CV for discharge rate is highly sensitive to the addition or subtraction of even a few discharges

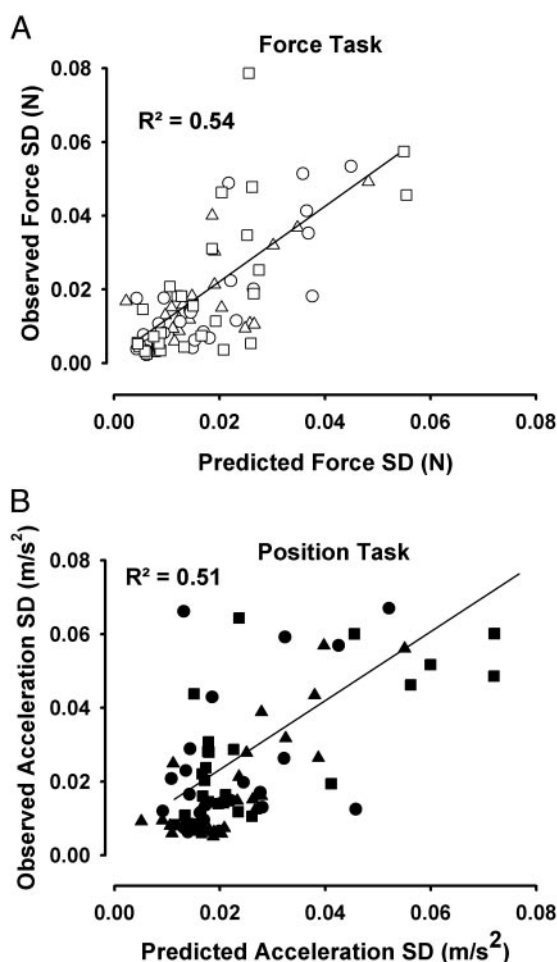


FIG. 7. Relations between the observed and predicted fluctuations in motor output for the force (A) and position (B) tasks. Each symbol represents the predicted vs. observed fluctuations in motor output for the 28 motor units at the start (\blacktriangle), middle (\bullet), and end (\blacksquare) of the respective tasks. Four frequencies (5–6, 9–10, 12–13, and 14–15 Hz) best predicted the SD of force during the force task, whereas 6 frequencies (6–7, 14–15, 17–18, 18–19, 20–21, and 23–24 Hz) best predicted the SD of acceleration during the position task. SD for force during the force task was predicted with the equation: $0.004 + (0.13 \times 5.5 \text{ Hz}) - (2.83 \times 14.5 \text{ Hz}) + (2.78 \times 12.5 \text{ Hz}) - (0.36 \times 9.5 \text{ Hz})$. SD for acceleration during the position task was predicted with the equation: $0.017 + (26.66 \times 14.5 \text{ Hz}) - (0.29 \times 6.5 \text{ Hz}) - (83.93 \times 23.5 \text{ Hz}) + (46.57 \times 20.5 \text{ Hz}) - (112.61 \times 18.5 \text{ Hz}) + (54.4 \times 17.5 \text{ Hz})$.

(Christou et al. 2004; Moritz et al. 2005), the discrepant findings between studies on the CV for discharge rate is not unexpected. Finally, despite the greater number of discharges included in the previous study, the task \times time interaction for the CV for discharge rate barely reached significance ($P = 0.035$), whereas in the current study it did not reach significance ($P = 0.10$). This discrepancy underscores the sensitivity of each motor unit to the CV for discharge rate, and the observation that the CV for discharge rate of single motor units is not always related to the fluctuations in motor output.

Frequency modulation between tasks

Neither the CV for discharge rate nor the power spectra for motor unit discharge could explain the different rates of increase in the fluctuations in motor output for the two tasks. Rather, modulation of *specific* frequencies in the motor unit discharge was associated with both the variability in motor unit discharge rate and the fluctuations in motor output (Fig. 5C; Figs. 6 and 7). For example, modulation of motor unit discharge rate at 1–3, 12–13, and 14–15 Hz during the force task and 0–2 Hz during the position task predicted approximately 70% of the variance in discharge rate variability. Similarly, modulation of motor unit discharge rate at 5–6, 9–10, 12–13, and 14–15 Hz during the force task and 6–7, 14–15, 17–19, 20–21, and 23–24 Hz during the position task predicted approximately 50% of the variance in the fluctuations in motor output. The modulation (1-Hz resolution) occurred in both the positive and negative directions during the two tasks. The different direction of the correlation coefficients may indicate that an increase or a decrease in the power in a given frequency bin was associated with the CV for discharge rate or the fluctuations in motor output. This result likely underscores the difference in synaptic inputs to the motor neuron pools between the two tasks.

