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Fluctuations in motor output of a hand muscle can be altered by the mechanical properties of the position sensor

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Abstract

Fluctuations in motor output are typically quantified by the standard deviation (SD) of displacement or acceleration. The aim of the study was to determine the influence of a linear variable-displacement transducer (LVDT) on the SDs and spectral content of displacement and acceleration during steady isometric and anisometric contractions performed with the first dorsal interosseus muscle. Thirteen young adults supported six loads when performing position-holding and position-tracking tasks when the LVDT either was or was not attached to the index finger. The LVDT reduced the magnitude of the SDs in displacement and acceleration and disrupted the load-dependent modulation of the spectral properties of these signals. When the LVDT was not connected to the finger, the displacement SD was greatest during concentric contractions, the acceleration SD was greatest during eccentric contractions, and there were load-dependent changes in the power density spectra. Although the LVDT may be used for assessing relative changes in displacement, its ability to provide absolute measures of fluctuations in motor output is limited. The results provide baseline measures of the fluctuations in motor output during steady contractions with a hand muscle and how the method used to detect displacement alters these measures.

Keywords

First dorsal interosseus muscle; Steadiness; Displacement; Acceleration

1. Introduction

Activation of motor units during a steady voluntary contraction results in a muscle force that fluctuates about an average value. Force fluctuations are greater in persons with essential tremor or Parkinson's disease (Bilodeau et al., 2000; Vaillancourt et al., 2002) compared with healthy adults, often greater in old adults (>59 years) compared with young adults (<40 years) (Galganski et al., 1993; Vaillancourt et al., 2003), and are enhanced in young adults after prolonged bed rest (Shinohara et al., 2003). These increases in force fluctuations can be counteracted by steadiness training in healthy old adults (Kornatz et al., 2005) and by strength training in healthy young and old adults (Hortobagyi et al., 2001; Keen et al., 1994; Shinohara et al., 2003) and in persons with essential tremor (Bilodeau et al., 2000). The force fluctuations depend critically on the variability in discharge rate among the active motor units (Moritz et al., 2005; Taylor et al., 2003), but also are influenced by other mechanisms (Barry et al., 2007; Graves et al., 2000; Shinohara et al., 2006; Welsh et al., 2007; Yoshitake et al., 2007).

The functional significance of force fluctuations in the hand is that they influence the smoothness of a trajectory and can, therefore, impair the ability of an individual to move a

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finger accurately to a desired target (Christou et al., 2003) and to produce the same trajectory across repeat performances of the task (Harris and Wolpert, 1998). Hence, the steadiness of a contraction produced by a hand muscle can influence the functional ability of individuals to reach, grasp, manipulate, and transport small objects. For example, steadiness training reduced the force fluctuations during a steady contraction of the first dorsal interosseus muscle and improved manual function as measured by the Purdue pegboard test in old adults (Kornatz et al., 2005).

In experimental studies, the amount of fluctuations in movement during steady contractions has been typically quantified as the standard deviation (SD) of displacement (Laidlaw et al., 1999; Manini et al., 2005; Tracy and Enoka, 2002) or as the SD of acceleration (Christou et al., 2003; Graves et al., 2000; Kornatz et al., 2005). However, Shinohara et al. (2005a) found only minor correlations between these two measures of fluctuations during steady contractions with the first dorsal interosseus muscle when displacement of the index finger was measured with a linear variable-displacement transducer (LVDT; Novotechnik, Stuttgart, Germany) and acceleration was determined with a miniature piezoresistive accelerometer as young and old subjects slowly lifted and lowered a weight that ranged between 2.5% and 40% of the subject's maximal force. The absence of a correlation between these measures prompted us to examine the methods used to assess fluctuations in movement during steady contractions with a hand muscle.

In tasks requiring steady index-finger movement, the fluctuations in acceleration and power below ~12 Hz are greater when the finger is not attached to the LVDT (Wessberg and Kakuda, 1999; Wessberg and Vallbo, 1996) compared with when it is connected to the LVDT (Laidlaw et al., 1999; Shinohara et al., 2005a). Although the LVDT comprises a low-friction mechanism, its attachment to the index finger may have attenuated the fluctuations in motor output in previous studies (Christou et al., 2003; Kornatz et al., 2005; Laidlaw et al., 1999; Shinohara et al., 2005a) and changed the frequency content as observed previously (Wessberg and Kakuda, 1999; Wessberg and Vallbo, 1996). The absence of a correlation between measures of fluctuations, therefore, may be due to the potential distortion of the signals by the LVDT.

