Handedness but not dominance influences variability in endurance time for sustained, submaximal contractions

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Gordon NM, Rudroff T, Enoka JA, Enoka RM. Handedness but not dominance influences variability in endurance time for sustained, submaximal contractions. J Neurophysiol 108: 1501–1510, 2012. First published June 13, 2012; doi:10.1152/jn.01144.2011.—The purpose of this study was to compare endurance time and accompanying neuromuscular adjustments when left- and right-handed subjects used the dominant and nondominant arms to sustain submaximal contractions that required either force or position control. Ten left-handed and 10 right-handed healthy adults (21 ± 5 yr) participated in the study. Each subject exerted a similar net torque about the elbow joint during the force and position tasks to achieve a target force of 20% maximal voluntary contraction (MVC) force (56 ± 18 N). MVC force declined to a similar level immediately after task failure for left- and right-handed subjects (27 ± 13 vs. 25 ± 15%, P = 0.9). Endurance time for the position task was similar for the dominant and nondominant arms (task × dominance interaction, P = 0.17). Although the difference in endurance time between the two tasks was similar for left-handed (136 ± 165 s) and right-handed individuals (92 ± 73 s, task × handedness interaction, P = 0.38), there was greater variance in the ratio of the endurance times for the force and position tasks for left-handed (0.77) than right-handed subjects (0.13, P < 0.001; see Fig. 2). Furthermore, endurance time for the force and position tasks was significantly correlated for right-handed subjects (r² = 0.62, P < 0.001), but not for left-handed subjects (r² = 0.004, P = 0.79). Multiple regression analyses identified sets of predictor variables for each endurance time, and these differed with handedness and task. Hand dominance, however, did not influence endurance time for either group of subjects. These findings indicate that endurance times for the elbow flexors when performing submaximal isometric contractions that required either force or position control were not influenced by hand dominance but did depend on handedness.

THE PREFERENTIAL USE OF ONE ARM during motor tasks is known as hand dominance and defines the handedness of an individual. A right-handed individual, for example, tends to use the right hand to perform most activities of daily living, such as writing, throwing, using scissors, brushing teeth, cutting with a knife, eating with a spoon, striking a match, and opening a box. However, some actions are more commonly performed with the nondominant limb, which results in each arm developing a unique set of motor skills (Adamo and Martin 2009; Bernard et al. 2011; Goble and Brown 2008; Gonzalez et al. 2006; Sale and Semmler 2005; Teixeira 2008; Tretriluxana et al. 2008).

According to the dynamic dominance model, lateralization of the control strategies for reaching movements results in the dominant cerebral hemisphere specializing in the control of multijoint dynamics and the nondominant hemisphere specializing in the control of limb impedance (Schaefer et al. 2009; Shabbott and Sainburg 2008; Wang and Sainburg 2007). In right-handed persons, the model suggests that the left hemisphere is responsible for coordinating task dynamics, whereas the right hemisphere attends to the postural demands of the task. Consistent with the model, the adaptations exhibited by the left and right arms of right-handed subjects differed when exposed to novel inertial dynamics during a reaching task (Duff and Sainburg 2007). Electromyography (EMG) recordings indicated that average muscle activity was less for the dominant arm, which suggested that the dominant arm more effectively anticipated task dynamics. Conversely, the left arm more accurately compensated for an unexpected load, which indicated that the nondominant arm specialized in the control of steady-state position.

Although the dynamic dominance model was developed to explain lateralization asymmetries in reaching and grasping actions, the question arises as to whether similar asymmetries exist for the control of other actions. One possibility may be tasks that require explicit control of the force exerted by the limb compared with those that require control of limb position. Previous work has shown that the strategies used to sustain force and position control differ during submaximal isometric contractions, even when the net muscle torque is similar across conditions. The rates of change in motor unit activity and modulation of reflex pathways, for example, are more rapid during position control (Baudry et al. 2011; Maluf et al. 2005; Mottram et al. 2005; Rudroff et al. 2010), which results in a briefer endurance time for a position task at low to moderate target forces (Baudry et al. 2009; Hunter et al. 2005, 2008; Klass et al. 2008; Maluf et al. 2005; Rudroff et al. 2010). Given that the motor performance capabilities of the nondominant arm of left-handed subjects are superior to those of right-handed subjects (Brouwer et al. 2001; Caroselli et al. 2006; Hoffmann 1997; Hoffmann et al. 1997; Judge and Stirling 2003; Przybyla et al. 2012), we expected to find that left-handed subjects would exhibit less of a difference in the endurance time for sustained isometric contractions that have been shown to involve unique control strategies. Such a finding would suggest that left-handed subjects are more adept at controlling different types of loads, at least with the nondominant arm.