Correlational methods are often used to identify the modulation of motor unit discharge at common frequencies and thereby provide information about strategies used by the nervous system to perform various tasks (Hamm et al. 2001; Myers et al. 2004). At least two different methods have been used. One approach has been to perform a finite Fourier transform on the discrete discharge times of motor units (Brillinger 1978; Rosenberg et al. 1989) and to identify common frequencies in the discharge rates with a coherence analysis (Farmer et al. 1993; Halliday et al. 1999; Kilner et al. 2002; Semmler et al. 2002, 2004). Significant peaks in a coherence spectrum can be identified, for example, as values exceeding the 95% confidence interval above the zero or mean level of coherence (Moritz et al. 2005a; Rosenberg et al. 1989). Results from these studies indicate that motor unit pairs often exhibit common modulation of discharge rate in the 1 to 12- and 16 to 32-Hz frequency bands.

Another approach is to analyze the interspike intervals derived from the motor unit discharge, which can be smoothed to produce a continuous signal before being compared with another continuous signal in either the time or the frequency domain (De Luca et al. 1982; Kamen and De Luca 1992; Vaillancourt et al. 2002). One application of this approach is to perform a correlational analysis of the smoothed ISIs with the force exerted by the muscle in which the motor units are located. This type of analysis has consistently found that most

of the power in the motor output and motor unit discharge spectra occur at low frequencies (0–3 Hz). Furthermore, a cross-correlation analysis on the ISIs for pairs of motor units has indicated that they share a common low-frequency modulation of discharge rate (De Luca and Erim, 1994).

The current study performed an analysis on the ISIs to examine frequency modulation of motor unit discharge, as done previously (De Luca et al. 1982; Vaillancourt et al. 2002). In contrast to prior studies, the present investigation examined modulation at multiple frequencies without the constraint of matching frequencies in the motor unit discharge and the motor output. The results indicated that most of the power in the force spectrum occurred at 0–3 Hz, yet the fluctuations in force during the force task were associated with frequency modulation of motor unit discharge at 5–6, 9–10, 12–13, and 14–15 Hz. Similarly, most of the power in the acceleration spectrum during the position task occurred at 3–7 Hz, yet the fluctuations in acceleration were associated with frequency modulation of motor unit discharge at 6–7, 14–15, 17–19, 20–21, and 23–24 Hz. The strongest contributor to the force fluctuations was the modulation of motor unit discharge at 5–6 Hz ($r = 0.43$), whereas the dominant effects for the fluctuations in acceleration occurred at frequencies of 6–7 Hz ($r = 0.38$) and 14–15 Hz ($r = 0.47$). Furthermore, the results indicated that there was a difference in frequency modulation of motor unit discharge at 0–1 Hz at the onset of the two tasks (Fig. 5A), and that the percentage change in the power from the start to the end differed between tasks (Fig. 5C).

Potential mechanisms for the difference in modulation of motor unit discharge

Because the *same* motor unit was monitored during both tasks, the differential frequency modulation of motor unit discharge for the two tasks likely involved differences in synaptic input to the motor neuron pool. The differences in low-frequency modulation (0–1 Hz) at the beginning of the task may reflect differences in a feature of the central command known as “common drive” (Christou et al. 2004; De Luca et al. 1982; Vaillancourt et al. 2002). Common drive is proposed to arise from neural centers including the brain stem, and is considered a source of the low-frequency (1–2 Hz) oscillations that are manifested in the discharge rates of the concurrently active motor units. In addition, the increase in the fluctuations in acceleration during the position task was associated with modulation at higher bandwidths (14–24 Hz) compared with the force task (9–15 Hz). It has been suggested that the neural commands contributing to coherence in motor unit discharge at these higher bandwidths (16–32 Hz) are also centrally mediated (Farmer et al. 1993; Mayston et al. 2001). Nonetheless, there is evidence to suggest that muscle spindle afferents discharge at frequencies around 25 Hz during low-force contractions (Al-Falahe et al. 1990; Vallbo 1981), and the 25-Hz peak in the power spectrum during a position task performed with the index finger has been attributed to the spinal reflex loop (Sakamoto et al. 1992). Because the activation of the muscle spindle is likely greater during the position task than the force task (Akazawa et al. 1983; De Serres et al. 2002; Hulliger 1993; Kakuda et al. 1996), it is possible that the enhanced contribution of motor unit discharge from 14 to 24

Hz to the fluctuations in motor output for the position task arises from enhanced afferent input (Farmer et al. 1993).

