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ORIGINAL ARTICLE

The time course of cross-education during short-term isometric strength training

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Abstract

Purpose This study examined the time course of contralateral adaptations in maximal isometric strength (MVC), rate of force development (RFD), and rate of electromyographic (EMG) rise (RER) during 4 weeks of unilateral isometric strength training with the non-dominant elbow flexors.

Methods Twenty participants were allocated to strength training ($n = 10$, three female, two left hand dominant) or control ($n = 10$, three female, two left hand dominant) groups. Both groups completed testing at baseline and following each week of training to evaluate MVC strength, EMG amplitude, RFD and RER at early (RFD_{50}, RER_{50}) and late (RFD_{200}, RER_{200}) contraction phases for the dominant 'untrained' elbow flexors. The training group completed 11 unilateral isometric training sessions across 4 weeks.

Results The contralateral improvements for MVC strength ($P < 0.01$) and RFD_{200} ($P = 0.017$) were evidenced after 2 weeks, whereas RFD_{50} ($P < 0.01$) and RER_{50} ($P = 0.02$) showed significant improvements after 3 weeks. Each of the dependent variables was significantly ($P < 0.05$) greater than baseline values at the end of the training intervention for the trained arm. No changes in any of the variables were observed for the control group ($P > 0.10$).

Conclusions Unilateral isometric strength training for 2–3 weeks can produce substantial increases in isometric muscle strength and RFD for both the trained and untrained arms. These data have implications for rehabilitative exercise design and prescription.

Keywords Contralateral adaptations · Unilateral strength training · Rate of force development · Rate of activation

Abbreviations

EMG Electromyography
MVC Maximal voluntary contraction
RER Rate of EMG rise
RFD Rate of force development

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Introduction

The improvement in maximal strength that follows short-term strength training is primarily attributed to neural adaptations (Moritani and deVries 1979; Del Balso and Cafarelli 2007). Strength training improves maximal muscle force, the rate of force development, and neural drive to the muscle (Aagaard et al. 2002; Del Balso and Cafarelli 2007). Strength adaptations have been well established in the untrained homologous muscle group following unilateral limb training. This transfer of motor function has been termed cross-education and has been quantified as the contralateral improvement in muscle strength or motor skill (Ruddy and Carson 2013; Green and Gabriel 2018a). Considerable progress has been made towards understanding this phenomenon, yet there is a paucity of data regarding the time course of cross-education and capacity to transfer improvements in muscle activation dynamics (Adamson et al. 2008; Tillin et al. 2012; Ruddy et al. 2016; Hester et al. 2018). This is a particularly important consideration for the design and implementation of unilateral training programs as rapid force production has vital applications in sport and daily living activities.

Some of the classic experiments (Komi et al. 1978; Moritani and deVries 1979; Houston et al. 1983; Narici et al. 1989) on the time course of strength training demonstrated that the initial increases in strength at the start of training (4–6 weeks) were due to neural adaptations and, importantly, these adaptations were also evident in the contralateral, untrained limb. Improvements in strength, muscle activation dynamics, and neural drive may present after only a week of training for a trained limb (Del Balso and Cafarelli 2007). However, the rate at which these adaptations manifest for the untrained, contralateral limb is not clear. Desirable contralateral adaptations have been documented following 4–6 weeks of unilateral training (Farthing et al. 2009; Boyes et al. 2017; Green and Gabriel 2018a; Hester et al. 2018), but the dose–response properties of this cross-limb transfer have only recently been given critical attention (Barss et al. 2018). To better translate this training modality in rehabilitation settings, it is necessary to determine the time course of cross-limb strength transfer.

Despite its long known existence, cross-education has only recently been employed to augment the rehabilitation of asymmetrical limb disorders (Andrushko et al. 2018a, b; Hendy et al. 2012; Magnus et al. 2013). Cross-education has broad clinical utility as it has been shown to attenuate strength loss and muscle atrophy for the contralateral, immobilized limb (Farthing et al. 2009, Magnus et al. 2013; Andrushko et al. 2018b) and improve strength and functional outcomes for the affected limb of hemiplegic stroke patients (Dragert and Zehr 2013; Kim et al. 2015; Sun et al. 2018). These findings illustrate the importance of cross-education for clinical populations, yet there is still a general lack of unilateral strength training prescription, perhaps due to an absence of standardized training interventions that yield consistent improvements for the affected limb (Collins et al. 2017). Moreover, the magnitude of cross-education that has been reported varies immensely. This may be attributed to the training protocol used (i.e., mode, frequency, volume, duration), whether the dominant or non-dominant limb was trained (Farthing 2009; Coombs et al. 2016), the novelty of the training (Farthing et al. 2007), or inter-individual adaptive responses (Ruddy et al. 2016). The influence of these factors places a premium on the further design and assessment of training interventions that produce meaningful improvements in motor function for the untrained homologous limb.

Although there is strong evidence to support the ipsilateral 'untrained' hemisphere as the primary mediator of cross-education (Lee et al. 2010), the specific cortical pathways and the adaptive neurophysiological responses are not fully understood (Manca et al. 2018). Nevertheless, these cortical adaptations are ultimately realized at the motor unit level. Training-related motor unit adaptations have been considerably more studied for the trained compared to the untrained limb. An approach that may offer insight regarding the influence of unilateral training on contralateral motor unit activity relates to the examination of the activation dynamics for the untrained homologous muscle. Enhanced motor unit activity at contraction onset is believed to be a primary contributor to the improved rate of force development and EMG rise that occurs following training (Van Cutsem et al. 1998; Aagaard et al. 2002; Del Balso and Cafarelli 2007). Generally speaking, the early phase (i.e. < 75 ms) of rising muscle force appears to be strongly influenced by the discharge properties of the activated motor units, whereas the latter phases (i.e., > 150 ms) become increasingly related to the maximal strength of the muscle (Aagaard et al. 2002; Andersen and Aagaard 2006; Maffiuletti et al. 2016). Some reports suggest that these different phases of rising muscle force are not only influenced by separate physiological processes but may also adapt differently to strength training (Andersen et al. 2010). Determining the extent to which these distinct segments of rapid force and EMG rise may be transferred to the contralateral limb provides a unique perspective to view the neural mechanisms which underpin cross-education.

