Bilateral improvements following unilateral home-based training in plantar flexors: A potential for Cross-education in Rehabilitation

ABSTRACT

***Context*:** Cross-education (CE) refers to neuromuscular gains in the untrained limb upon contralateral limb training. To date, only laboratory-based exercise programs have demonstrated CE. Home-based exercise prescription eliciting CE could have greater clinical applicability.

Objective: This study aimed to determine the effect of an **eight week,** home-based unilateral strength training intervention on isokinetic muscle strength, **muscular excitation,** and power in trained and untrained plantar flexors.

Design: Randomized controlled trial.

Methods: Thirty-four healthy participants were randomized to intervention (*n*=20) or control (*n*=14). The intervention group completed three sets of 12 repetitions of progressively loaded unilateral calf raises three days per week. Concentric and eccentric peak torque were measured using isokinetic dynamometry at 30°/s and 120°/s. Maximal EMG amplitude was simultaneously measured. Power was measured using a jump-mat. All variables were measured at PRE, MID and POST-intervention.

Results: Significance level was set at $p \leq 0.05$. Strength significantly increased bilaterally PRE-POST at both velocities concentrically and eccentrically in intervention group participants. Maximal EMG amplitude significantly increased PRE-POST bilaterally at both velocities in the medial gastrocnemii (GM) of the intervention group. Power significantly increased bilaterally PRE-POST in the intervention group, with a dose-response effect demonstrated in the untrained plantar flexors. The CE effects of strength, power and EMG activation were 23.4%, 14.6% and 25.3% respectively. All control group values were unchanged PRE-POST.

Conclusion: This study shows that a simple at-home unilateral plantar flexor exercise protocol induces significant increases in contralateral strength, **muscular excitation** and power. These results suggest the applicability of CE in home rehabilitation programs aiming to restore or maintain neuromuscular function in inactive or immobilized lower limbs.

Key Words: Ankle, EMG, Instrument-assisted Interventions, Strength

INTRODUCTION

The Cross-education (CE) effect refers to contralateral improvements in muscle function including strength, power and skill acquisition, following unilateral limb training[1,2]. **Neurophysiological adaptations following unilateral resistance training are thought to explain CE, given that there are no changes in muscle morphology, enzymatic activity, and hormonal response[1,3]**.

There are currently two hypotheses explaining the mechanisms underlying CE. In the 'Cross-activation' hypothesis, a bilateral increase in cortical motor activity during unilateral training reduces intracortical and interhemispheric inhibition, **with Lee & Carrol postulating that this leads to adaptations in both the 'trained' and 'untrained' motor pathways[4,5].** Conversely, the 'Bilateral-access hypothesis' suggests that neural adaptations in the trained hemisphere following unilateral strength training can be accessed by the untrained hemisphere[6,7]. Both types of adaptations would eventually lead to enhanced neural signaling during voluntary contractions in both limbs, resulting in greater motor unit recruitment, firing frequency and improved synchronicity[8,9]. This results in improved strength and power output from the ipsilateral trained limb and its untrained counterpart. **Previous research in healthy and functionally disabled populations reported that contralateral strength increased by 17% and 29% respectively[7].**

Ankle injuries, requiring surgery and immobilization, are common in both sporting and general populations, with Achilles tendon rupture incidence being reported as 29.3 per 100,000 person-years[10]. The plantar flexors are particularly susceptible to immobilization-induced muscle atrophy due to a higher proportion of slow type I fibers to fast type II fibers[8,11]. CE may help to preserve plantar flexor function and reduce time taken to rehabilitate from such injuries, as lab-based studies have shown that contralateral limb resistance training attenuates functional losses and prevents loss of muscle cross-sectional area in an injured, immobilized limb[2,4,12].

Laboratory-based unilateral plantar flexor strength training protocols have significantly increased contralateral limb strength by between 1.5% to 30.1%[12–18]. Whilst at-home rehabilitation programs are more convenient, cost-effective, and are less travel and resource-intensive, there are currently no published home-based CE interventions in the plantar flexors. To date, only Magnus et al. have conducted a home-based CE intervention, finding contralateral strength gains of 9.6% and 16.6% in the internal and external shoulder rotators respectively[19].

Muscle excitation, as measured by the electromyogram (EMG), and muscle power are closely linked to muscular strength[14]. EMG amplitude values in plantarflexion movements are strongly correlated to plantar flexor strength. Li et al. found that the mean EMG amplitude values of the gastrocnemius and tibialis anterior muscles during plantarflexion were linearly correlated to muscle strength levels (R^2=0.903)[20]. Power is a crucial determinant of muscle function, however, to date only one study has explored plantar flexor power in CE, finding a significant CE effect of 18%[18].