In summary, modulation of motor unit discharge at different frequencies was able to predict both the CV for discharge rate and the fluctuations in motor output during the force and position tasks. The two tasks exhibited differences in low-frequency modulation (0–1 Hz) at the onset of the contraction and the greater rate of increase in the fluctuations in motor output during the position task was predicted by modulation at higher frequencies in motor unit discharge (position task: 6–7, 14–15, 17–19, 20–21, and 23–24 Hz; force task: 5–6, 9–10, 12–13, and 14–15 Hz). These differences indicate that the frequency modulation of discharge rate for the same motor units varied with the type of load supported during the submaximal isometric contractions.

ACKNOWLEDGMENTS

The authors thank M. Anderson for assistance with motor unit analysis and Dr. Thomas Hamm for comments on a draft of the manuscript.

GRANTS

This research was supported by National Institute of Neurological Disorders and Stroke Grant NS-43275 to R. M. Enoka, a Promotion of Doctoral Studies II scholarship from the Foundation for Physical Therapy, and an American College of Sports Medicine Foundation Research Grant to C. J. Mottram.

REFERENCES

- Akazawa K, Milner TE, and Stein RB.** Modulation of reflex EMG and stiffness in response to stretch of human finger muscle. *J Neurophysiol* 49: 16–27, 1983.
- Al-Falahe NA, Nagaoka M, and Vallbo AB.** Response profiles of human muscle afferents during active finger movements. *Brain* 113: 325–346, 1990.
- Brillinger DR.** Comparative aspects of the study of ordinary time series and of point processes. In: *Developments in Statistics*, edited by Krishnaiah PR. New York: Academic Press, 1978, vol. 1, p. 33–133.
- Brillinger DR.** *Time Series Data Analysis and Theory*. Philadelphia, PA: Society for Industrial and Applied Mathematics, 2001.
- Brown EN, Barbieri R, Ventura V, Kass RE, and Frank LM.** The time-rescaling theorem and its application to neural spike train data analysis. *Neural Comput* 14: 325–346, 2002.
- Calvin WH and Stevens CF.** Synaptic noise and other sources of randomness in motoneuron interspike intervals. *J Neurophysiol* 31: 574–587, 1968.
- Christou EA, Mottram CJ, and Enoka RM.** Modulation of motor unit discharge has task-dependent influences on fluctuations in motor output. *Med Sci Sports Exerc* 36: S320, 2004a.
- Christou EA, Rudroff T, Moritz C, and Enoka RM.** The variability in motor unit discharge is determined by low frequency oscillations in motor unit discharge. Program No. 188.9. *2004 Abstract Viewer/Itinerary Planner*. Washington, DC: Society for Neuroscience, 2004.
- Daley DJ and Vere-Jones D.** *An Introduction to the Theory of Point Processes*. New York: Springer-Verlag, 2003.
- De Luca CJ.** Control properties of motor units. *J Exp Biol* 115: 125–136, 1985.
- De Luca CJ and Erim Z.** Common drive of motor units in regulation of muscle force. *Trends Neurosci* 17: 299–305, 1994.
- De Luca CJ, LeFever RS, McCue MP, and Xenakis AP.** Control scheme governing concurrently active human motor units during voluntary contractions. *J Physiol* 329: 129–142, 1982.
- De Serres SJ, Bennett DJ, and Stein RB.** Stretch reflex gain in cat triceps surae muscles with compliant loads. *J Physiol* 545: 1027–1040, 2002.
- Elble RJ and Randall JE.** Motor-unit activity responsible for 8- to 12-Hz component of human physiological finger tremor. *J Neurophysiol* 39: 370–383, 1976.
- Enoka RM, Christou EA, Hunter SK, Kornatz KW, Semmler JG, Taylor AM, and Tracy BL.** Mechanisms that contribute to differences in motor performance between young and old adults. *J Electromyogr Kinesiol* 13: 1–12, 2003.
- Erimaki S and Christakos CN.** Occurrence of widespread motor-unit firing correlations in muscle contractions: their role in the generation of tremor and time-varying voluntary force. *J Neurophysiol* 82: 2839–2846, 1999.
- Farmer SF, Bremner FD, Halliday DM, Rosenberg JR, and Stephens JA.** The frequency content of common synaptic inputs to motoneurons studied during voluntary isometric contraction in man. *J Physiol* 470: 127–155, 1993.