Although cross-education has been investigated for over a century (Scripture et al. 1894), the contralateral adaptations in rapid force and EMG rise are not well established (Adamson et al. 2008; Tillin et al. 2012; Ruddy et al. 2016). The inter-limb transfer of rapid force has been documented with only a single training session (Lee et al. 2010; Ruddy et al. 2016, 2017), yet the adaptations that manifest with chronic unilateral training are much less clear (Adamson et al. 2008; Tillin et al. 2012; Hester et al. 2018). The crucial nature of rapid force for sport and daily living activities (Maffiuletti et al. 2016) places obvious importance on determining the extent to which this motor control property may be transferred to the untrained homologous limb. It is reasoned that favorable contralateral adaptations of rapid force in a healthy population would strengthen unilateral training as a simple intervention to attenuate the loss of rapid force in the affected limb for individuals suffering from an asymmetrical limb disorder. The present study had two aims: first, to investigate whether improvements in the rate of force development and the rate of EMG rise can be transferred to the contralateral arm with unilateral isometric training of the non-dominant elbow flexors and second, to assess the time course of these contralateral adaptations during the 4 weeks of training.

Methods

Participants

Prior to recruitment, an a priori power analysis was performed as described by Beck (2013) for a within–between subjects design. The analysis was performed with G*Power software (3.1.9.2; Heinrich Heine University, Dusseldorf, Germany) with an effect size similar to a meta-analysis on cross-education (Green and Gabriel 2018b). As a result, twenty healthy participants were assigned to strength training ($n = 10$, three female, two left hand dominant; age = 23.0 ± 2.0 years, stature = 175.9 ± 10.2 cm, mass = 74.3 ± 10.1 kg) or control ($n = 10$, three female, two left hand dominant; age = 25 ± 3 years, stature = 177.2 ± 10.4 cm, mass = 83.2 ± 15.3 kg) groups. Participants were recruited for the training group first and then the control group. The study was approved by the University of Oklahoma Institutional Review Board and all participants completed a health history questionnaire and signed an informed consent document prior to data collection. The participants had not engaged in programmed resistance training for at least 3 months prior to enrollment in the study. None of the participants reported any previous orthopedic injuries to their upper limbs.

Study design

A non-randomized controlled study design was used to investigate the time course of cross-education during short-term unilateral strength training. The training group performed 11 unilateral isometric training sessions of the non-dominant elbow flexors across 4 weeks. Strength and EMG measurements were collected for both arms at baseline and after each week of training for the training group. Strength testing for the untrained arm was performed immediately prior to the respective training intervention. The control group only completed baseline and post-testing with their non-dominant arm but performed the exact same weekly testing procedures with their dominant 'untrained' arm. Baseline measurements were performed 3–5 days following familiarization and the training sessions were separated by at least 48 h. Data collection was performed by the same investigator and the order of testing was the same for all sessions.

Isometric testing

Each participant performed a familiarization visit which totaled 20 submaximal and 10 maximal contractions for each arm prior to the baseline measurements. Baseline MVC and EMG values were collected for both arms prior to the first training session. For the training and testing sessions, participants were seated upright in a chair with their back supported and were secured to the isometric testing apparatus. For each contraction, the participant's elbow was placed on a pad so their shoulder and elbow angles were maintained at 90° from horizontal. The participants used a supinated grip position and their wrist was placed within a cuff attached to a tension–compression load cell (Model SSM-AJ-500, Interface, Inc., Scottsdale, AZ.). Before testing elbow flexor MVC strength, the participants were instructed to perform three, 5-s isometric contractions at ~ 50% MVC to warmup. Participants then performed two, 3-s MVCs of the elbow flexors with 2 min of recovery between the contractions. The participants were provided with a verbal countdown "three, two, one, pull" and visual force feedback during each MVC, with specific instructions to "pull as hard and fast as possible". EMG was collected with a bipolar surface electrode (DE 2.1, Delsys, Inc., Natick, MA; 10 mm interelectrode distance) placed over the belly of the biceps brachii and a ground electrode was placed over the seventh cervical vertebrae in accordance with the recommendations of the SENIAM project (Hermens et al. 1999).

Isometric strength training

The training intensity was set at 80% of isometric MVC for each training session and required the participants to perform five sets of five isometric contractions held steadily for 5 s. The recovery intervals between contractions and sets were 10 and 90 s, respectively. The participants were provided with visual force feedback for the entire strength training session. The participants were instructed to rapidly produce force at contraction onset and match their force output as closely as possible to the force tracing during each 5-s contraction.

Force and EMG signal processing

The force and EMG signals were sampled at 20 k Hz with a 16-channel Bagnoli™ desktop EMG system (Delsys, Inc., Natick, MA). The force and EMG signals were then processed offline using custom software (LabVIEW, National Instruments, Austin, Texas). The force signal was smoothed with a 25 ms zero-shift moving average and the EMG signals were pre-amplified (gain: 1000), high (20 Hz) and low pass (450 Hz) filtered with a 100 ms zero-shift moving RMS. The onset of force and EMG activity was visually determined by placing cursors around the regions of interest and then magnifying the time curves in a separate plot. The onsets were viewed within a 20 ms time window and were defined as the point at which the signal exceeded the baseline by 2% of the baseline-to-peak value (Andersen et al. 2010). The isometric MVC value was determined as the highest mean

500 ms portion of the force plateau during the contraction. EMG amplitude was defined as the maximum value of the filtered EMG signal during the MVC (i.e., highest 100 ms window). RFD was determined from the linear slope of the force–time curve (Δforce/Δtime) at time intervals of 0–50 (RFD_{50}) and 0–200 (RFD_{200}) ms from onset. Similarly, RER was quantified from the linear slope of the EMG-time curve (ΔEMG/Δtime) at time intervals of 0–50 (RER_{50}) and 0–200 (RER_{200}) ms from onset. RER_{50} and RER_{200} were then normalized ($nRER_{50}$, $nRER_{200}$) to the maximal EMG amplitude (%EMG_{Max}) value for each respective contraction.