Thus, given the effectiveness of CE in lab or gym-based rehabilitation programs, the purpose of this study was to determine if a home-based unilateral strength intervention can elicit a CE effect of muscle strength as well as markers of muscle function. **We hypothesized that eight weeks of strength training would result in bilateral increases in plantar flexor strength, muscular excitation, and power.**

METHODS

Study design

A single-blind randomized controlled trial design was utilized to explore the effects of a home-based unilateral plantar flexor training programme on untrained participants. **All testing was carried out in a physiology lab between December 2018 and March 2019**. One month before testing, the participants were enrolled by the chief investigators, and they were familiarized with the testing and intervention protocols to reduce learning effects. **Participants were assigned a unique computer-generated eight-digit code** and were blindly randomized to CONTROL (n=15) or INTERVENTION (n=20). Allocation was done **via opaque, sealed envelopes distributed by an independent colleague**.

Strength, power and EMG testing was conducted before the start of training (PRE), at four weeks (MID), and after the completion of the **eight week** intervention program (POST). To exclude limb dominance as a potential confounder, INTERVENTION was further randomized to train their dominant (n=11) or non-dominant (n=9) limb. CONTROL had both dominant and non-dominant limbs tested. Leg dominance was ascertained by asking participants which leg they would kick a ball with[14]**. For data analysis, control limb data was randomly chosen after unpaired t-tests found no significant between-limb differences in CONTROL at PRE, MID or POST.**

Participants

A power calculation generated a sample size of 36. **Thirty-five** healthy adult participants were recruited. Participants were excluded if they had undertaken resistance training in the past six months, participated in more than three weekly physical activity sessions, or had a known lower limb orthopedic or neurological condition. Participant demographics were as follows: CONTROL (**n=15,** 8 females, 7 males; Age: 21.4 ±1.8 years; Height: 164.4 ±8.3cm; Weight: 61.5 ±14.0kg) and INTERVENTION (**n=20**, 11 females, 9 males; Age: 20.7 ±1.3 years; Height: 166.2 ±7.3cm; Weight: 62.8 ±16.3kg). One CONTROL participant was excluded due to participation in strength training during intervention, leaving 34 participants for data analysis. All testing was approved by the University Ethics Committee, in line with the declaration of Helsinki. Informed consent was obtained from all participants.

Procedures

Strength testing

The Biodex System 4 (Biodex Corporation, NY, USA) was used to measure the isokinetic plantar flexor strength of both limbs by average peak torque (PT) in two modes: concentric (CON) and eccentric (ECC), at two velocities: 30°/s and 120°/s.

Participants performed 20 sub-maximal straight leg calf raises on each leg as a warm-up **immediately before testing.** Participants were positioned on the Biodex with the hip and knee flexed to 135° and 30° respectively and the ankle neutrally positioned. After performing a trial repetition, participants performed two sets of five repetitions on the right leg, followed by the left leg, with 30 seconds rest between sets. Gandevia's criteria for maximal voluntary force production were closely followed[21]. The highest PT of the two sets was used for data analysis[22].

EMG testing

Double differentiated, Trigno wireless electrodes (Delsys Europe, Manchester, UK) were used to record EMG during strength testing. The electrodes were placed on the most prominent bulge in the middle of the medial gastrocnemius (GM) and lateral gastrocnemius (GL) muscles, parallel to the orientation of the muscle fibers, and along the mid-dorsal line of the soleus (SOL) five cm distal to the GM, localized using ultrasound imaging. Participants' calves were shaved and cleaned beforehand. Electrode locations were marked on tracing paper at PRE for reference at MID and POST.

EMG signals were sampled at 500 Hz and amplified 1000x, bandpass filtered (20-450Hz) and transferred to an EMGWorks Analysis Software (Delsys Europe, Manchester, UK). Traces for each set were converted to root mean square (RMS), and the peak amplitude for each contraction in both sets was pooled.

Power testing

Power testing followed strength and EMG measurements. Chronojump jump-mat software (Chronojump-Boscosystem, Spain) was used to measure plantar flexor power output during a single leg squat jump[23]. The squat jump was modified so that participants started from a flexed-knee position, with their knee in alignment with their big toe to increase the activation of the soleus muscle. To minimize quadriceps involvement, participants were instructed to jump with minimal arm swing. Power (PO) and Flight Time (FT), measured in Watts and seconds respectively, were used to assess plantar flexor power output. These variables and the squat jump, as an assessment modality, have been shown to be valid and reliable measures of functional muscle power[24].

After performing two trial repetitions on each leg, participants performed three maximal jumps on the right, followed by the left, with four minutes rest between jumps[24,25]. Data analysis used the average PO and FT of the three maximal jumps.