The purpose of this study was to determine the influence of the method used to measure displacement on the standard deviations and spectral content of displacement and acceleration during steady isometric and anisometric contractions performed with the first dorsal interosseus muscle. This was accomplished by evaluating the accuracy of the LVDT, by assessing its influence on time- and frequency-domain measures of fluctuations, and by correlating the standard deviations for displacement and acceleration across contraction types and loads. A preliminary account of this study has been presented in abstract form (Shinohara et al., 2005b).

2. Methods

The study was performed on 13 adults (9 men, 4 women 20–40 years), all of whom reported an absence of neuromuscular disorders. All subjects were right-handed according to hand preference for such daily activities as writing, throwing, and using scissors (Edinburgh Handedness Inventory). No subjects participated in activities that involved skilled activities with either hand, such as playing a musical instrument. The Institutional Review Board at the University of Colorado approved the experimental procedures and all subjects gave informed consent prior to participation in the study.

2.1. Experimental arrangement

The experiment was performed on the first dorsal interosseus muscle of the left hand. The experimental arrangement for orienting the arm and hand was identical to that reported recently

(see Fig. 1 in Maluf et al., 2005; Moritz et al., 2005). The subject was seated and faced a video display monitor that was located 1.2 m in front of the subject at eye level. The left arm was abducted ~ 0.8 rad ($\sim 45^\circ$), the elbow flexed to ~ 1.57 rad ($\sim 90^\circ$), and the forearm was restrained in a neutral position and resting on a platform. The elbow joint and forearm were immobilized with a vacuum pillow (Tumble Forms, Trenton, Ontario, Canada) and Velcro straps. The hand was supported with the palm vertical and the three fingers, except the index finger, were restrained in a brace with the metacarpophalangeal joints flexed to ~ 0.8 rad ($\sim 45^\circ$) and both interphalangeal joints fully extended. Flexion of the three fingers was necessary so that the inertial load could be attached to the proximal interphalangeal joint of the index finger. The index finger was placed in a splint to maintain both interphalangeal joints in full extension. The thumb was extended vertically and held with a brace in the same plane as the palm of the hand at an angle of ~ 1.1 rad ($\sim 60^\circ$) to the index finger.

2.2. Mechanical recording

The abduction force exerted during the maximal voluntary contraction (MVC) by the first dorsal interosseus was measured with a force transducer (Model 13, Sensotec, Columbus, OH, USA) that was attached to a metal bar positioned just above the index finger at the radial border of the proximal interphalangeal joint (see Fig. 1 in Maluf et al., 2005). The metacarpophalangeal joint of the index finger was maintained at 0 rad of abduction (neutral position).

When the subject was required to maintain the position of the index finger or to perform a position-tracking task, the metal bar above the index finger was removed and the abduction–adduction displacement of the index finger was measured from a distance with a CCD (charge coupled device) laser displacement sensor (LK-2503, Keyence, Osaka, Japan) that has a spatial resolution of 10 μm (Fig. 1a). A flat circular aluminum plate (diameter 4.6 cm) was attached to the radial surface of the index finger centered at the proximal interphalangeal joint (Fig. 1b). The laser displacement sensor was positioned 25 cm above the aluminum plate and finely adjusted so that the laser beam contacted the aluminum plate over the proximal interphalangeal joint when the index finger was in the neutral position. The CCD laser displacement sensor was calibrated for each subject over the range of motion used in the experiment (0.17 rad, 10°).

For some measurements, a linear variable-displacement transducer (LVDT; Novotechnik, Stuttgart, Germany) was attached to the index finger (Fig. 1c). The LVDT was mounted on a platform perpendicular to the proximal interphalangeal joint when the index finger was in the neutral position. The inner shaft of LVDT was attached to a stiff string that was connected to the finger splint at the ulnar border of the proximal interphalangeal joint. The LVDT measured the abduction–adduction displacement of the index finger about the metacarpophalangeal joint. The LVDT was calibrated for each subject over the range of motion used in the experiment.