Statistical analysis

Separate two-way mixed factorial ANOVA tests were performed on the non-dominant (trained) arm (group [training, control] × time [baseline, week 4]) and the dominant (untrained) arm (group [training, control] × time [baseline, week 1, week 2, week 3, week 4]) for all dependent variables. Greenhouse–Geisser adjustments were made to adjust the degrees of freedom if significant sphericity violations were observed. Significant interactions were decomposed with simple main effects tests with Bonferroni adjustments (Keppel 1991; Chapter 12). The partial-eta squared (η_p^2) statistic is reported for all repeated measures ANOVAs, with values of 0.01, 0.06, and 0.14 corresponding to small, medium, and large effects, respectively (Stevens 2007). A paired samples *t* test was used to examine the change in isometric MVC from the familiarization session to the baseline measurements. Mean percent change values from baseline were also computed. Intraclass correlation coefficients (ICC), the standard error of the measurement (SEM), and the SEM expressed as a percentage (SEM%) were calculated to evaluate reliability. Additionally, the minimal difference needed to be considered real statistic was computed for all dependent variables from the dominant arm of the control group to interpret the importance of their change on an individual basis in the training group with the following equation (Weir 2005):

$$MD = \sqrt{MS_E} \times 1.96 \times \sqrt{2}.$$

The statistical analyses were performed with SPSS software (version 18.0, IBM SPSS Inc., Chicago, IL, USA). An alpha value of 0.05 was used to determine statistical significance for all comparisons.

Results

Isometric MVC and RFD

Trained arm

There was a significant increase in isometric MVC values from the familiarization to baseline (+6.7%; $P < 0.001$) for the non-dominant arm of both groups. Significant group × time interactions were observed for isometric MVC ($F_{1,18} = 14.796$, $P < 0.001$, $\eta_p^2 = 0.451$, observed power = 0.953), RFD_{50} ($F_{1,18} = 17.908$, $P < 0.001$, $\eta_p^2 = 0.499$, observed power = 0.979), and RFD_{200} ($F_{1,18} = 11.441$, $P = 0.003$, $\eta_p^2 = 0.389$, observed power = 0.892). Simple effects tests showed that for the trained arm of the training group, isometric MVC (427.9 ± 80.7 N vs. 639.9 ± 202.6 N, $P < 0.001$), RFD_{50} (1270.1 ± 497.9 $N \cdot s^{-1}$ vs. 3494.2 ± 1639.1 $N \cdot s^{-1}$, $P < 0.001$), and RFD_{200} (1206.1 ± 438.5 $N \cdot s^{-1}$ vs. 1950.7 ± 643.9 $N \cdot s^{-1}$, $P = 0.001$) were significantly greater at week 4 compared to baseline.

Time course for the untrained arm

There was a significant increase in isometric MVC values from the familiarization to baseline (+6.7%; $P < 0.001$) for the dominant arm of both groups. There were significant group × time interactions for isometric MVC ($F_{1.48,26.62} = 10.093$, $P < 0.001$, $\eta_p^2 = 0.359$, observed power = 0.939), RFD_{50} ($F_{4,72} = 3.908$, $P = 0.006$, $\eta_p^2 = 0.178$, observed power = 0.883), and RFD_{200} ($F_{2.63,47.31} = 6.783$, $P = 0.001$, $\eta_p^2 = 0.274$, observed power = 0.949) for the (dominant) untrained arm. Simple effects tests for the untrained arm of the training group showed significant increases in mean isometric MVC values (413.4 ± 82.1 N vs. 505.4 ± 102.3 N, $P < 0.001$; Fig. 1) and RFD_{200} (1225.9 ± 513.8 $N \cdot s^{-1}$ vs. 1625.2 ± 585.4 $N \cdot s^{-1}$, $P = 0.017$; Fig. 3) at week 2, whereas RFD_{50} (1308.1 ± 717.1 $N \cdot s^{-1}$ vs. 2528.9 ± 1409.2 $N \cdot s^{-1}$, $P < 0.001$; Fig. 2) significantly increased above baseline at week 3. There were no significant ($P > 0.10$) mean differences for any comparisons in the control group.

EMG amplitude and RER

Trained arm

There were significant group × time interactions for EMG amplitude ($F_{1,18} = 5.974$, $P = 0.025$, $\eta_p^2 = 0.249$, observed power = 0.638), RER_{50} ($F_{1,18} = 30.663$, $P < 0.001$, $\eta_p^2 = 0.630$, observed power = 0.999), RER_{200} ($F_{1,18} = 5.238$, $P = 0.034$, $\eta_p^2 = 0.225$, observed

