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Title

Bilateral deficit in strength but not rapid force during maximal handgrip contractions

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Title

Bilateral deficit in strength but not rapid force during maximal handgrip contractions

Abstract

The purpose of this experiment was to evaluate the bilateral index in force and electromyographic (EMG) responses for the dominant and non-dominant hands during maximal handgrip contractions in males and females. Thirty-two right-handed participants (16 females) performed maximal unilateral and bilateral handgrip contractions on two separate visits. Bilateral indices were computed for maximal force, rate of force development (RFD_{100}), EMG amplitude, and the rate of EMG rise (RER). There was a bilateral deficit for maximal force in the dominant ($-4.98 \pm 7.39\%$, $p < 0.001$; $d = 0.674$) but not the non-dominant hand ($-1.57 \pm 9.10\%$, $p = 0.334$; $d = 0.173$). No deficits were observed for rapid force. The non-dominant flexor carpi radialis showed a bilateral facilitation in EMG amplitude ($+12.32 \pm 19.29\%$, $p < 0.001$; $d = 0.638$), yet a bilateral deficit for RER ($-22.10 \pm 27.80\%$, $p < 0.001$; $d = 0.795$). No sex differences were observed for any of the bilateral indices. These data suggest that maximal but not rapid force is susceptible to a bilateral deficit during contractions of the hands. The EMG responses did not parallel the force data. We show sex does not influence the magnitude or direction of the bilateral index in this muscle group.

Keywords

Bilateral index, EMG, MVC, neuromuscular, sex differences, flexor carpi radialis

Introduction

The bilateral deficit represents a functional limitation of the human motor system. It describes a situation where the maximal force during simultaneous bilateral contraction of the same muscle groups are less than the summed forces of separate unilateral contractions. This topic continues to garner interest from sports scientists, yet its presence has not been unanimously observed (23). Many features of the bilateral deficit remain unresolved: the influence of sex and handedness; the uniformity of dominant versus non-dominant limbs; and the susceptibility of a deficit for rapid force. A stronger understanding of these factors may shape exercise design and prescription given the training-dependent plasticity of the bilateral deficit (10,24).

Although the majority of published studies show a bilateral deficit, few (7,10) have observed a bilateral facilitation. Here, the summed forces are greater for bilateral versus unilateral contraction. The bilateral index quantifies maximal bilateral and unilateral forces as a percentage, where a negative and positive bilateral index reflect a bilateral deficit and bilateral facilitation, respectively (10). Many factors may contribute to a bilateral deficit, but the fact that it presents only during synchronous contraction of homologous muscle pairs is strong evidence for neural mediation (9,18). Electromyography (EMG) is the most common method used to examine the neural features of the bilateral deficit. It is important to recognize, however, that EMG cannot identify the specific site(s) of impairment and may be influenced by many nonphysiological factors. Typically, the activation of homologous muscle pairs assessed via maximal EMG amplitude is compared between unilateral and bilateral contraction. Some reports show a bilateral deficit in maximal EMG amplitude similar to maximal force, whereas others have not (23). The non-linearity of the force-EMG relationship may partially explain the incongruent reports on maximal muscle activation during bilateral contraction (10,23). An alternative approach is to examine the rate of force development (RFD) and the rate of EMG rise (RER) of unilateral versus bilateral contraction. Since motor unit activity determines both RFD and RER (1,2), these variables offer a unique lens to view the neural contribution to the bilateral deficit.

There is data showing rapid force is susceptible to a bilateral deficit, yet the focus for the majority of these studies has been on the lower limb (3,5,6,12,20,25). Although upper and lower limbs express similar consistency and magnitude for the bilateral deficit, it is recommended to study them separately given their inherent neuroanatomical differences (23). The bilateral deficit was first documented during handgrip contraction (8) and investigations with this muscle group have continued with mixed results (23). The reasons for the discrepancies are unclear, but differences in handedness (6) and sex within and between these studies may have a role as there is recent evidence (27) showing males are more susceptible to a bilateral deficit than females. Studying the bilateral index for the hands is advantageous as concerns of posture, stability, and body positioning are comparatively less than that for the lower limbs (22). The aim of this study was to evaluate the bilateral deficit in maximal strength, rapid force, and the rate of EMG rise for the dominant and non-dominant limbs during maximal handgrip contractions. A secondary aim was to compare these responses between males and females. We hypothesized that our dependent variables would show a bilateral deficit, yet males would show a greater deficit compared to females.