Intervention

INTERVENTION completed a unilateral dynamic home-based intervention, three days per week for **eight weeks**. Calf raises were performed using resistance bands (Topelek, China), which were graded in strength: yellow (4.5kg), green (6.8kg), red (9.1kg), blue (11.3kg) and black (13.6kg). **Starting resistance was determined by the band which scored seven on the BORG CR10 scale after the participants performed 12 calf raises[26]. Throughout the eight weeks, participants were asked to increase resistance band strength if their score was seven or less[19]. A score of seven correlates with an intensity of 70-80% maximal voluntary contraction (MVC)[26]. High MVC, as used in previous lab-based plantar flexor studies, have been shown to reduce corticospinal inhibition, and consequently increase CE[13,15,16,25].**

During the first four weeks, unilateral straight leg calf raises targeting the gastrocnemii were performed for three sets of 12 repetitions **(figure 1).** From week five, flexed-knee calf raises, targeting the soleus, were included for progression **(figure 2).** This intervention incorporated strength training protocols taken from past CE studies, and was implemented in order to achieve improvements in strength in the absence of muscular hypertrophy[1,14,16,19,25]. Participants were instructed to pace the exercise at two seconds in both the concentric and eccentric phases, with one-minute rest between sets. Instructional videos with a real-time metronome to standardize exercise technique were provided.

Adherence was monitored using an online questionnaire which participants filled each time they completed a workout, and was found to be 80%. The questionnaire was promoted weekly via social media to all participants to maintain blinding.

Statistical Analyses

Data was stored in line with the 1998 Data Protection Act. Statistical analysis was completed using IBM SPSS version 25 (Armonk, NY) and significance was assumed at $p \leq 0.05$.

Independent t-tests were used to analyze demographic variables of CONTROL and INTERVENTION after allocation. Intraclass correlation coefficient (ICC) was used to assess test-retest reliability, calculated using a two-way random calculation with absolute agreement.

For strength and power, **a 2 x 2 x 3 mixed model ANOVA [GROUP (control vs intervention) x LIMB (trained vs untrained) x TIME (PRE vs MID vs POST)] was used to detect interactions in average PT in two modes (CON and ECC) at two angular velocities (30°/s and 120°/s), in PO and FT.** Significant interactions were assessed using repeated-measures and one-way ANOVAs. Post-hoc testing was performed with Bonferroni and Tukey's tests, as used in plantar flexor CE studies[16,18]. Independent t-tests were used to analyze PRE-POST % change in both trained and untrained limbs between i) CON and ECC, ii) velocity (30°/s vs 120°/s) and iii) dominant and non-dominant limb.

For EMG, repeated-measures ANOVA was used to assess within-group differences (PRE vs MID vs POST) for normally distributed data. Post-hoc Bonferroni and Tukey's tests were carried out upon detecting a significant within-group difference. Friedman's tests with post-hoc Wilcoxon Signed-Rank tests were used to detect within-group differences in non-normally distributed data. One-tailed independent t-tests were used to determine if changes in the trained and untrained limb of INTERVENTION were greater than that of the control limb.

Trained and untrained limbs in the INTERVENTION group are hereafter referred to as TRAINED and UNTRAINED respectively.

RESULTS

Reliability

ICC values for Biodex measurement of concentric and eccentric contractions at 30°/s and 120°/s, EMG, PO, and FT indicated good-to-excellent reliability (0.74-0.99).

Strength

Significant GROUP x TIME interactions were seen at 30°/s CON ($F_{2,64}=10.50$, $p<0.001$, $\eta^2=0.247$), 30°/s ECC ($F_{2,64}=9.69$, $p<0.001$, $\eta^2=0.232$), 120°/s CON ($F_{2,64}=14.63$, $p<0.001$, $\eta^2=0.314$) and 120°/s ECC ($F_{2,64} = 14.07$, $p<0.001$, $\eta^2=0.305$). No significant GROUP x LIMB x TIME, or LIMB x TIME interactions were seen at both modes and velocities of contraction.

Post-hoc testing showed a significant PRE-POST increase in average PT for TRAINED at 30°/s CON ($p=0.001$), 30°/s ECC ($p<0.001$), 120°/s CON ($p=0.002$) and 120°/s ECC ($p=0.002$). Average PT significantly increased PRE-MID at 30°/s ECC ($p=0.005$) and

120°/s ECC (p=0.049), and MID-POST at 120°/s CON (p=0.012) and 120°/s ECC (p=0.023) **(Table 1; Figure 3; Figure 4).**

There was a significant PRE-POST increase in average PT for UNTRAINED at 30°/s CON (p=0.003), 30°/s ECC (p=0.006), 120°/s CON (p=0.002) and 120°/s ECC (p=0.001). Average PT significantly increased PRE-MID at 30°/s CON (p<0.001), 30°/s ECC (p=0.001), 120°/s CON (p=0.001) and 120°/s ECC (p=0.046). No significant differences were seen from MID-POST (**Table 1; Figure 3; Figure 4**).