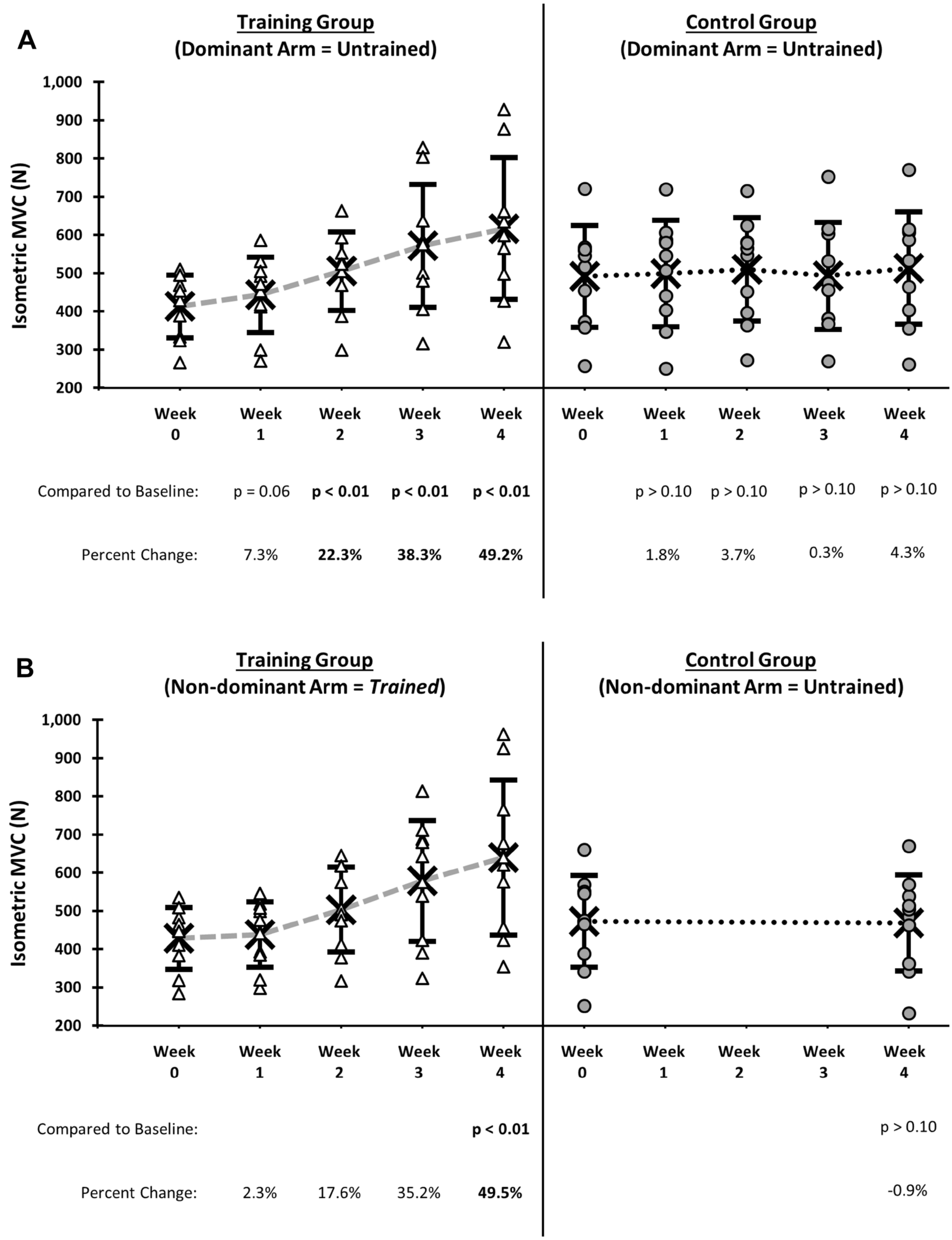

Fig. 1 Scatterplots for individual isometric MVC values at baseline and following each week of training for the dominant (**a**) and non-dominant (**b**) arms in the training (left) and control (right) groups. The mean is represented by the *X* symbol and the vertical bars reflect the SD at each time point. The *P* value from the comparisons to baseline is provided for each week along with the mean percent changes

power = 0.582), and $nRER_{50}$ ($F_{1,18} = 8.368$, $P = 0.01$, $\eta_p^2 = 0.317$, observed power = 0.781), but not for $nRER_{200}$ ($F_{1,18} = 1.824$, $P = 0.194$, $\eta_p^2 = 0.092$, observed power = 0.249). Simple effects tests showed that for the trained arm of the training group, EMG amplitude (1089.9 ± 467.5 μV vs. 1359.4 ± 752.2 μV,

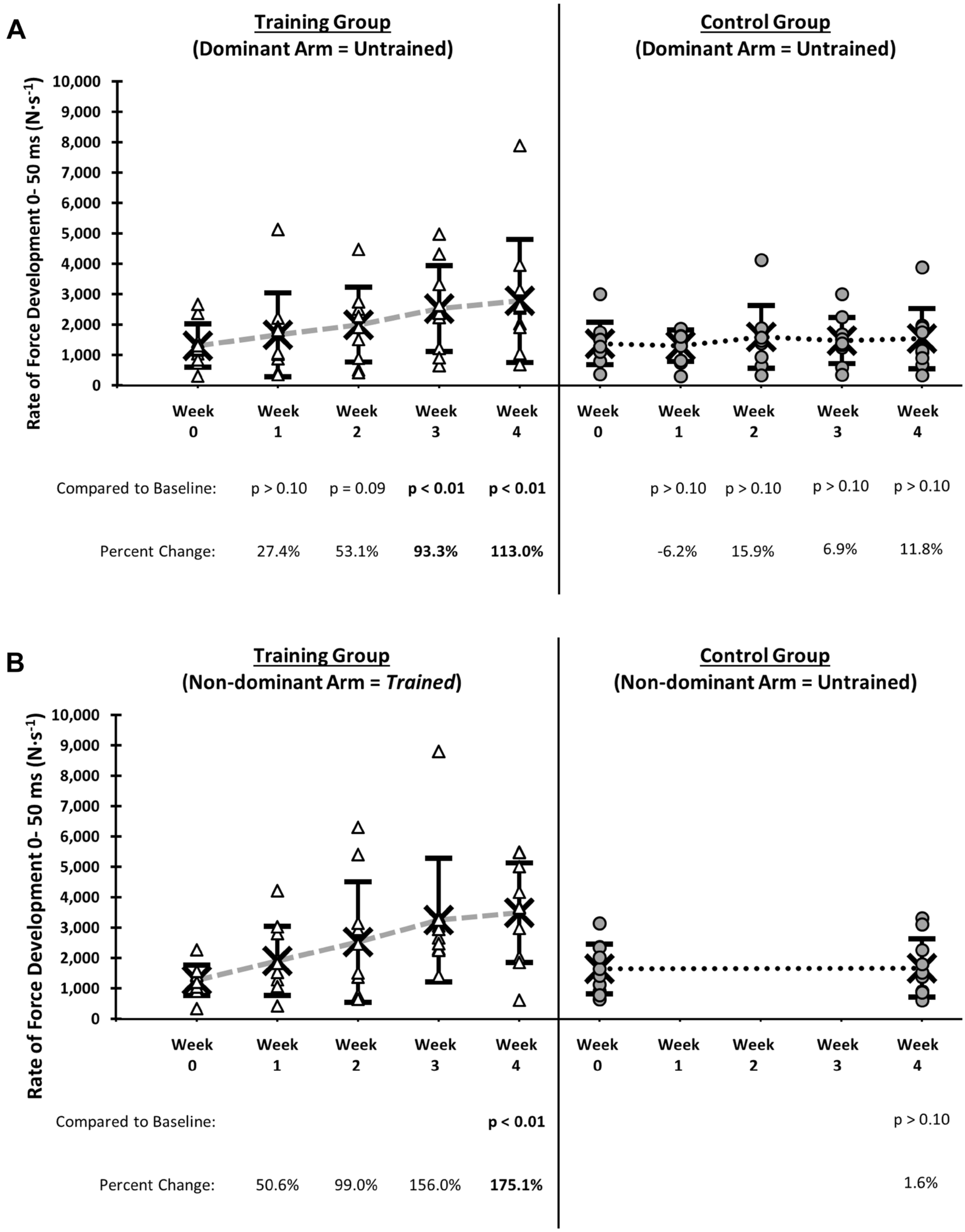

Fig. 2 Scatterplots for individual RFD_{50} values at baseline and following each week of training for the dominant (**a**) and non-dominant (**b**) arms in the training (left) and control (right) groups. The mean is represented by the *X* symbol and the vertical bars reflect the SD at each time point. The *P* value from the comparisons to baseline is provided for each week along with the mean percent changes