If the lateralization asymmetries observed during reaching tasks extend to force and position control, we would expect to find differences between dominant and nondominant arms in the endurance time of tasks that require force and position control. Compared with the nondominant arm, for example, the dominant arm requires less elbow flexor muscle activity to coordinate multijoint dynamics (Bagesteiro and Sainburg...
METHODS

Twenty healthy adults (23 ± 4 yr; 10 left-handed, 15 men) participated in the study. A modified version of the Edinburgh Handedness Inventory (Oldfield 1971) based on 10 everyday tasks was used to quantify handedness with a laterality quotient (LQ). The LQ scores ranged from 40 to 100, with 100 denoting a complete preference for one hand across the 10 tasks. Left-handed subjects had lower LQ scores compared with right-handed subjects (75.5 ± 21.9 vs. 94 ± 8.1%, respectively, \( P = 0.03 \)). The two groups of participants were similar in height (\( P = 0.72 \)) and body mass (\( P = 0.49 \)):

- Left-handers, 182 ± 9.2 cm and 76.4 ± 12.9 kg; right-handers, 181 ± 6.4 cm and 81.5 ± 19.0 kg. All subjects completed a general health screening and did not report any neurological diseases or cardiovascular disorders. Moreover, all subjects reported moderate levels of structured physical activity (2–4 times/wk) except for one left-handed and two right-handed subjects who exercised more often (>4 times/wk). The Human Subjects Committee at the University of Colorado Boulder approved the protocol. All subjects provided informed, written consent before participating in the study. The experimental design and procedures were similar to those described previously (Rudroff et al. 2007, 2011).

Experimental Arrangement

Participants were seated in an upright position with the upper arm vertical and slightly abducted, the elbow flexed to \( \sim 1.57 \) rad and placed on a pad for support, and the forearm in a horizontal and neutral position. The uninvolved limb was relaxed and placed on a flat surface with the hand at heart level. The test hand and forearm were placed in a modified wrist-hand-thumb orthosis (Orthoamerica, Newport Beach, CA) and attached to a strain-gauge transducer (200-lb range, SB200, S/N 174968; Transducer Techniques, Temecula, CA) that was suspended from the subject’s wrist, placing it in series with the rigid restraint for the force task and in series with the inertial load for the position task (Fig. 1). The wrist was connected to the rigid restraint with an adjustable cable during the force task. An electrogoniometer (SG110 and K100; Biometrics, Cwmfelinfach, UK) was secured to the lateral aspect of the elbow joint to measure elbow joint angle during the position task. Output from the strain-gauge transducer and electrogoniometer were recorded and stored on a computer.

Experimental Procedures

Each subject participated in five sessions: a familiarization session and four experimental sessions. Subjects were introduced to the equipment and procedures during the familiarization session, and grip strength was assessed with a standardized protocol using a hand dynamometer (Marmon et al. 2011). Grip force was increased gradually over 3 s, and maximal force was maintained for \( \sim 3 \) s. Three trials were performed per arm, and the average was calculated for the final value.

One of the fatiguing contractions was performed in each of the four experimental sessions: a force task with the dominant arm, a position task with the dominant arm, a force task with the nondominant arm, and a position task with the nondominant arm. The order for the four fatiguing contractions was determined randomly by first selecting the task to be performed and then choosing the arm (dominant or non-
dominant). The sequences were drawn from an envelope: 12 of the 20 subjects performed the force task first, and 12 of the subjects began the sequence with the dominant arm. There were at least 48 h between sessions when the task involved the same arm.

**MVC force.** MVC force was measured at the beginning of each experimental session by asking the subject to increase the force exerted at the wrist by the elbow flexors from rest to maximum over 3 s and then holding the maximal force for ~3 s. Strong verbal encouragement was provided during each MVC. Subjects rested for ~75 s between trials. Three to five MVC trials were performed. When two MVC forces were within 5% of one another, the greatest force was taken as the MVC force and then used as the reference value for the 20% target force.

The maximal EMG amplitude was measured for each of the elbow flexor muscles during the MVCs. Additional MVC trials were performed for the triceps brachii and posterior deltoid muscles by asking the seated participant to perform maximal elbow extension and maximal shoulder extension actions, respectively.