Methods

Participants

Thirty-two right-handed participants (n = 16 males; mean ± SD: age = 24 ± 4 years; stature = 183.7 ± 4.9 cm; mass = 84.7 ± 10.6 kg; n = 16 females; mean ± SD: age = 24 ± 4 years; stature = 165.2 ± 9.7; mass = 69.6 ±18.6 kg, n = 9 reported active oral contraceptive use) volunteered to participate in this study. Before testing, the participants completed a health history questionnaire, a modified Edinburgh handedness questionnaire, and they read and signed an informed consent document. This study was approved by the University of Oklahoma Institutional Review Board for Human Subjects.

Research Design

This study was performed alongside other experiments as part of a larger study with independent research hypotheses. A cross-sectional design was used with the current data to examine the bilateral index in males and females during maximal isometric contractions of the handgrip muscles. After two familiarization sessions, the participants completed two experimental visits, the average of which were retained for analysis. The same experimental protocol was employed for both visits and consisted of maximal unilateral and bilateral contractions. The visits were separated by a minimum of 72 hours and were scheduled at the same time of day (± 2 hours).

Instrumentation and Procedures

Isometric Strength Assessment

All strength testing was performed in a custom-built strength testing apparatus. The participants were seated in front of the apparatus and both arms were placed on a pad in front of them. Each hand separately gripped a modified handgrip dynamometer that was attached to a tension-compression load cell (Model SSM-AJ-500, Interface Inc., Scottsdale, AZ.). The participant's hands were in a neutral handgrip position (i.e., palms facing each other). Before strength testing, the participants performed 3, 5-second isometric contractions of the handgrip muscles at ~25, 50, and 75% of their perceived maximum force. Each maximal voluntary contraction was 3 seconds in duration with 30 seconds of recovery provided between attempts. The strength measurements were exactly the same for each visit but were performed in a randomized order: (1) maximal unilateral handgrip contractions of the right hand (×2), (2) maximal unilateral handgrip contractions of the left hand (×2), and (3) maximal bilateral handgrip contractions for both hands (×2). Each contraction was performed twice. Standardized verbal instructions to *"squeeze as fast and hard as possible in 3, 2, 1, squeeze"* were provided to the participants for each strength assessment. An illustrative example of our experimental setup is shown in Figure 1.

Signal Processing

Electromyography and force

Surface electromyographic (EMG) activity was collected from the flexor carpi radialis (FCR) and extensor carpi radialis (ECR) of both arms with a bipolar surface electrode (DE-2.1; Delsys, Inc., Natick, MA.) during all strength testing. The sensor for the FCR was placed approximately one-third of the distance from the antecubital space to the lateral radial styloid process. The sensor for the ECR was placed approximately one-third of the distance from the lateral epicondyle of the humerus to the lateral radial styloid process. It is important to note, however, that the specific sensor site was determined on a subject-by-subject basis to acquire maximal signal fidelity. Once determined, the site was cleansed with alcohol and outlined with permanent ink in order to replicate its placement for the subsequent visits. A reference electrode was placed over the seventh cervical vertebrae. Custom-made LabVIEW software was used to process the EMG signals (LabVIEW 13.0; National Instruments). The EMG signals were preamplified (gain, 1000), band-pass filtered with a fourth-order Butterworth between 20 and 450 Hz, and smoothed with a 50 ms zero-shift moving RMS. The force signal was also filtered with a 50 ms zero-shift moving average. The force and EMG signals were sampled at 20k Hz with a 12-bit analog-to-digital converter (National Instruments). Both the maximal voluntary contraction force and the maximal EMG amplitude values were quantified as the highest 500 ms average of the 3-second MVC. To determine the rates of rise for the EMG and force signals, cursors were placed around the regions of interest and their time curves were magnified for visual inspection in a separate plot. The onsets were viewed within a 20 ms time window and were visually determined as the point at which the signal deflected 2 SD away from its baseline value. RFD was determined from the change in the linear slope of the force-time curve (Δforce/Δtime) at a time interval of 0-100 ms (RFD_{100}) from onset. RER was calculated from the linear slope of the EMG-time curve (ΔEMG/Δtime) at a time interval of 0-30ms from the onset. The rate of EMG rise from 0-30 ms (RER_{30}) was then normalized ($_{n}RER_{30}$) to the maximal EMG amplitude ($\%EMG_{Max}$) value for each contraction.