- Gerstner W and Kistler W.** *Spiking Neuron Models*. Cambridge, UK: Cambridge Univ. Press, 2002.
- Halliday DM, Conway BA, Farmer SF, and Rosenberg JR.** Load-independent contributions from motor-unit synchronization to human physiological tremor. *J Neurophysiol* 82: 664–675, 1999.
- Halliday DM, Rosenberg JR, Amjad AM, Breeze P, Conway BA, and Farmer SF.** A framework for the analysis of mixed time series/point process data—theory and application to the study of physiological tremor, single motor unit discharges and electromyograms. *Prog Biophys Mol Biol* 64: 237–278, 1995.
- Hamm TM, McCurdy ML, Trank TV, and Turkin VV.** The use of correlational methods to investigate the organization of spinal networks for pattern generation. In: *Motor Neurobiology of the Spinal Cord*, edited by Cope TC. Boca Raton, FL: CRC Press, 2001, p. 135–170.
- Hulliger M.** Fusimotor control of proprioceptive feedback during locomotion and balancing: can simple lessons be learned for artificial control of gait? *Prog Brain Res* 97: 173–180, 1993.
- Hunter SK, Lepers R, MacGillis CJ, and Enoka RM.** Activation among the elbow flexor muscles differs when maintaining arm position during a fatiguing contraction. *J Appl Physiol* 94: 2439–2447, 2003.
- Hunter SK, Ryan DL, Ortega JD, and Enoka RM.** Task differences with the same load torque alter the endurance time of submaximal fatiguing contractions in humans. *J Neurophysiol* 88: 3087–3096, 2002.
- Jones KE, Hamilton AF, and Wolpert DM.** Sources of signal-dependent noise during isometric force production. *J Neurophysiol* 88: 1533–1544, 2002.
- Kakuda N, Nagaoka M, and Wessberg J.** Common modulation of motor unit pairs during slow wrist movement in man. *J Physiol* 520: 929–940, 1999.
- Kakuda N, Vallbo AB, and Wessberg J.** Fusimotor and skeletomotor activities are increased with precision finger movement in man. *J Physiol* 492: 921–929, 1996.
- Kamen G and De Luca CJ.** Firing rate interactions among human orbicularis oris motor units. *Int J Neurosci* 64: 167–175, 1992.
- Kilner JM, Alonso-Alonso M, Fisher R, and Lemon RN.** Modulation of synchrony between single motor units during precision grip tasks in humans. *J Physiol* 541: 937–948, 2002.
- Knight CA and Kamen G.** Enhanced motor unit rate coding with improvements in a force-matching task. *J Electromyogr Kinesiol* 14: 619–629, 2004.
- Kornatz KW, Christou EA, and Enoka RM.** Practice reduces motor unit discharge variability in a hand muscle and improves manual dexterity in old adults. *J Appl Physiol* 98: 2072–2080, 2005.
- Laidlaw DH, Bilodeau M, and Enoka RM.** Steadiness is reduced and motor unit discharge is more variable in old adults. *Muscle Nerve* 23: 600–612, 2000.
- Lánský P, Rodriguez R, and Sacerdote L.** Mean instantaneous firing frequency is always higher than the firing rate. *Neural Comput* 16: 477–489, 2004.
- Maluf KS, Shinohara M, Stephenson JL, and Enoka RM.** Muscle activation and time to task failure differ with load type for low but not high intensity contractions of a human hand muscle. *Exp Brain Res* In press.
- Matthews PB.** Relationship of firing intervals of human motor units to the trajectory of post-spike after-hyperpolarization and synaptic noise. *J Physiol* 492: 597–628, 1996.
- Mayston MJ, Harrison LM, Stephens JA, and Farmer SF.** Physiological tremor in human subjects with X-linked Kallmann's syndrome and mirror movements. *J Physiol* 530: 551–563, 2001.
- McAuley JH and Marsden CD.** Physiological and pathological tremors and rhythmic central motor control. *Brain* 123: 1545–1567, 2000.
- Moritz CT, Barry BK, Pascoe MA, and Enoka RM.** Discharge rate variability influences the variation in force fluctuations across the working range of a hand muscle. *J Neurophysiol* 93: 2449–2459, 2005b.
- Moritz CT, Christou EA, Meyer FG, and Enoka RM.** Coherence at 16–32 Hz can be caused by short-term synchrony of motor units. *J Neurophysiol* 94: 105–118, 2005a.