Acceleration of the index finger in the abduction–adduction plane was detected by a miniature piezoresistive accelerometer (model 7265A-HS; Endevco, San Juan Capistrano, CA, USA) that was attached to the aluminum plate over the index finger, 1 cm medial to the radial center of the proximal interphalangeal joint. The accelerometer had a mass of 5.9 g, a linear acceleration response up to ± 196.2 m/s², a linear frequency response from 0 to 125 Hz, and it was insensitive ($<5\%$) to accelerations in other directions.

The index-finger abduction force, acceleration, and displacement were digitized at 128 samples/s (Power 1401, Cambridge Electronic Design, Cambridge, England). These data were stored on a personal computer for later analyses.

2.3. Experimental procedures

The subjects were asked to perform an MVC and position-holding and position-tracking tasks with the first dorsal interosseus muscle of the left hand.

2.3.1. MVC task—Subjects gradually increased the abduction force exerted by the index finger from baseline to maximum in 3–4 s and then sustained it at maximum for 1–2 s. The index finger force was displayed on the monitor. The timing of the task was based on a verbal count given at 1-s intervals, with vigorous encouragement from the investigators when the force began to plateau. Each subject performed three MVC trials, with subsequent trials performed when the difference in peak force between two MVCs was >5%. The trial with the highest peak force was chosen for analysis. Rest periods of at least 60 s were given between each MVC trial. This task was performed at the start and end of the experiment.

2.3.2. Position-holding and position-tracking tasks—The position-holding task involved maintaining the position of the metacarpophalangeal joint of the index finger at 0.085 rad (5°) of abduction as steady as possible for 12 s while supporting a range of inertial loads. The position-tracking task involved lifting the load from the neutral position during a 6-s concentric contraction and then lowering it during a 6-s eccentric contraction. The range of motion was 0.17 rad (10°). The subject received visual feedback of index-finger displacement (signal from the laser displacement sensor) on the monitor during both tasks along with the target (horizontal line or ramp up and down). Subjects were instructed to match the target as steadily as possible. Each task was performed with and without the LVDT connected to the finger. The load (Fig. 1d) was suspended either from the inner shaft of LVDT or from the index finger splint at the proximal interphalangeal joint. Six different loads that ranged from 0.3 to 10 N were used. The weight of the LVDT shaft (0.3 N) was included in the load. The order of the load and condition (with and without LVDT) was balanced across subjects. Subjects were not aware whether the LVDT was attached or not.

2.4. Data analysis

The analysis was performed on the middle 10 s of the position-holding task and the middle 4 s of the concentric and eccentric contractions for the position-tracking task. The displacement and acceleration signals were analyzed in time- and frequency-domains (MATLAB™; Mathworks, Natick, MA, USA). The time-domain measures included the SD of displacement and the SD of acceleration after the linear component was removed. In the frequency domain, a fast Fourier transformation was applied to the data with a block size of 512, which yielded a bin width of 0.25 Hz. Each segment was windowed by a Hanning window and detrended. The power spectrum density was normalized to the total power for each subject.

2.5. Statistical analysis

The dependent variables included the displacement SD and the acceleration SD. A previous study that did not use the LVDT showed fluctuations in finger movement mostly below ~12 Hz (Wessberg and Kakuda, 1999; Wessberg and Vallbo, 1996). Hence, we were interested in the influence of the LVDT on the movement fluctuations below ~12 Hz by the LVDT. Visual inspection of the power spectral density of the displacement signal indicated that power within the range between 4 and 8 Hz was most influenced by the LVDT across loads and subjects, and this was included as a dependent variable in the analysis.

These variables were compared with a three-factor ANOVA (2 conditions × 3 contraction types × 6 loads) with repeated measures on conditions (with and without the LVDT), contraction types (isometric, concentric, and eccentric), and loads. Correlation coefficients (r) and the coefficient of determination (r^2) were determined between the displacement SD and the acceleration SD. An alpha level of 0.05 was chosen for all initial statistical comparisons, with

post-hoc comparisons (Neuman-Keuls) performed when appropriate. The statistical analysis was performed with STATISTICA (Statsoft, Tulsa, OK, USA). $P < 0.05$ or $P < 0.01$ was indicated when significance was found. Unless stated otherwise, the data are presented as mean $\pm$ SD in the text and as mean $\pm$ SE in the figures.