**Fatiguing contractions.** The force task required the participant to exert a constant force against a rigid restraint to match a target force set at 20% of MVC force. The position task required the subject to keep the arm in a constant position by matching the elbow joint angle to a target of 1.57 rad while supporting an inertial load that was equivalent to 20% MVC force. Both tasks were sustained for as long as possible. The target (force or angle) was displayed with a customized LabView program (version 8.2; National Instruments, Austin, TX) on a 17-in. computer monitor that was located in front of the subject. The visual gain for the feedback signals was 1% MVC/cm during the force task and 0.02 rad/cm during the position task. The typical fluctuations in the feedback signal during the force and position tasks resulted in a similar range of on-screen movement based on these visual gain settings (Mottram et al. 2005).

Failure criteria for the force task comprised either 1) an inability to sustain the force within 5% of the target value for 5 s or 2) an elevation of the elbow off the pad or away from the force transducer without correction. Failure for the position task was defined as either 1) an inability to maintain the elbow angle within 0.2 rad of the target for 5 s or 2) displacement of the forearm from the neutral position for 5 s without correction, despite strong verbal encouragement from the investigators. One investigator was responsible for monitoring the required arm position and giving feedback to the subject throughout all experiments. The force and joint angle signals were monitored with LabView (version 8.2 with PCI-6052E; National Instruments), and a visual signal indicating task termination was displayed when a failure criterion was detected. Endurance time was recorded. Immediately after task failure, a final MVC was performed.

**Measures of activation.** EMG signals were recorded with bipolar surface electrodes (Ag-AgCl, 8-mm diameter, 20-mm distance between electrodes) that were placed on the skin over both the short and long heads of the biceps brachii, brachioradialis, triceps brachii, and the posterior deltoid muscles at locations distal to the innervation zones. The EMG for brachialis was measured with an intramuscular electrode that was inserted ~3 cm proximal to the antecubital fossa. The electrode comprised a 30-gauge, 1-in. hypodermic needle and two stainless steel wires (50-μm diameter) that were insulated with Formvar (California Fine Wire, Grover Beach, CA). One wire in each pair had ~2 mm of insulation removed from the end to increase the recording volume of the electrode. Reference electrodes were placed on a bony prominence over the clavicle or acromion. The EMG signal was amplified 1,000 times, bandpass filtered (13–500 Hz; Coulbourn Instruments, Allentown, PA), recorded, and stored on a computer. The force signal was low-pass filtered (0–50 Hz; Coulbourn Instruments) before being recorded and stored on the computer. The force, position, and EMG signals were digitized at a rate of 1,000 samples/s.

Heart rate and mean arterial pressure (MAP) were recorded during the sustained contractions at 200 samples/s with an automated blood pressure monitor (Finapres 2300; Ohmeda, Madison, WI). The blood pressure cuff was placed around the middle finger of the relaxed hand, and the relaxed arm was placed on a flat surface with the hand at heart level. Ratings of perceived exertion (RPE) were assessed by asking subjects to estimate the effort of the arm muscles performing the task, based on the modified Borg 10-point scale (Borg 1982), with 0 corresponding with little to no effort and 10 denoting maximal effort.

**Data Analysis**

All data were analyzed off-line using Spike2 (Cambridge Electronic Design, Cambridge, UK) and MATLAB (version 7.2, R2006a; The MathWorks, Natick, MA). Heart rate and MAP were quantified over 20-s intervals at 20% epochs of task duration. The blood pressure signal was analyzed in 10-s intervals for mean systolic blood pressure (SBP), mean diastolic blood pressure (DBP), and the number of pulses per second to determine heart rate. MAP was calculated as $MAP = DBP + \frac{1}{3}(SBP - DBP)$.

Force was measured with a strain-gauge transducer (Fig. 1), and steadiness was quantified during all four tasks as absolute (standard deviation) and relative (coefficient of variation) fluctuations in the force signal. Average values were obtained during 30-s intervals. The rates of change in MAP, heart rate, RPE, and coefficient of variation for force during each task were quantified by the slopes of linear or exponential functions fit to the data for individual trials.

Maximal EMG data were recorded prior to the fatiguing contraction in each session. EMG data were rectified, and a 1-s window was advanced through the EMG signal to identify the peak EMG amplitude. EMG activity of the elbow flexors and extensors were quantified during the fatiguing contractions by averaging the rectified EMG (aEMG) over 20-s intervals at the start, 25%, 50%, 75%, and end of task duration. The EMG values were normalized to the aEMG obtained during the MVC. The rate of change in aEMG during each task was quantified by the slope of linear or exponential functions fit to the data for individual trials. Coactivation ratios for the elbow extensors and flexors were quantified as the quotient of the average normalized EMG amplitude for the triceps brachii (antagonist) relative to that for the elbow flexors (agonists) at each time point.