Statistical Analysis

All data are presented as means ± standard deviations. The mean bilateral indices (%) were compared against zero with a one-sample t-test for both hands. An independent samples t-test was used to compare the bilateral indices between males and females. The bilateral indices for the dependent variables were of primary interest as the indices are normalized and ignore sex-based differences in absolute force and EMG values. The Shapiro-Wilk test was used to assess normality. If the data was not normally distributed, non-parametric tests (Mann-Whitney and Wilcoxon Signed-Rank) were used. Cohen's *d* values and 95% confidence intervals (CI) are reported for mean comparisons. Statistical analyses were performed with SPSS software (version 26.0, IBM SPSS Inc., Chicago, IL, USA). Alpha was set at 0.05. To control for familywise error rate, Bonferroni corrections were applied based on the total number of comparisons. The bilateral index (%) was computed with the following equation for each dependent variable (10), positive and negative values reflect a bilateral facilitation and bilateral deficit, respectively:

$$Bilateral\ index\ (\%) = \left(100 \times \frac{(MVC_{Bilateral})}{(MVC_{unilateral})}\right) - 100$$

Results

Isometric Force

Figure 2 shows the mean bilateral index for MVC strength for the dominant hand ($-4.98 \pm 7.39\%$, $p < 0.001$, $d = 0.674$, 95% CI = -7.65, -2.32) was less than zero, but this was not observed for the non-dominant hand ($-1.57 \pm 9.10\%$, $p = 0.334$, $d = 0.173$, 95% CI = -4.53, 1.43). Figure 3 shows the mean bilateral index for RFD_{100} for the dominant ($-5.87 \pm 19.75\%$, $p = 0.103$, $d = 0.297$, 95% CI = -12.99, 1.25) and the non-dominant hand ($-0.10 \pm 21.42\%$, $p = 0.978$, $d = 0.005$, 95% CI = -7.62, 7.83) were not different from zero. There were no significant differences between sex for the bilateral index of MVC ($p = 0.750$, $d = 0.114$, 95% CI = -5.61, 7.69; $p = 0.885$, $d = 0.051$, 95% CI = -5.04, 5.81) or RFD_{100} ($p = 0.805$, $d = 0.088$, 95% CI = -17.62, 13.79; $p = 0.466$, $d = 0.261$, 95% CI = -9.17, 19.56) for the left or right hands, respectively.

Electromyography

Extensor Carpi Radialis

The mean bilateral index for EMG_{Max} for the dominant (+2.84 ± 23.49%, p = 0.500, *d* = 0.121, 95% CI = -5.63, 11.30) and the non-dominant ECR (+4.42 ± 31.40%, p = 0.432, *d* = 0.141, 95% CI = -6.90, 15.74) were not different from zero. The mean bilateral index for $_{n}RER_{30}$ for the dominant (Wilcoxon test: -4.20 ± 43.81%, p = 0.369, *d* = 0.186, 95% CI = -21.40, 9.04) and non-dominant ECR (-7.09 ± 39.89%, p = 0.322, *d* = 0.178, 95% CI = 21.48, 7.29) were not different from zero. There were no significant differences between sex for the bilateral index of EMG_{Max} (p = 0.688, *d* = 0.143, 95% CI = -18.42, 27.55, p = 0.327, *d* = 0.352, 95% CI = -8.69, 25.23) or $_{n}RER_{30}$ (p = 0.542, *d* = 0.218, 95% CI = -20.31, 37.88; Mann-Whitney test: p = 0.468, *d* = 0.156, 95% CI = -33.53, 30.77) for the left or right ECRs, respectively.