3. Results

The results comprised measures of index-finger steadiness as determined with an LVDT and a laser displacement system when subjects performed different types of contractions with loads that ranged from light to moderate. The measures of steadiness were the SDs of acceleration and displacement. The MVC force was 36.3 ± 6.0 N, and the load ranged from 0.8% to 31% of MVC force.

3.1. Fluctuations in displacement and acceleration

Despite attempts to hold a constant finger position or to track the target position as steadily as possible, there were fluctuations in displacement and acceleration (Fig. 2). When the LVDT was attached to the index finger, the displacement SD measured by the laser displacement sensor was significantly ($P < 0.01$) correlated with the displacement SD measured by LVDT system across the three contraction types (Fig. 3). In addition, normalized power spectral density of the displacement signal was similar for measurements with the laser displacement sensor and the LVDT (data not shown). As measures of displacement SD and power spectra were not different when measured using the LVDT or laser displacement sensor, this indicates the sensitivity to detect displacement SD did not differ for the two displacement devices. The following comparison of index-finger displacement across conditions was based on the measurements with the laser displacement sensor.

The magnitude of the displacement and acceleration SDs were influenced by the LVDT, load, and contraction type (Fig. 4 Table 1). Both SDs were significantly reduced across loads and contraction types when the LVDT was attached to the index finger. The average reduction in displacement SD was 22% (from $0.361 \pm 0.208^\circ$ to $0.280 \pm 0.132^\circ$, $P < 0.05$) and the decrease in acceleration SD was 33% (from 0.184 ± 0.122 to 0.124 ± 0.071 m/s², $P < 0.01$). The two SDs did not change across conditions and contraction types as load increased from 0.8% to 15% MVC force (range: from $0.281 \pm 0.129^\circ$ to $0.324 \pm 0.156^\circ$ for the displacement SD; from 0.133 ± 0.072 to 0.152 ± 0.084 m/s² for the acceleration SD). The two SDs increased significantly at the highest load tested ($0.443 \pm 0.261^\circ$ for the displacement SD, $P < 0.05$; 0.193 ± 0.122 m/s² for the acceleration SD, $P < 0.01$). However, there was a significant ($P < 0.05$) interaction for displacement SD between condition and load, which indicated that the main effect of load was primarily due to a large increase in the displacement SD when the LVDT was not connected to the finger. When collapsed across contraction types, the displacement SD at the highest load was $0.552 \pm 0.333^\circ$ when the LVDT was not attached and $0.333 \pm 0.169^\circ$ when it was attached ($P < 0.05$). For comparison, the displacement SD for the other loads ranged from 0.291° to 0.369° when the LVDT was not attached and from 0.249° to 0.282° when it was attached.

The displacement SD was also greater for the concentric contractions ($0.374 \pm 0.142^\circ$) across loads and conditions ($P < 0.01$) compared with isometric ($0.248 \pm 0.192^\circ$) and eccentric ($0.343 \pm 0.174^\circ$) contractions. In contrast, the acceleration SD for the eccentric contractions (0.171 ± 0.115 m/s²) was significantly greater across loads and conditions ($P < 0.05$) compared with isometric (0.138 ± 0.105 m/s²) and concentric (0.153 ± 0.090 m/s²) contractions. There was no significant interaction between condition and contraction type.

3.2. Frequency content of displacement and acceleration

The frequency distribution of the power spectra of displacement and acceleration was influenced by the attachment of the LVDT across contraction types. To capture the distinct characteristics of frequency distribution between conditions that are common to all subjects, the power spectra were averaged across subjects and contraction types for each signal (Fig. 5). It was evident that the majority of power for the displacement signal was below 4 Hz for both conditions ($93.0 \pm 5.7\%$ with the LVDT, $80.3 \pm 5.7\%$ without the LVDT when individual data were collapsed across loads and contraction types). Without the LVDT, however, there was additional power around 4–8 Hz that increased with load. The power in the spectrum for acceleration was distributed over a broader band when the LVDT was connected to the finger. This resulted in the reduction in the relative power in each frequency with the LVDT. In other words, sharp spectral peaks in acceleration were not observed with the LVDT. The shape of the power spectrum for acceleration changed with an increase in load for both conditions. Without the LVDT, the acceleration power changed from a relatively broad distribution to a narrow band with an increase in load. In contrast, the spectrum remained broad with an increase in load when the LVDT was attached, although the shape changed from a single-peak distribution to one with two peaks.