**Statistical Analysis**

The independent variables were the task (force and position), time, muscle (elbow flexors, elbow extensors, and accessory), handedness (left and right), and dominance (dominant and nondominant). The dependent variables were endurance time, MAP, heart rate, RPE, coefficient of variation for force, and aEMG amplitude. Three-factor ANOVAs (task, dominance, handedness) with repeated measures for task and dominance were used to compare endurance time, MAP, heart rate, RPE, coefficient of variation for force, and aEMG amplitude. A four-factor ANOVA (task, dominance, time, muscle) with repeated measures on all factors was used to compare the aEMG of the elbow flexors during the fatiguing contractions by averaging the rectified EMG (aEMG) over 20-s intervals at the start, 25%, 50%, 75%, and end of task duration. The EMG values were normalized to the aEMG obtained during the MVC. The rates of change in aEMG during each task was quantified by the slope of linear or exponential functions fit to the data for individual trials. Coactivation ratios for the elbow extensors and flexors were quantified as the quotient of the average normalized EMG amplitude for the triceps brachii (antagonist) relative to that for the elbow flexors (agonists) at each time point.
correlation coefficients were used to identify the unique contribution of each independent variable to the time to task failure. The performance of the predictor variables is reported as the squared multiple correlation coefficient ($R^2$). The part correlations ($r$) estimated the relative contribution of each predictor variable from the correlation between the criterion variable and the predictor variable when the other independent variables were removed from the model (Green 2002). A positive part correlation denotes a positive association between the predictor and criterion variables, and conversely for a negative part correlation.

The significance level for all statistical tests was set at $P = 0.05$. Data are reported as means ± SD within the text and displayed as means ± SE in figures.

RESULTS

The initial elbow flexor MVC forces were similar for the force and position tasks ($P = 0.27$), left- and right-handed subjects ($P = 0.13$), and dominant and non-dominant arms ($P = 0.35$). Consequently, there were no differences in the target forces (49 ± 16, 52 ± 16, 64 ± 21, and 62 ± 17 N) for the dominant and non-dominant arms of the left- and right-handed subjects, respectively, across tasks. The relative change in MVC force immediately after task failure was similar for the force and position tasks ($P = 0.73$), left- and right-handed subjects ($P = 0.51$), and dominant and non-dominant arms ($P = 0.74$) (Table 1). There were no differences ($P = 0.42$) in handgrip strength for the dominant and non-dominant arms of the left-handed (44 ± 13 and 45 ± 13 kg, respectively) and right-handed subjects (44 ± 8 and 44 ± 9 kg, respectively).

Endurance Time

There was no statistical difference ($P = 0.94$) in endurance time for the dominant (311 ± 127 s) and non-dominant arms (309 ± 137 s) (Table 2). In contrast, endurance time was longer for the force task (367 ± 133 s) than for the position task (253 ± 103 s) ($P < 0.001$) and longer for left-handed subjects (348 ± 142 s) than for right-handed subjects (271 ± 142 s) ($P = 0.04$). However, an ANCOVA with initial MVC force as a covariate revealed no difference in endurance time for left- and right-handed subjects ($P = 0.18$).

There were no significant interactions for endurance time ($P = 0.07$), indicating that endurance time was similar for the dominant and non-dominant arms across tasks (task × dominance, $P = 0.17$) and that the difference in endurance time between the two tasks was similar for left- and right-handed individuals (task × handedness, $P = 0.38$). Although the variance in the ratio of the endurance times for the force and position tasks was similar for dominant (0.34) and non-dominant (0.59) arms ($P = 0.25$), it was greater for left-handed (0.77) than for right-handed subjects (0.13, $P < 0.001$; Fig. 2) and similar for dominant (0.34) and non-dominant arms (0.59, $P = 0.25$). Furthermore, endurance time for the force and position tasks was significantly correlated for right-handed subjects ($r^2 = 0.62$, $P < 0.001$), but not for left-handed subjects ($r^2 = 0.004$, $P = 0.79$; Fig. 2).