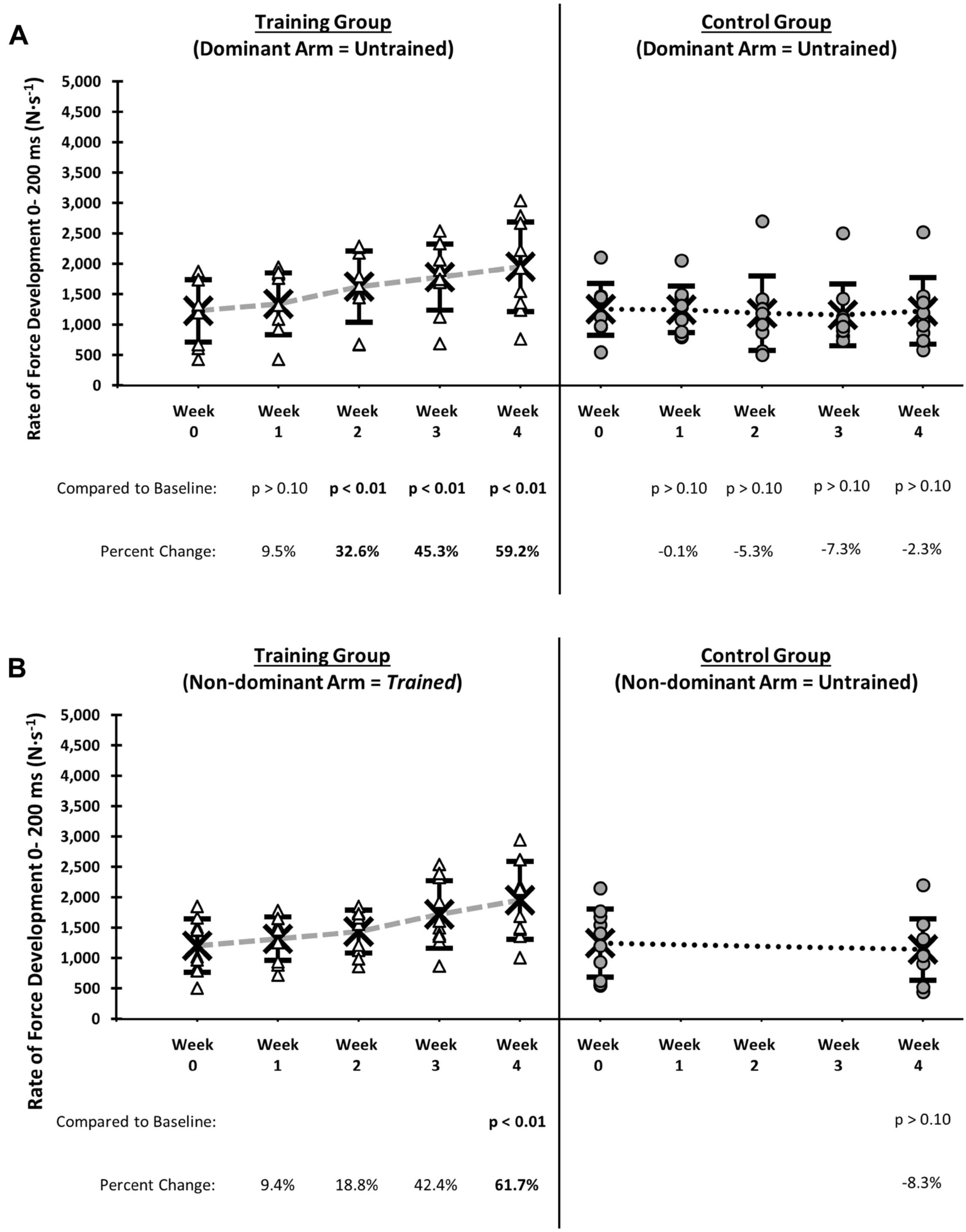

Fig. 3 Scatterplots for individual RFD_{200} values at baseline and following each week of training for the dominant (**a**) and non-dominant (**b**) arms in the training (left) and control (right) groups. The mean is represented by the *X* symbol and the vertical bars reflect the SD at each time point. The *P* value from the comparisons to baseline is provided for each week along with the mean percent changes

$P = 0.031$), RER_{50} (2939.2 ± 1841.6 μV·s^{-1} vs. 7052.8 ± 3093.2 μV·s^{-1}, $P < 0.001$), RER_{200} (2238.6 ± 1549.9 μV·s^{-1} vs. 3158.8 ± 1739.6 μV·s^{-1}, $P = 0.049$), and $nRER_{50}$ (271.9 ± 126.5%EMG_{Max}·s^{-1} vs. 579.3 ± 264.8%EMG_{Max}·s^{-1}) were significantly greater at week 4 compared to baseline.