Because the additional power in displacement around 4–8 Hz appeared to be most influenced by the LVDT, the significance of the fluctuations in this frequency band was subsequently analyzed statistically (Fig. 6). When the relative power in the 4–8 Hz band was determined in each subject, it was significantly less when the LVDT was attached to the finger across loads and contraction types ($4.6 \pm 1.6\%$ with the LVDT and $16.9 \pm 8.7\%$ without the LVDT when collapsed across loads and contraction types, $P < 0.05$). This resulted in a greater relative power in the < 4 Hz band when the LVDT was attached to the finger (93.0% versus 80.3% as described above, $P < 0.05$). The relative power in the 4–8 Hz band was significantly ($P < 0.01$) greater during isometric contractions ($14.4 \pm 5.3\%$ when collapsed across loads) compared with concentric ($7.3 \pm 4.4\%$) and eccentric ($10.4 \pm 3.3\%$) contractions, and significantly ($P < 0.05$) greater during eccentric contractions compared with concentric contractions.

3.3. Correlation between measures of steadiness

The association between the two measures of steadiness (the displacement SD and the acceleration SD) was determined across subjects for each load and contraction type (Fig. 7). There was a significant ($P < 0.05$) correlation between the two measures at all loads and contraction types when the LVDT was not attached, except for lighter loads during concentric and eccentric contractions. In contrast, the attachment of the LVDT to the index finger resulted in significant ($P < 0.05$) correlations only during isometric contractions. In addition, the correlation between the SDs for displacement and acceleration (data points in Fig. 7) was positively associated with the percent power in the 4–8 Hz band for displacement (data points in Fig. 6) with a steeper slope when the LVDT was attached (0.15% , $r^2 = 0.496$, $P < 0.05$) compared with when it was not attached (0.02% , $r^2 = 0.425$, $P < 0.05$).

4. Discussion

The main findings of this study were that: (1) the LVDT provides an accurate measure of displacement; (2) the magnitude of the fluctuations in displacement and acceleration were reduced when the LVDT was attached to the index finger; (3) the correlation between the SDs of displacement and acceleration was greater when the LVDT was not connected, especially during concentric and eccentric contractions; (4) the correlation between the SDs was greater during isometric contractions than during concentric and eccentric contractions; and (5) the correlation between the SDs of displacement and acceleration was higher when the relative power in the 4–8 Hz band for displacement was greater. The LVDT is a less expensive tool

compared with the laser displacement sensor and may be used for assessing relative changes in displacement, but it distorts the absolute measures of movement dynamics.

4.1. Magnitude of movement fluctuations

With the recent technological development of a laser displacement sensor that can measure small fluctuations in displacement without contacting the limb, it was possible to evaluate the influence of the LVDT on limb kinematics. A number of studies have previously measured finger displacement with the LVDT (Christou et al., 2003; Kornatz et al., 2005; Laidlaw et al., 1999; Shinohara et al., 2005a). The linear relation between the displacement SD measured by the LVDT and the laser displacement sensor (Fig. 3) indicates that both devices can be used interchangeably in measuring displacement of the index finger when the LVDT is attached to the finger.

Attachment of the LVDT to the index finger, however, reduced the fluctuations in both displacement and acceleration, which indicates that the physical mechanics including friction in the LVDT is substantial enough to alter the recorded kinematics of the index finger during steady contractions with the first dorsal interosseus muscle. Although the amount of friction in the LVDT is unknown, the magnitude of the fluctuations was uniformly reduced for contractions with loads < 31% MVC force due to the LVDT (Fig. 4). In addition, the absence of an interaction between condition (LVDT and no LVDT) and contraction type for both SDs indicates that the influence of the LVDT was similar across contraction types. Therefore, findings from previous studies that used the LVDT during contractions with the first dorsal interosseus muscle (Christou et al., 2003; Kornatz et al., 2005; Laidlaw et al., 2002; Laidlaw et al., 1999; Shinohara et al., 2005a) provide valid measures of the magnitude of the fluctuations despite the friction of the LVDT.