EMG Amplitude

EMG amplitude (aEMG) for all elbow flexor muscles increased during the fatiguing contractions, as indicated by the representative data shown in Fig. 3 (time main effect; $P = 0.001$). The influence of task in the increase in elbow flexor aEMG varied with handedness and dominance (Fig. 4). Although elbow flexor aEMG amplitude was greater for left-handed subjects (25.1 ± 9.7% MVC) than for right-handed subjects (21.2 ± 8.3% MVC) (handedness main effect; $P = 0.03$), the rates of increase were similar across handedness conditions ($P = 0.49$). In addition, rates of increase in aEMG for triceps brachii were similar for left-handed (1.002 ± 0.0005% MVC/s) and right-handed subjects (1.002 ± 0.0004% MVC/s) ($P = 0.996$), which resulted in similar rates of increase in coactivation ratios for left-handed (0.00007 ± 0.0005) and right-handed subjects (−0.0005 ± 0.0005) ($P = 0.44$). The rates of increase in the aEMG for the posterior deltoid muscle were similar for left- and right-handed subjects ($P = 0.998$), but a task × handedness interaction indicated that posterior deltoid aEMG for left-handed subjects (13.5 ± 9.2% MVC) was greater than that for right-handed subjects (7.6 ± 5% MVC) (post hoc, $P < 0.001$) during the force task.

The aEMG for the elbow flexor muscles was greater for the dominant arm (24.7 ± 9.1% MVC) than for the non-dominant arm (21.6 ± 9.1% MVC) ($P = 0.03$), which can be attributed to the lower amplitudes for the non-dominant arm of right-handed subjects (18.1 ± 7.9% MVC) (post hoc tests, $P < 0.001$) (Fig. 4) compared with both the dominant (25.1 ± 10.5% MVC) and non-dominant arms of left-handed subjects (25.1 ± 8.9% MVC) (handedness × dominance; $P = 0.03$, post hoc, $P = 0.82$) as well as the dominant arm of right-handed subjects (24.2 ± 7.4% MVC) (post hoc, $P = 0.52$). The aEMG for triceps brachii was similar for the dominant (4.5 ± 0.2% MVC) and non-dominant arms (5.2 ± 0.3% MVC) ($P = 0.001$).

Table 1. Initial and final MVC forces for elbow flexors in each condition

<table>
<thead>
<tr>
<th>Condition</th>
<th>Initial</th>
<th>Final</th>
<th>% Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Task</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Force</td>
<td>273 ± 90</td>
<td>185 ± 60</td>
<td>30 ± 14*</td>
</tr>
<tr>
<td>Position</td>
<td>291 ± 93</td>
<td>228 ± 89</td>
<td>23 ± 13*</td>
</tr>
<tr>
<td>Handedness</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Left</td>
<td>251 ± 78</td>
<td>182 ± 75</td>
<td>27 ± 13*</td>
</tr>
<tr>
<td>Right</td>
<td>314 ± 94</td>
<td>231 ± 76</td>
<td>25 ± 15*</td>
</tr>
<tr>
<td>Dominance</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dominant</td>
<td>282 ± 99</td>
<td>209 ± 79</td>
<td>26 ± 13*</td>
</tr>
<tr>
<td>Nondominant</td>
<td>283 ± 84</td>
<td>205 ± 79</td>
<td>27 ± 15*</td>
</tr>
</tbody>
</table>

Values are means ± SD for maximal voluntary contraction (MVC) force. *$P < 0.05$, final compared with initial value.

Table 2. Endurance time for each condition

<table>
<thead>
<tr>
<th>Condition</th>
<th>Time to Failure, s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Task</td>
<td></td>
</tr>
<tr>
<td>Force</td>
<td>367 ± 133</td>
</tr>
<tr>
<td>Position</td>
<td>253 ± 103</td>
</tr>
<tr>
<td>Handedness</td>
<td></td>
</tr>
<tr>
<td>Left</td>
<td>348 ± 142</td>
</tr>
<tr>
<td>Right</td>
<td>271 ± 142</td>
</tr>
<tr>
<td>Dominance</td>
<td></td>
</tr>
<tr>
<td>Dominant</td>
<td>311 ± 127</td>
</tr>
<tr>
<td>Nondominant</td>
<td>309 ± 137</td>
</tr>
</tbody>
</table>

Values are means ± SD. *$P < 0.05$, compared across conditions.
0.21), whereas the aEMG for the posterior deltoid was greater for the dominant arm (10.8 ± 6.9% MVC) than for the nondominant arm (8.8 ± 6.6% MVC) (dominance main effect, \( P = 0.04 \)). However, aEMG and rates of increase for the triceps brachii and posterior deltoid were not statistically significant (\( P \geq 0.23 \)) across handedness and dominance.