Flexor Carpi Radialis

Figure 4 shows the mean bilateral index for EMG_{Max} for the non-dominant FCR (+12.32 ± 19.29%, p < 0.001, *d* = 0.638, 95% CI = 5.36, 19.27) was greater than zero, whereas there was no difference for the dominant FCR (-6.09 ± 19.14%, p = 0.082, *d* = 0.318, 95% CI = -12.98, 0.815). The mean bilateral index for $_{n}RER_{30}$ for the non-dominant (-22.10 ± 27.80%, p < 0.001, *d* = 0.795, 95% CI = -32.12, -12.07), but not the dominant FCR (+10.20 ± 58.16%, p = 0.328, *d* = 0.176, 95% CI = -10.76, 31.17) was less than zero. There were no significant differences between sex for the bilateral index of EMG_{Max} (p = 0.847, *d* = 0.069, 95% CI = -15.50, 12.81; p = 0.689, *d* = 0.143, 95% CI = -16.79, 11.24) or $_{n}RER_{30}$ (p = 0.399, *d* = 0.303, 95% CI = -20.31, 37.88; p = 0.259, *d* = 0.407, 95% CI = -18.23, 65.32) for the left or right FCRs, respectively.

Discussion

The aim of this study was to examine the bilateral index during maximal handgrip contractions in males and females. The main findings show: (1) a bilateral deficit in strength for the dominant hand, but not the non-dominant hand; (2) no bilateral deficit in rapid force; and (3) no sex-related differences in the expression of the bilateral index. The observations here regarding the deficit in strength are similar to some previous reports (5,8,15), but not others (12,14). The novel findings show an absence of a deficit in rapid force along with no sex-related differences in the bilateral indices.

Approximately 70% of the published studies investigating the bilateral index for the handgrip muscles have shown a deficit (23). The magnitude of the deficit (-4.98% for the dominant hand) observed here agrees with these studies (4,5,8,15,16). Our finding of a significant deficit for the dominant but not the non-dominant hand supports the original hypothesis of Henry & Smith – the bilateral deficit originates in the dominant limb (8). The only study that has tested this hypothesis directly found that left-hand, but not right-hand dominant participants had a bilateral deficit in the dominant limb (5). The reason for the discrepant reports is unclear. Within our sample, the range of bilateral indices were large for both the non-dominant (-22.64% to +18.61%) and dominant (-18.02% to +8.24%) hands, but ~84% of the sample had a larger mean deficit for their dominant versus non-dominant hand. An advantage of our experimental setup was the simultaneous measurement of maximal force for each hand during bilateral contraction. This allowed us to determine whether the bilateral deficit was uniform or lateralized between hands. Nevertheless, the explanation for a greater bilateral deficit in the dominant limb remains unresolved. There is some evidence showing the stronger limb is more susceptible to a bilateral deficit (5,18). A speculative explanation may be that when strength is lateralized, there is more strength to lose on the stronger side during bilateral contraction. The obvious question relates to the locus of the bilateral deficit's lateralization – at what point along the motor pathway may the *dominant limb* lose maximal force capacity? Some reports suggest there is no neural basis for the bilateral deficit, the smaller forces during bilateral contraction are simply an artifact of postural stability, body positioning, and mechanical configuration of the testing apparatus (22). Though the data is compelling for the lower limb, the ability to control for postural stability and limb position is one advantage of studying the bilateral deficit in the hand muscles (9). Nevertheless, participant orientation (i.e., seated, standing, supine, elbow position) may have a role for the different findings between studies for the bilateral deficit in the hand muscles (23).