The divergent influence of contraction type on displacement SD and acceleration SD indicates that these two measures provide unique indices of steadiness. The influence of contraction type on the magnitude of the fluctuations in displacement has varied across studies. For example, Manini et al. (2005) reported a greater displacement SD during concentric contractions with the knee extensor muscles than during eccentric contractions, whereas Tracy and Enoka (2002) found no difference. Similarly, Laidlaw et al. (1999) reported a greater displacement SD during eccentric contractions with the first dorsal interosseus muscle than during concentric contractions, whereas Shinohara et al. (2005a) found no difference, and the current study found the displacement SD to be greater during concentric contractions than eccentric contractions. In contrast to these disparate results for the displacement SD, the acceleration SD has commonly been reported as being greater during eccentric contractions than concentric contractions (Christou et al., 2003; Graves et al., 2000; Kornatz et al., 2005; Shinohara et al., 2005a) and in the current study this trend was upheld whether or not the LVDT was attached. Hence, the acceleration SD appears to be a more consistent measure of movement fluctuations across variable conditions compared with the displacement SD.

4.2. Frequency content and correlation between measures of fluctuations

The LVDT had a major effect on the power density spectra for displacement and acceleration. The power spectral density for displacement and acceleration when the LVDT was attached were similar to those reported previously (Burnett et al., 2000; Shinohara et al., 2005a). The LVDT had a relatively minor influence on displacement at low frequencies (<4 Hz) (Fig. 5), but the effect was more substantial at higher frequencies. When the LVDT was not attached, power in the 4–8 Hz band for displacement increased with the load supported by the finger. The shapes and locations of the peaks in the spectra for displacement and acceleration when the LVDT was not attached were similar to those reported previously for the index finger (Duval and Jones, 2005; Randall and Stiles, 1964; Stiles and Hahs, 1991; Takanokura and

Sakamoto, 2001). The reduction in the frequency for the peak with an increase in load suggests that the fluctuations were most likely influenced by the oscillations at resonant frequencies of the system that depend on mechanical factors, such as its mass and stiffness of the entire finger including the muscle (Stiles and Randall, 1967). Accordingly, the attachment of the LVDT altered the mechanical characteristics of the system and the oscillations about its resonant frequency.

Modulation of the spectra for displacement and acceleration by the attachment of the LVDT influenced the correlation between the SDs of displacement and acceleration. Consistent with a previous study (Shinohara et al., 2005a), the correlation between the displacement SD and the acceleration SD during concentric and eccentric contractions were weak when the LVDT was attached. In the present study, the correlation was influenced by load in both conditions (with and without the LVDT), and power in the 4–8 Hz band for displacement varied with a change in load (Figs. 6 and 7). Given the influence of load on both the two SDs and the 4–8 Hz band, the strength of the correlation between the displacement SD and the acceleration SD was linearly related to power at the 4–8 Hz band in displacement. The slope of the relation between the strength of the correlation and power in the 4–8 Hz band depended on whether or not the LVDT was attached to the finger, although the coefficient of determination for the linear relation was similar for the two conditions. The difference in slope presumably reflects a change in the mechanical characteristics of the system with the attachment of the LVDT to the finger.

The correlations between the two measures were also influenced by the magnitude of the load and type of muscle contraction. The correlation between the two SDs was weak for contractions with light loads and when the LVDT was attached (Fig. 7). This is likely due to small fluctuations in the common frequency range (4–8 Hz) since the correlation is positively associated with the percent power in the 4–8 Hz band for displacement. The highest correlation during isometric contractions for the no-LVDT condition may also be explained by the greater power in the 4–8 Hz band compared with other contraction types. In contrast, the correlations were relatively high during isometric contractions when the LVDT was attached despite the low power in the 4–8 Hz band, which suggests that other factors can also influence this relation.