- Mottram CJ, Jakobi JM, Semmler JG, and Enoka RM.** Motor-unit activity differs with load type during a fatiguing contraction. *J Neurophysiol* 93: 1381–1392, 2005.
- Myers LJ, Erim Z, and Lowery MM.** Time and frequency domain methods for quantifying common modulation of motor unit firing patterns. *J Neuro-Eng Rehab* 1:2 doi:10.1186/1743-0003-1-2, 2004.
- Nawrot M, Aertsen A, and Rotter S.** Single-trial estimation of neuronal firing rates: from single-neuron spike trains to population. *J Neurosci Methods* 94: 81–92, 1999.
- Oldfield RC.** The assessment and analysis of handedness: the Edinburgh inventory. *Neuropsychologia* 9: 97–113, 1971.
- Pauluis Q and Baker SN.** An accurate measure of the instantaneous discharge probability, with application to unitary joint-even analysis. *Neural Comput* 12: 647–669, 2000.
- Person RS and Kudina LP.** Discharge frequency and discharge pattern of human motor units during voluntary contraction of muscle. *Electroencephalogr Clin Neurophysiol* 32: 471–483, 1972.
- Rosenberg JR, Amjad AM, Breeze P, Brillinger DR, and Halliday DM.** The Fourier approach to the identification of functional coupling between neuronal spike trains. *Prog Biophys Mol Biol* 53: 1–31, 1989.
- Rudroff T, Poston B, Shin IS, Bojsen-Moller J, and Enoka RM.** Net excitation of the motor unit pool varies with load type during fatiguing contractions. *Muscle Nerve* 31: 78–87, 2005.
- Sakamoto K, Nishida K, Zhou L, Itakura N, Seki K, and Hamba S.** Characteristics of physiological tremor in five fingers and evaluations of fatigue of fingers in typing. *Ann Physiol Anthropol* 11: 61–68, 1992.
- Semmler JG, Kornatz KW, Dinno DV, Zhou S, and Enoka RM.** Motor unit synchronisation is enhanced during slow lengthening contractions of a hand muscle. *J Physiol* 545: 681–695, 2002.
- Semmler JG and Nordstrom MA.** Motor unit discharge and force tremor in skill- and strength-trained individuals. *Exp Brain Res* 119: 27–38, 1998.
- Semmler JG, Sale MV, Meyer FG, and Nordstrom MA.** Motor-unit coherence and its relation with synchrony are influenced by training. *J Neurophysiol* 92: 3320–3331, 2004.
- Semmler JG, Steege JW, Kornatz KW, and Enoka RM.** Motor-unit synchronization is not responsible for larger motor-unit forces in old adults. *J Neurophysiol* 84: 358–366, 2000.
- Spiegel KM, Stratton J, Burke JR, Glendinning DS, and Enoka RM.** The influence of age on the assessment of motor unit activation in a human hand muscle. *Exp Physiol* 81: 805–819, 1996.
- Stiles RN and Randall JE.** Mechanical factors in human tremor frequency. *J Appl Physiol* 23: 324–330, 1967.
- Taylor AM, Christou EA, and Enoka RM.** Multiple features of motor-unit activity influence force fluctuations during isometric contractions. *J Neurophysiol* 90: 1350–1361, 2003.
- Vaillancourt DE, Larsson L, and Newell KM.** Time-dependent structure in the discharge rate of human motor units. *Clin Neurophysiol* 113: 1325–1338, 2002.
- Vallbo AB.** Basic patterns of muscle spindle discharge in man. In: *Muscle Receptors and Movement*, edited by Taylor A and Prochazka A. London: Macmillan, 1981, p. 263–275.