The absence of a bilateral deficit in rapid force is somewhat surprising since many investigations on the topic have shown a larger bilateral deficit for rapid force than strength (11,15,25). Although more is known about the bilateral deficit in rapid force for the lower limb, there is limited data showing the upper limb is also susceptible (5,14). Our observation of a bilateral deficit for maximal strength but not rapid force directly contrasts recent data for the knee extensors (3). The number of activated motor units and the rate at which they discharge their action potentials is a primary neural determinant of rapid force (2), but the explanations for a bilateral deficit in rapid force are unclear. Previous authors (11,15,26) speculate that preferential inhibition of type II muscle fibers may contribute to the deficit in rapid force. Some data for the lower limb suggests lower neural drive (i.e., voluntary activation) to the agonist muscle is responsible (25), yet others show no evidence for this possibility and emphasize the role of participant stability (3,22). The only other study that has investigated rapid force during handgrip observed a significant bilateral deficit (5). It is interesting to note the mean deficit in rapid force for the group of right-handed participants in the previous study (5) is comparable (-3.48%) to the mean deficit (-5.87%) observed here. The comparatively high-degree of interindividual variability for the bilateral indices in the present study may explain the lack of agreement with others (5).

Data regarding the bilateral index for maximal EMG amplitude is conflicting; some reports show a significant bilateral deficit (4,15,16,17) – even a parallel between the deficit in strength and EMG amplitude (12,15,18), others have observed no significant bilateral index (9,12,14), and few have shown a bilateral facilitation (5,7,10). We found no evidence of a significant bilateral index in EMG amplitude for either extensor carpi radialis. This finding agrees with the majority of studies examining the EMG response for the antagonist muscle between unilateral and bilateral contractions (23). An unexpected finding was the bilateral facilitation in EMG amplitude for the non-dominant flexor carpi radialis. Similarly, there was a significant bilateral deficit in the rate of muscle activation ($_{n}RER_{30}$) for the non-dominant flexor carpi radialis yet this trend was not observed for the dominant arm. A bilateral facilitation for maximal EMG amplitude with a deficit in the rate of muscle activation has been observed during handgrip (5). It is challenging to reconcile the unique EMG and force responses between dominant and non-dominant hands. One suggestion is the central nervous system may attempt to equate force output of homologous muscle pairs for symmetrical bilateral output (5). Although the data is insufficient to support this hypothesis, it is interesting to note the EMG facilitation for the (weaker) non-dominant hand together with the force deficit for the (stronger) dominant hand.

This is the second study to directly compare the bilateral index between sexes. The previous observation (27) found that males exhibited a bilateral deficit for index finger abduction while females demonstrated a non-significant bilateral facilitation. In contrast to these previous observations, there was no evidence that sex moderated any of the bilateral indices in the present study. The effect size for the bilateral index in maximal strength between sexes was negligible for both the non-dominant (d = 0.114) and dominant (d = 0.051) hands. Despite speculation that differences in cortical excitability and hemispheric inhibition (21) may explain unique bilateral indices between sexes (27), the present data show the motor control properties of maximal handgrip contractions are similar between males and females. Overall, the present force and EMG data do not support the notion that sex moderates the magnitude nor the direction of the bilateral index.

Limitations

It is important to address the limitations of the present study. We were unable to use stimulation techniques for EMG sensor placement or normalization. The EMG recordings were collected from the superficial muscles of the forearm and may, therefore, not represent the activity of the deeper finger flexors or hand muscles. There were also no assessments of cortical activity, voluntary activation, or motor unit firing properties, therefore, the interpretations are limited to the force and bipolar surface EMG data. It is also important to recognize that RFD and MVC values were measured from the same contraction and not separately as some have suggested (13). As a result, the output of these measures may have been strengthened with independent contractions emphasizing either rapid force or maximal strength. Lastly, menstrual cycle information was not collected from our female participants so the influence of menstrual phase on the present data is unknown.

Conclusions

In conclusion, we show a bilateral deficit in maximal force but not rapid force during handgrip contractions. The dominant hand was more susceptible to the bilateral deficit in force, yet the EMG response of the non-dominant flexor carpi radialis was the only muscle showing a significant bilateral index. Overall, the force and EMG data suggest that muscle activation kinetics are not susceptible to a bilateral deficit and are independent of the deficit in maximal force during handgrip. The present findings show no evidence of sex-related differences in bilateral indices of force and EMG. The variability in the bilateral index within and between participants agrees with previous reports and this should be a point of consideration for practitioners during bilateral versus unilateral strength assessment.