In summary, although the LVDT can provide an accurate measure of index-finger displacement, the attachment of the device to the index finger reduced the absolute magnitude of the fluctuations in displacement and acceleration, disturbed the change in the spectral content of these signals with an increase in load, and masked the associations between the three measures of steadiness during the different contraction types. The results also indicated that when the LVDT was not connected to the finger, the SD of displacement was greatest during concentric contractions, the SD of acceleration was greatest during eccentric contractions, and an increase in load was accompanied by distinct changes in the power density spectra for displacement and acceleration of the index finger.

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Fig. 1. Schematic of the experimental arrangement for position-holding and position-tracking tasks. The left hand was supported with the palm vertical and the three fingers, except the index finger, were restrained in a brace. The index finger was placed in a splint, and a flat circular aluminum plate was attached to the radial surface of the index finger centered at the proximal interphalangeal joint. The thumb was extended vertically and held with a brace. The abduction–adduction displacement of the index finger was measured with a CCD laser displacement sensor (a) that was positioned 25 cm above the index finger. Acceleration of the index finger in the abduction–adduction plane was detected by a miniature piezoresistive accelerometer (b) that was attached to the aluminum plate over the index finger. For some measurements, a linear variable-displacement transducer (LVDT; c) was attached to the index finger. The load (d) was suspended either from the inner shaft of LVDT or from the index finger splint at the proximal interphalangeal joint. In MVC tasks, the accelerometer, LVDT, and load were removed and a force transducer was attached to a metal bar positioned just above the index finger at the radial border of the proximal interphalangeal joint.

Fig. 2.

Representative recordings of displacement and acceleration for a subject performing the position-holding and position-tracking tasks with the first dorsal interosseous muscle. The recordings were obtained with the LVDT either attached (right column) or not attached (left column) to the index finger. Top three traces are acceleration and displacement of the index finger during the position-holding task, which involved an isometric contraction, and the bottom three traces are acceleration and displacement during the position-tracking task, which involved concentric (ramp up) and eccentric (ramp down) contractions.

Fig. 3.

The correlations between the displacement SD measured by the laser displacement sensor and by the LVDT during the position-holding task (isometric contraction) and position-tracking task (concentric and eccentric contractions). Each data point indicates the two displacement SD measurements during a single trial. The 13 subjects each performed 6 trials.

Fig. 4. The displacement SD and acceleration SD during isometric, concentric, and eccentric contractions for each load with the LVDT either attached (open symbols) or not attached (filled symbols) to the index finger. Values are means $\pm$ SE.

Fig. 5. Power density spectra for displacement and acceleration for the six loads tested when the LVDT was and was not connected to the index finger. The data are averaged values across contraction types.

Fig. 6. The relative power (% total) for displacement in the 4–8 Hz band for each load when the LVDT was (open symbols) and was not (filled symbols) attached to the index finger. Values are means $\pm$ SE.

Fig. 7.

The coefficient of determination (r^2) between the displacement SD and acceleration SD at each load when the LVDT was (filled symbols) and was not (open symbols) connected to the index finger. The dotted horizontal lines indicate the cutoff for significant ($P = 0.05$) data points.

Table 1

Main effects for condition, load, and contraction type on the displacement SD and the acceleration SD

	Displacement SD (°)	Acceleration SD (m/s ²)
Condition		
No LVDT	0.361 ± 0.208 *	0.184 ± 0.122 **
With LVDT	0.280 ± 0.132	0.124 ± 0.071
Load (%MVC)		
0.8	0.281 ± 0.129	0.152 ± 0.084
1.3	0.305 ± 0.127	0.150 ± 0.084
3.3	0.301 ± 0.154	0.146 ± 0.084
7.3	0.284 ± 0.127	0.133 ± 0.072
15	0.324 ± 0.156	0.151 ± 0.097
31	0.443 ± 0.261 *	0.193 ± 0.122 *
Contraction type		
Isometric	0.248 ± 0.192	0.138 ± 0.105
Concentric	0.374 ± 0.142 **	0.153 ± 0.090
Eccentric	0.343 ± 0.174	0.171 ± 0.115 **

Mean ± SD.

* $P < 0.05$ ** $P < 0.01$ for main effects.