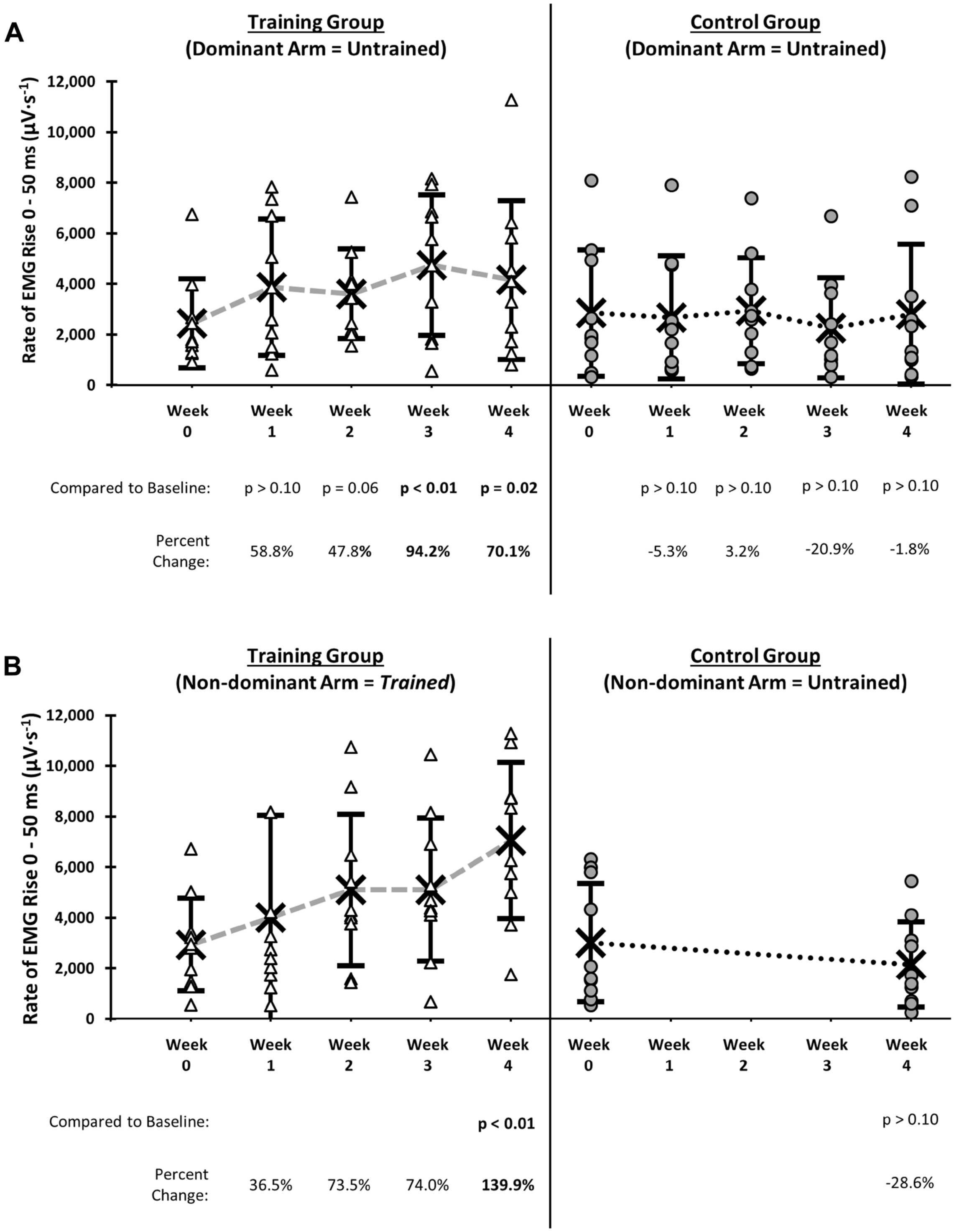

Fig. 4 Scatterplots for individual RER_{50} values at baseline and following each week of training for the dominant (**a**) and non-dominant (**b**) arms in the training (left) and control (right) groups. The mean is represented by the X symbol and the vertical bars reflect the SD at each time point. The *P* value from the comparisons to baseline is provided for each week along with the mean percent changes

Time course for the untrained arm

There were significant group × time interactions for EMG amplitude ($F_{2.14, 38.52} = 3.763$, $P = 0.030$, $\eta_p^2 = 0.173$, observed power = 0.674) and RER_{50} ($F_{4,72} = 3.136$, $P = 0.020$, $\eta_p^2 = 0.148$, observed power = 0.793), but not for RER_{200} ($F_{4,72} = 1.525$, $P = 0.204$, $\eta_p^2 = 0.078$, observed power = 0.449), $nRER_{50}$ ($F_{4,72} = 0.400$, $P = 0.808$, $\eta_p^2 = 0.022$, observed power = 0.137), or $nRER_{200}$ ($F_{4,72} = 0.260$, $P = 0.903$, $\eta_p^2 = 0.014$, observed power = 0.104) in the (dominant) untrained arm. Simple effects tests showed no significant mean differences for EMG amplitude for the training or control groups ($P > 0.05$). The mean RER_{50} values at week 3 were significantly greater than baseline for the training group (2442.9 ± 1753.6 $\mu V \cdot s^{-1}$ vs. 4743.9 ± 2766.5 $\mu V \cdot s^{-1}$, $P = 0.002$; Fig. 4). There were no significant ($P > 0.10$) mean differences for any comparisons in the control group.

Discussion

This study examined the time course for improvements in muscle strength, rapid force production, and EMG rise for the trained and untrained elbow flexors during short-term unilateral isometric strength training. The main findings show that: (1) submaximal isometric strength training produced contralateral improvements in isometric MVC, RFD_{50}, RFD_{200}, and RER_{50}, (2) the untrained limb exhibited significant improvements in MVC force after only five training sessions, and (3) the magnitude of strength improvements was relatively large, yet similar for the trained (49.5%) and untrained (49.2%) arms. These findings are similar to others that have observed substantial contralateral adaptations following short-term unilateral training (Green and Gabriel 2018b). No significant changes in isometric strength were observed for the dominant (+4.3%) or non-dominant (-0.9%) arms of the control group. The novel contributions presented by these data show the time course for cross-education of strength and rapid force production with unilateral strength training.

There are two different theoretical models that have been put forth to explain how cortical adaptations mediate cross-education; they are not mutually exclusive and both describe the complex interhemispheric interactions that may account for the observed adaptations of the ipsilateral 'untrained' motor cortex. Simply put, the cross-activation hypothesis suggests that forceful unilateral contractions generate somatotopically organized bilateral cortical activity which scales with the intensity of effort, whereas the bilateral access hypothesis maintains that motor engrams formed during unilateral training are allocated within sites that are accessible for the 'untrained' motor cortex (Ruddy and Carson 2013). It is possible that both models uniquely support cross-education, though the relative degree is likely to depend on the training intervention and the task demands. Nevertheless, the supraspinal adaptations that improve motor performance are ultimately realized through optimized motor unit activity. With strength training, motor units exhibit greater firing rates at contraction onset (Van Cutsem et al. 1998), yet these adaptations for the untrained homologous limb have only recently received meaningful attention (Ruddy et al. 2016). Since motor unit activity at contraction onset is the primary determinant of rapid force and EMG rise (Aagaard et al. 2002, Del Balso and Cafarelli 2007; Van Cutsem et al. 1998), these variables are prime candidates to examine the functional and mechanistic qualities of cross-education.