**Force Fluctuations**

The coefficient of variation for the force applied to the load at the beginning of the fatiguing contractions was greater for the force task (2.79 ± 2.49%) than for the position task (1.33 ± 1.27%; \( P < 0.001 \)) and for left-handed subjects (2.59 ± 2.2%) relative to right-handed subjects (1.53 ± 1.86%; \( P = 0.023 \)), but there was no difference in the initial value between arms (dominant: 2.17 ± 2.52%; nondominant: 1.95 ± 1.57%; \( P = 0.56 \)). The coefficients of variation for force were normalized to the initial values to compare the rates of change during the fatiguing contractions (Fig. 5). A task × time interaction (\( P < 0.001 \)) indicated that the coefficient of variation for force increased at a faster rate for the position task (100.6 ± 0.31%/s) than for the force task (100.3 ± 0.21%/s; \( P < 0.001 \)) (Fig. 5A). The rates of increase in the normalized coefficients of variation for force were similar for left-handed (100.4 ± 0.3%/s) and right-handed subjects (100.5 ± 0.27%/s; \( P = 0.173 \); Fig. 5B) and for the dominant (100.4 ± 0.23%/s) and nondominant arms (100.5 ± 0.32%/s; \( P = 0.09 \); Fig. 5C).

**MAP, heart rate, and RPE**

MAP, heart rate, and RPE (time main effects, \( P < 0.001 \)) increased during the fatiguing contractions. MAP was similar at the beginning of the force and position tasks (100 ± 16 and 99 ± 16 mmHg, respectively) and at the end (129 ± 18 and 128 ± 17 mmHg, respectively; post hoc tests, \( P > 0.84 \)). The rate of increase in the MAP was greater for the position task (1.0007 ± 0.0005 mmHg/s) than for the force task (1.001 ± 0.0007 mmHg/s) (task main effect; \( P = 0.03 \)). Heart rate was similar at the beginning (87 ± 12 and 91 ± 10 beats/min, respectively) and end (111 ± 18 and 106 ± 16 beats/min, respectively; post hoc tests, \( P > 0.07 \)) of the tasks and increased at a similar rate during the two tasks (\( P = 0.78 \)). RPE was similar at the start of the force and position tasks (3.3 ± 1.3 and 3.4 ± 1.2, respectively; \( P = 0.56 \)) and, as indicated by the task × time interaction (\( P = 0.01 \)), increased at a greater rate during the position task (0.022 ± 0.007 RPE/min) than during the force task (0.018 ± 0.006 RPE/min, \( P = 0.002 \)).

The rates of increase in MAP (\( P = 0.38 \)) and heart rate (\( P = 0.95 \)) were similar for left- and right-handed subjects. The rate of increase in RPE, however, was greater for right-handed subjects (0.03 ± 0.007 RPE/min) than for left-handed subjects (0.017 ± 0.009 RPE/min, \( P = 0.015 \)). The rates of increase in MAP, heart rate, and RPE (\( P \geq 0.19 \)) were similar for the dominant and nondominant arms.

There were no significant interactions for either MAP (\( P \geq 0.22 \)) or RPE (\( P \geq 0.54 \)). However, there were significant interactions between task, handedness, and time for heart rate (\( P = 0.01 \)) and between task and handedness for rate of increase in heart rate (\( P = 0.03 \)). Post hoc analyses indicated similar rates of increase across conditions (\( P \geq 0.14 \)).

**Predictions of Endurance Time**

The independent variables were entered into multiple linear regression analyses to predict endurance times separately for the force and position tasks for left- and right-handed subjects (Fig. 6). The significant predictors for endurance time for the force task performed by the left-handed subjects (\( R^2 = 0.84, P = 0.004 \); Fig. 6A) were the rate of increase in elbow flexor aEMG (\( r = -0.55 \)), grip strength (\( r = 0.48 \)), average coactivation ratio (\( r = 0.35 \)), and rate of increase in heart rate (\( r = -0.27 \)). The significant predictors for endurance time for the force task performed by the right-handed subjects (\( R^2 = 0.75, P = 0.005 \); Fig. 6B) were grip strength (\( r = -0.50 \)), rate of increase in MAP (\( r = -0.41 \)), and rate of increase in the posterior deltoid aEMG (\( r = -0.27 \)). The significant predictors for endurance time for the position task performed by left-handed subjects (\( R^2 = 0.76, P = 0.048 \); Fig. 6C) were the rates of increase in elbow flexor aEMG (\( r = -0.84 \)) and RPE (\( r = -0.25 \)), and the significant predictors for the right-handed subjects (\( R^2 = 0.68, P = 0.004 \); Fig. 6D) were the rates of increase in coefficient of variation for force (\( r = -0.63 \)) and elbow flexor MVC force (\( r = -0.46 \)).