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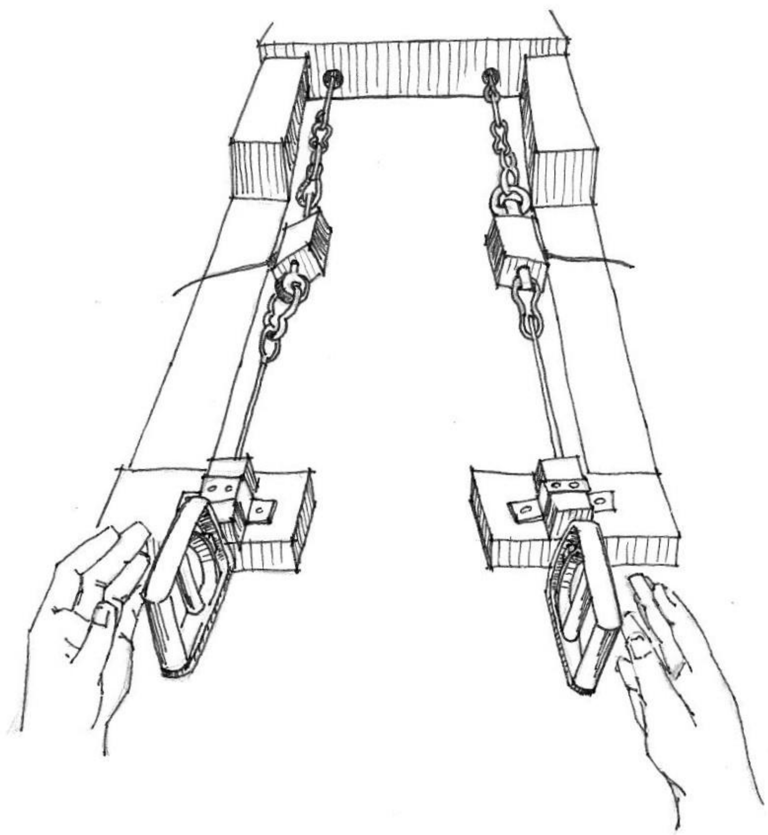

Figure 1. An illustration of the experimental setup used in the present study.