There are very limited data regarding the time course for cross-limb strength improvements (Moritani and deVries 1979; Houston et al. 1983; Barss et al. 2018). The present study observed that after five unilateral training sessions, the untrained arm had significantly greater mean MVC (Fig. 1) and RFD_{200} (Fig. 3) values compared to baseline. At week 3, mean RFD_{50} (Fig. 2) and RER_{50} values were significantly greater than baseline and these values remained elevated through week 4. Neither maximal EMG amplitude nor RER_{200} showed training-related adaptations for the untrained arm. Most cross-education studies have reported EMG data, and although some have observed elevated EMG amplitude values for the contralateral limb following unilateral training, this finding has not been consistently observed (Manca et al. 2018). The reasons for this are difficult to reconcile, especially with findings that have shown greater efferent neural drive (i.e., V-wave) (Green and Gabriel 2018a) and voluntary activation (Lee et al. 2009) for the untrained limb following unilateral training. Although there was no change in EMG amplitude for the untrained arm, the mean EMG amplitude values were significantly greater at week 4 compared to baseline for the trained arm. This training-dependent pattern of EMG response is similar to other recent reports (Barss et al. 2018).

Despite thorough reviews (Andrushko et al. 2018a; Hendy et al. 2012; Manca et al. 2018) outlining key aspects and candidate mechanisms for cross-education, discussion of the cross-limb transfer in rapid force is generally absent. The critical nature of rapid force for sport and daily living activities illustrates the value of examining this motor control property in an untrained homologous muscle. It has been suggested that the adaptive plasticity of rapid force production has functional relevance for athletes, elderly, and clinical populations as quick athletic movements and reactions to gait perturbations occur within a time frame (i.e., < 300 ms) well before maximal force is reached (Maffiuletti et al. 2016). Rapid force is affected by several physiological variables: intrinsic muscle properties, muscle–tendon stiffness, muscle size and strength, as well as the level of neural drive all influence RFD (Andersen and Aagaard 2006; Tillin et al. 2012; Maffiuletti et al. 2016). The few studies that have examined rapid force production for the contralateral limb following unilateral training have differed in their approach (i.e., intervention type, duration, limb) and outcome variables (i.e., force, torque, acceleration) (Adamson et al. 2008; Brown et al. 1990; Farthing and Chilibeck 2003; Hester et al. 2018; Tillin et al. 2012). Nevertheless, there is evidence (Adamson et al. 2008; Brown et al. 1990; Farthing and Chilibeck 2003; Hester et al. 2018) which shows that sustained improvements in rapid force may be transferred to the untrained contralateral limb. However, this observation has not been consistently observed. Although Tillin et al. (2012) found that contralateral leg strength increased following 4 weeks of ballistic unilateral isometric knee extension training, improvements in rapid force were observed only for the trained leg. The incongruent findings are challenging to resolve, but it is possible that methodological issues related to contraction onset determination, the specific variables interpreted, and the participant demographics may partially explain these differences. The present data offer further insight for these contralateral adaptations by assessing RER, the time course of improvement, and documenting this transfer with isometric training. These data agree with a recent report (Peltonen et al. 2018) which documented a high degree of inter-individuality for the training-induced adaptations in rapid force. The range of magnitudes for improvements in RFD and RER in both arms in this study adds further support to this notion (Peltonen et al. 2018). This and the higher level of variability for early compared to late RFD measurements may at least partially explain the disparate time course for significance between RFD_{50} and RFD_{200}.

Some have observed that the early and late phases of rapid force adapt differently following strength training (Andersen et al. 2010; Blazevich et al. 2008). Specifically, Andersen et al. (2010) found that after a 14-week training intervention consisting of isotonic exercises, only the later phase (i.e., $> RFD_{250}$) of rising muscle force was increased; however, Blazevich et al. (2008) reported that the early phases (i.e., $< RFD_{50}$) of rising force increased sooner and to a greater extent compared to the later phases following 10 weeks of isokinetic training. Yet, increases in both early and late phases of contraction force have been observed, though some observations (Barry et al. 2005; Tillin et al. 2012) suggest that the earlier time intervals exhibit larger training-based improvements. Although the present study found that mean RER_{50} values significantly improved above baseline at week 3 for the untrained arm (Fig. 4), this finding should be interpreted with caution for two reasons: (1) only three participants exceeded the minimal difference needed to be considered real at week 4 (Table 1) and (2) there was no significant improvement for the mean $nRER_{50}$ values following the training intervention. Instead, the greater improvements in RER_{50} and $nRER_{50}$ for the trained compared to the untrained arm following training may suggest a training dependency for increased RER, although this suggestion is challenged by the findings of Ruddy et al. (2016), who observed significant increases in EMG rise for the contralateral wrist flexors with acute unilateral training. Moreover, the decreased time from EMG onset to maximum RER for the untrained wrist flexors was associated with the level of cross-limb transfer (Ruddy et al. 2016). The greater training-induced changes of the early phase (i.e., $> RER_{100}$) of EMG rise in this study are similar to previous reports (Aagaard et al. 2002; Barry et al. 2005; Blazevich et al. 2008) that observed larger increases at early compared to late phases of the rising EMG signal. The present findings along with others (Aagaard et al. 2002; Barry et al. 2005; Del Balso

Table 1 Reliability statistics for the dependent variables of the dominant elbow flexors in the control group and the minimal difference ratios for the training group

	Isometric MVC (*N*)	EMG amplitude (μV)	RFD_{50} ($N \cdot s^{-1}$)	RFD_{200} ($N \cdot s^{-1}$)	RER_{50} ($\mu V \cdot s^{-1}$)	RER_{200} ($\mu V \cdot s^{-1}$)	$nRER_{50}$ ($\%EMG_{Max} \cdot s^{-1}$)	$nRER_{200}$ ($\%EMG_{Max} \cdot s^{-1}$)
$ICC_{2,1}$	0.974	0.679	0.786	0.859	0.794	0.576	0.831	0.722
SEM	21.5	479.9	379.3	188.2	1074.4	1020.3	72.7	64.5
SEM%	4.3	47.6	25.9	15.5	39.6	47.9	27.9	24.6
MD	59.6	1330.5	1051.5	521.7	2978.4	2828.3	201.6	178.9
Trained arm > MD	9/10	1/10	6/10	6/10	7/10	1/10	6/10	2/10
Untrained arm > MD	9/10	0/10	7/10	6/10	3/10	0/10	3/10	0/10