Fig. 2. Endurance times for the force and position tasks were strongly associated (\( r^2 = 0.62 \)) for dominant and nondominant arms of right-handed subjects (A), but not for left-handed subjects (B).
DISCUSSION

This study compared the endurance time and accompanying neuromuscular adjustments when left- and right-handed subjects used the elbow flexor muscles of the dominant and nondominant arms to sustain submaximal contractions (20% MVC force) that required either force or position control. The main findings of the study were that 1) left-handed subjects displayed greater variance than right-handed subjects in the ratio of the endurance time for the force and the position tasks; 2) there was a strong association between endurance times for the force and position tasks for right-handed subjects, but not for left-handed subjects; 3) endurance time for the position task was similar for the dominant and nondominant arms; and 4) the difference in endurance time for the two fatiguing contractions was similar for left- and right-handed subjects.

Handedness and Endurance Time

The dominant arm of left- and right-handed subjects exhibits similar abilities when performing manual tasks, whereas the nondominant arm of left-handed subjects is superior to that of right-handed subjects (Brouwer et al. 2001; Caroselli et al. 2006; Hoffmann 1997; Hoffmann et al. 1997; Judge and Stirling 2003; Przybyla et al. 2012). When endurance times were collapsed across arms, however, the difference in endurance time for the two tasks in the current study was similar for left- and right-handed individuals. Nonetheless, two observations in the current study suggest that there may be significant differences in the motor control strategies used by left- and right-handed individuals during the performance of sustained, submaximal contractions. First, left-handed subjects exhibited greater variation in the relative endurance times for the force and position tasks. This handedness observation was further supported by a strong association between the two tasks for the dominant and nondominant arms of right-handed subjects, but not for left-handed subjects (Fig. 2). Second, despite strong associations ($R^2 \geq 0.68$) between predicted and observed endurance times for both types of fatiguing contractions for the two handedness groups (Fig. 6), the predictor variables for the two tasks differed for left- and right-handed subjects. The significant predictors for the left-handed subjects included indexes of central neural activity (heart rate, RPE), activation of agonist and antagonist muscles (elbow flexor aEMG, coactivation ratio), and muscle strength (grip strength). The signifi-
cant predictors for the right-handed subjects included activa-
tion of a postural muscle (posterior deltoid aEMG), muscle
strength (grip strength, elbow flexor MVC force), an index of
afferent feedback (MAP), and the steadiness of contraction
(coefficient of variation for force). Given these differences,
more mechanistic studies are needed to determine why the
specific variables emerge as significant predictors for the dif-
terent conditions.

Previous studies have found that the characteristics of
both force and muscle activation differ between left- and
right-handed subjects when they perform brief, steady con-
tractions. Although Pereira et al. (in press) reported no
differences in the coefficient of variation for force between
the dominant and nondominant arms of left- and right-

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Fig. 4. Average EMG amplitude (aEMG, normalized to the peak MVC value)
for the elbow flexor muscles (brachialis, short and long heads of biceps brachii,
brachioradialis) during the force and position tasks for the dominant and
nondominant arms of left-handed (LH) and right-handed (RH) individuals.
Values are means ± SE.

Hand Dominance Did Not Influence Endurance Time

Bagesteiro and Sainburg (2002, 2003) proposed a dynamic
dominance model in which the dominant arm is purported to
employ more torque-efficient control strategies (trajectory con-
trol), whereas the nondominant arm is supposedly more effec-
tive at maintaining position accuracy in response to unexpected
load perturbations (postural control). The current study sought

Fig. 5. Coefficient of variation (CV) for the force (% initial) applied to the load
during the two tasks (A), by the left- and right-handed participants (B), and
with the dominant and nondominant arms (C).
to determine whether the dynamic dominance model can extend from reaching actions to control strategies used during sustained contractions that require either force or position control. On the basis of the dynamic dominance model, we hypothesized that endurance time during position control would be less for the dominant arm than the nondominant arm. However, there were no differences due to limb dominance in either MVC force (dominant: 282 ± 99 N; nondominant: 283 ± 84 N, P = 0.99) or endurance time (dominant: 311 ± 127 s; nondominant: 309 ± 137 s, P = 0.71). This was further supported by similar differences between the two arms in the rates of increase in aEMG of the elbow flexor muscles, coefficient of variation for force, MAP, heart rate, and RPE during these fatiguing contractions.

**Handedness and Dominance Influence Elbow Flexor aEMG**

Despite the similar endurance times and rates of increase in aEMG for the dominant and nondominant arms, there was a significant handedness × dominance interaction for elbow flexor aEMG. As indicated in Fig. 4, aEMG for the elbow flexors of the nondominant arm of the right-handed subjects was significantly less than that for the other three conditions, at least for the first 75% of contraction duration. The elbow flexor aEMG data for the nondominant arm of the right-handed subjects, however, was similar to that reported in other studies in which the nondominant arm of right-handed participants performed the two types of fatiguing contractions (Klass et al. 2008; Rudroff et al. 2011). The new finding is that elbow flexor aEMG was greater for much of the fatiguing contractions for the dominant arm of right-handed subjects and both arms of left-handed subjects than for the nondominant arm of the right-handed participants.