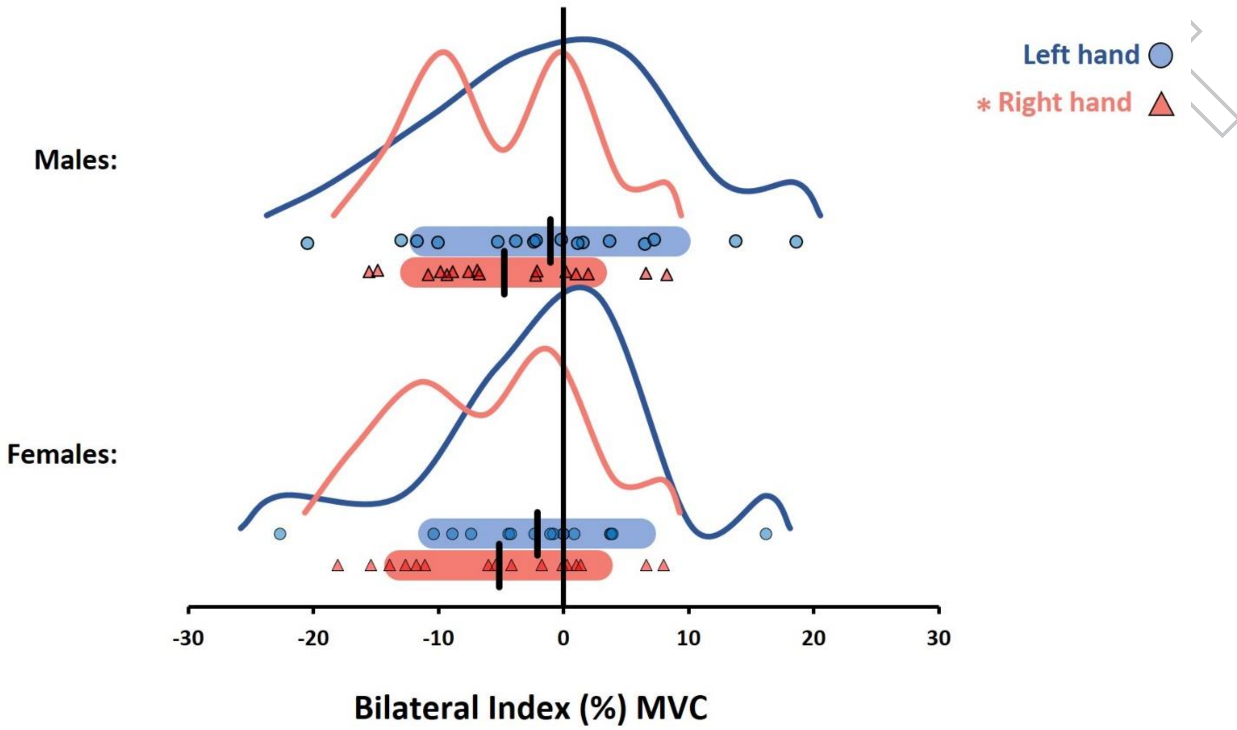

Figure 2. A scatterplot of individual values with the relative frequency distribution shown above for the bilateral index (%) in maximal force for both sexes and hands. The means and standard deviations are represented by the vertical bars and shaded regions, respectively. Left hand ($p = 0.334$, $d = 0.173$, 95% CI = -4.85, 1.69). Right hand ($p < 0.001$, $d = 0.674$, 95% CI = -7.65, -2.32). *Significantly less than zero collapsed across sex.