$ICC_{2,1}$, Intraclass correlation coefficient model 2,1 (Shrout and Fleiss 1979). SEM, standard error of the measurement. SEM%, standard error of the measurement expressed as a percentage of the mean. MD, minimal difference needed to be considered real (Weir 2005). > MD, the number of participants in the *training group* that exceeded the minimal difference needed to be considered real statistic at the conclusion of the training intervention for each dependent variable and Cafarelli 2007) suggest that increased EMG rise at early time intervals following strength training reflects enhanced motor unit activity at contraction onset, yet these interpretations for an untrained contralateral limb need further examination (Ruddy et al. 2016).

Perhaps best described by Scripture et al. (1894), it was stated that cross-education lies principally in the "steadiness of attention". Further, Behm and Sale (1993) suggested that the intended motor act is a primary factor driving the intended motor adaptations. It may be speculated that the visuomotor features of the present training intervention underscored both of these suppositions. For instance, each contraction during training required a ballistic intent at onset followed by 5 s of strong attentive focus on force control. Significant increases in strength and muscle activation dynamics have been observed after three training sessions for a trained limb (Del Balso and Cafarelli 2007). An aim of this investigation was to determine if a similar rate of strength improvement would manifest for the untrained homologous limb. The current data suggest that the neural elements responsible for cross-education present with a similar timeline as those mediating the adaptations for the trained limb. The rapid cross-education observed in the present study differs from a recent study (Hester et al. 2018) that examined contralateral adaptations after two (six training sessions) and 4 weeks (12 training sessions) of unilateral training of the knee extensors. Although acceleration significantly improved for the untrained leg after 4 weeks of training, no meaningful changes were detected at week 2 (Hester et al. 2018). However, the most thorough study (Barss et al. 2018) to date regarding the time course of cross-education showed that a similar number of training sessions (12–15) were required for significant contralateral strength improvements with maximal isometric handgrip training at two different training frequencies (e.g., daily versus 3×/wk). The authors (Barss et al. 2018) also reported that training frequency did not result in significantly different magnitudes of transfer (7.8%–12.5%) after the intervention. It is interesting to note that despite a different number of training sessions required for significant inter-limb strength transfer between Barss et al. (2018) and the current study, meaningful contralateral adaptations presented around the same time (i.e., ~ 2 weeks) after training began. These contrasting findings may be attributed to differences in the responsiveness of the trained musculature, the training and testing modalities, and the participant demographics.

Although a recent meta-analysis has reported contralateral strength improvements average ~ 18% in healthy individuals, there is a considerable range in the magnitude of transfer between studies (2.4–110%; Green and Gabriel 2018b). The mean strength improvement for the untrained arm observed here was relatively large (49.2%), though it should be noted that this was influenced by two high responders (Fig. 1). Even still, the magnitude of transfer observed here is difficult to explain when compared to others (Ebersole et al. 2002) that did not observe a significant transfer of strength to the untrained elbow flexors despite a similar training routine of longer duration. Nevertheless, there are some considerations that can be made: (1) the novelty of the training modality may have provided robust learning effects, (2) the degree of stability required for the shoulder joint may have brought about adaptations in postural stabilizers, and (3) the integration of weekly strength testing for the untrained arm may have provided an additional motor learning stimulus, although this is challenged by the small difference (+5.2%) in strength gain for the non-dominant versus dominant arm in the control group. Still, the last point deserves further inquiry as the populations that will benefit from unilateral training (i.e., asymmetrical limb patients) will eventually introduce training stimuli to their affected limb during rehabilitation.

There are some limitations that should be considered when interpreting the present results. Group allocation was not truly random, and it is possible that between-subject factors within groups (i.e., sex, handedness, training age and status) contributed to the large degree of inter-individual responses. Nevertheless, the non-randomized controlled design allowed the participants in the control group to be matched for sex and limb-dominance. Importantly, maximal EMG amplitude was not normalized in any way (i.e., compound muscle action potential), thus intersession variability in the EMG response (i.e., peripheral factors, electrode placement, etc.) was unable to be controlled. Despite this limitation, it should be noted that Barss et al. (2018) normalized the EMG response to the compound muscle action potential yet observed similar EMG amplitude responses for the trained and untrained limbs as the present study. In addition, EMG was not collected from local synergists, postural stabilizers, or antagonist muscles. There were also no assessments of the adaptive cortical sites, muscle cross-sectional area, or voluntary activation. Therefore, the interpretations are limited solely to the force and biceps brachii EMG data. Although a non-training control group performed the exact same testing procedures for the dominant 'untrained' arm, it is interesting to consider the cumulative effects that the weekly strength testing may have provided for the untrained arm in the training group. Further, a more parsimonious statistical analysis would have been afforded by testing both limbs of the control group throughout the study. Finally, the generalizability of the strength gains observed here should be done so with caution due to the small sample size, the high degree of inter-individual responsiveness, and training specificity.

Conclusion

Collectively, the present study demonstrated that a unilateral isometric training intervention with an emphasis on visuomotor integration produced substantial improvements in isometric strength and rapid force production for the untrained arm. After five unilateral training sessions, the untrained arm demonstrated significant increases in isometric strength and RFD_{200}, while contralateral improvements in RFD_{50} and RER_{50} were evidenced after the eighth training session. The rapid time course of cross-education observed here indirectly supports the implementation of unilateral training interventions immediately following unilateral limb trauma. Although these contralateral adaptations were observed in a healthy population, it is not unreasonable to speculate that similar interventions may be used to attenuate rapid force losses during periods of unilateral limb immobilization. Future studies are needed to apply these hypotheses in clinical settings to determine if rehabilitation outcomes may be improved for athletic, elderly, and pathological populations.

Author contributions JC and XY conceived and designed the study. JD wrote the software for data analysis and created the figures. JC conducted experiments, analyzed data, and drafted the first version of the manuscript. XY, MS, MB, and JD critically revised the manuscript. All authors read and approved the manuscript.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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