Given that the amplitude of an interference EMG signal corresponds to the algebraic sum of the contributing muscle fiber action potentials (Dideriksen et al. 2011; Keenan et al. 2005), it is difficult to explain how different amounts of
activity in the agonist muscles can produce the same net muscle torque. One possibility is that there were different contributions by antagonist or accessory muscles to the force exerted at the wrist (Rudroff et al. 2007). Coactivation of the antagonist muscle does not appear to have contributed to the lower elbow flexor aEMG for the nondominant arm of the right-handed subjects, because similar rates of increase were observed for the triceps brachii aEMG and coactivation ratio across the handedness and dominance conditions. Furthermore, aEMG for posterior deltoid, a representative accessory muscle, increased similarly across conditions. However, the average amplitude was greater for the dominant arm and for left-handed participants. These findings suggest that significant differences existed in the intensity and distribution of muscle activity that were not monitored during the fatiguing contractions across the handedness and dominance conditions. Nonetheless, the differences in muscle activity during the fatiguing contractions did not result in a handedness \times dominance interaction ($P = 0.69$) for endurance time.

**Force and Position Tasks**

Consistent with previous findings (Baudry et al. 2009; Hunter et al. 2005, 2008; Klass et al. 2008; Maluf et al. 2005; Rudroff et al. 2010), the current study found that endurance time for the position task was briefer than that for the force task when the two tasks involved submaximal, isometric contractions with the elbow flexor muscles of both the dominant and nondominant arms of left- and right-handed participants. As observed in prior studies when the two fatiguing contractions were performed at 15–20% MVC force with the elbow flexor muscles (Hunter et al. 2002; Rudroff et al. 2011), the mechanical fluctuations (coefficient of variation for force), RPE, and MAP all increased more rapidly during the position task than the force task. Presumably, these measures indicate that the muscle mass contributing to the net muscle torque increased at a faster rate during the position task, despite the two tasks requiring the same net muscle torque and having similar rates of increase in elbow flexor aEMG (Hunter et al. 2002; Klass et al. 2008). Consistent with this interpretation, the biceps brachii motor unit pool has been shown to experience significantly faster rates of depression in the responsiveness of spinal pathways (Baudry et al. 2009; Klass et al. 2008) and more substantial adjustments in motor unit activity (Mottram et al. 2005, Rudroff et al. 2010) during the position task. Collectively, these adjustments indicate that position control is more difficult to sustain than force control, which the current findings demonstrate is experienced by both the dominant and nondominant arms of left- and right-handed participants.

Despite the strength of the elbow flexor muscles being similar for the dominant and nondominant arms of left- and right-handed subjects, the left-handed subjects exhibited greater variability in the relative endurance times for the force and position tasks, and right-handed subjects showed a stronger association in endurance times for the force and position tasks. In contrast to previous observations demonstrating less of a difference in performance capabilities between the dominant and nondominant arms and hands of left-handed subjects compared with right-handed subjects (Adam et al. 2012; Klöppel et al. 2007; Przybyla et al. 2012), the current findings indicate greater relative variability in endurance time for left-handed subjects when performing submaximal fatiguing contractions that required either force or position control. The greater variability exhibited by the left-handed subjects may be a consequence of the fatiguing contractions engaging extensive cortical networks (Korotkov et al. 2005; Liu et al. 2003; Post et al. 2009) that involve previously reported cortical asymmetries in left-handed individuals (van den Berg et al. 2011). Although the current study does not provide insight on the underlying mechanisms, one functional consequence of the greater variability exhibited by left-handed participants is that interventions capable of prolonging endurance time for these types of fatiguing contractions (Barry et al. 2008; Mottram et al. 2006; Riley et al. 2008; Semmler et al. 2000; Yue et al. 1997) would more consistently transfer changes in performance across tasks in right-handed than in left-handed persons.

In conclusion, the results indicate that the dynamic dominance model, which suggests that the dominant and nondominant arms specialize in control strategies during reaching actions, does not generalize to submaximal isometric contractions sustained at 20% MVC force with the elbow flexor muscles, but the strategies used to perform the fatiguing contractions did vary with the handedness of the individual.

**DISCLOSURES**

No conflicts of interest, financial or otherwise, are declared by the authors.

**AUTHOR CONTRIBUTIONS**


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