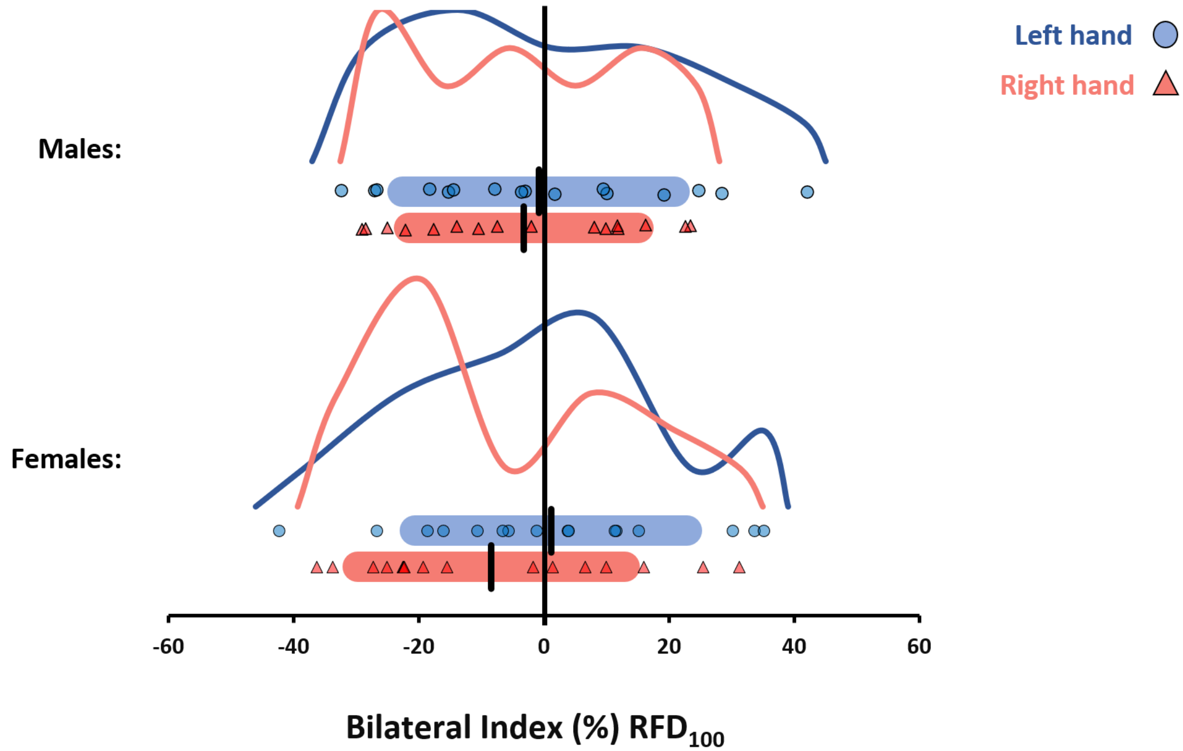

Figure 3. A scatterplot of individual values with the relative frequency distribution shown above for the bilateral index (%) in RFD_{100} for both sexes and hands. The means and standard deviations are represented by the vertical bars and shaded regions, respectively. Left hand (-0.10 ± 21.42%, p = 0.978, *d* = 0.005, 95% CI = -7.62, 7.83). Right hand (-5.87 ± 19.75%, p = 0.103, *d* = 0.297, 95% CI = -12.99, 1.25).

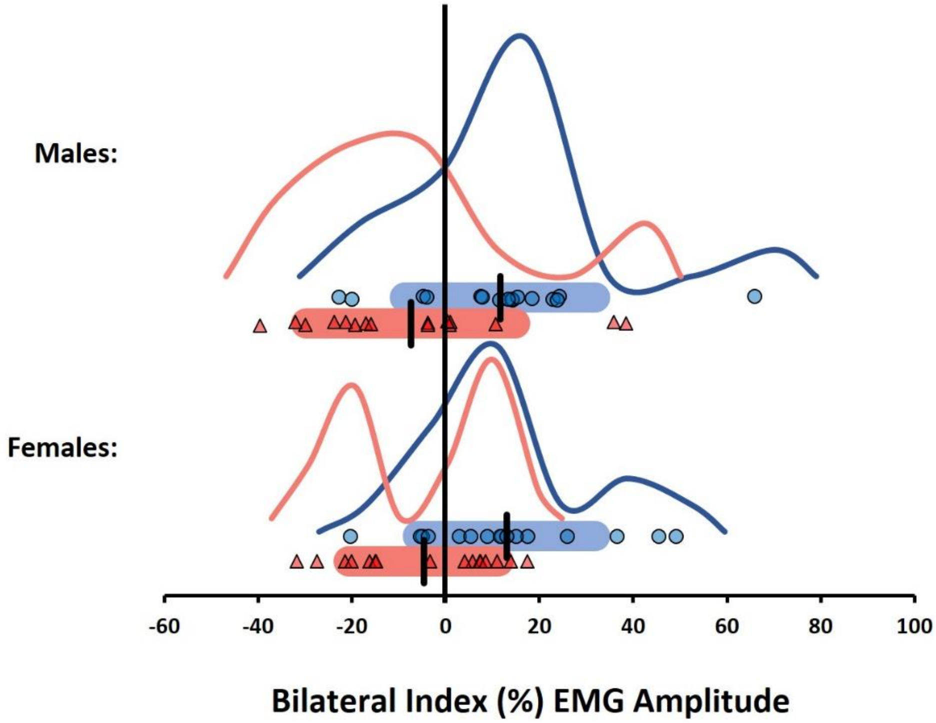

Figure 4. A scatterplot of individual values with the relative frequency distribution shown above for the bilateral index (%) in FCR EMG amplitude for both sexes and hands. The means and standard deviations are represented by the vertical bars and shaded regions, respectively. Left hand (+12.32 ± 19.29%, $p < 0.001$, $d = 0.638$, 95% CI = 5.36, 19.27). Right hand (-6.09 ± 19.14%, $p = 0.082$, $d = 0.318$, 95% CI = -12.98, 0.815). *Significantly greater than zero collapsed across sex.