In CONTROL, average PT significantly decreased MID-POST at 120°/s CON (p=0.006) and 120°/s ECC (p=0.010). No other significant differences in CONTROL were seen (p>0.05) (**figure 3, figure 4**).

The combined mean strength increase PRE-POST at both velocities and contraction modes was 24.3% (95% CI 18.1, 30.5) in TRAINED and 16.9% (95% CI 12.2, 21.6) in UNTRAINED. Applying the Goodwill et al. formula, that adjusts for strength increase in the control limb, the CE effect for strength in this study was 23.4%[9].

Between-group analysis showed significant differences at POST between TRAINED and CONTROL at 30°/s CON (p=0.037), 30°/s ECC (p=0.010), 120°/s CON (p=0.007) and

120°/s ECC ($p=0.003$), and between UNTRAINED and CONTROL at 30°/s ECC ($p=0.030$), 120°/s CON ($p=0.008$) and 120°/s ECC ($p=0.006$). In both TRAINED and UNTRAINED, there was no significant strength difference between i) CON and ECC, ii) 30°/s and 120°/s and iii) dominant and non-dominant limb ($p>0.05$).

EMG

There was a significant PRE-POST increase in mean EMG amplitude values for TRAINED at 30°/s ($F_{2,38}=9.94$, $p=0.012$, $\eta^2=0.344$) and 120°/s ($F_{2,38}=7.432$, $p=0.023$, $\eta^2=0.281$) in GM and at 30°/s in GL ($F_{2,38}=7.14$, $p=0.028$, $\eta^2=0.273$). Mean EMG amplitude significantly increased PRE-MID in GM at 30°/s ($T_{38}=0.489$, $p=0.039$, $D=-0.675$) (Table 1; Figure 5; Figure 6).

There was a significant PRE-POST increase in mean EMG amplitude for UNTRAINED at 30°/s ($F_{2,38}=6.431$, $p=0.022$, $\eta^2=0.253$) and 120°/s ($F_{2,38}=3.564$, $p=0.046$, $\eta^2=0.158$) in GM and at 120°/s in SOL ($F_{2,38}=5.58$, $p=0.037$, $\eta^2=0.227$). Mean EMG amplitude significantly increased PRE-MID in GM at 30°/s ($T_{38}=1.208$, $p=0.049$, $D=-0.644$) (Table 1; Figure 5; Figure 6).

The combined mean increase in EMG amplitude PRE-POST for GM in TRAINED was 95.1% (95% CI 30.2, 159.8) at 30°/s and 65.8% (95% CI 14.8, 117.2) at 120°/s, while GL increased by 41.7% (95% CI 18.8, 65.2) at 30°/s. The mean increase in EMG amplitude PRE-POST for GM in UNTRAINED was 40.9% (95% CI 16.5, 65.5) at 30°/s and 24.1% (95% CI 8.7, 39.3) at 120°/s while SOL increased by 27.5% (95% CI 9.9, 44.1) at 120°/s. Applying the Goodwill et al. formula, the CE effect for **muscle excitation** in this study was 25.3% [9].

Between-group analysis showed significant differences at POST between TRAINED and CONTROL at 30°/s **(T_{32}=2.57, p=0.008, D=0.90)** and 120°/**s** **(T_{32}=2.36, p=0.012, D=0.82)** in GM and at 30°/s in GL **(T_{32}=1.96, p=0.029, D=0.68),** and between UNTRAINED and CONTROL for GM at 30°/s **(T_{32}=1.84, p=0.037, D=0.64)** and SOL at 120°/s (**$T_{28.7}$=3.43, p<0.001, D=1.20).** In UNTRAINED, a significant positive Pearson correlation was found between strength gain and EMG amplitude increase in UNTRAINED GM (r=0.47, **p=0.037**) at 30°/s. A significant positive Pearson correlation was also found between strength increase and EMG of UNTRAINED SOL (r=0.59, **p=0.006**) at 120°/s.

There was no significant difference in CONTROL from PRE-POST for all three muscles at either velocity **(Figure 5; Figure 6).**

Power

Significant GROUP x TIME interactions were seen for PO ($F_{2,62}=8.960$, $p<0.001$, $\eta^2=0.224$) and FT ($F_{2,60}=7.508$, $p=0.001$, $\eta^2=0.200$). No significant GROUP x LIMB x TIME, or LIMB x TIME interactions were seen for either variable.

Post-hoc testing showed a significant PRE-POST increase in PO ($p<0.001$) and FT ($p<0.001$) for TRAINED. There was also a significant increase PRE-MID [PO ($p=0.025$); FT ($p=0.03$)] and MID-POST [PO ($p=0.002$); FT ($p=0.007$)] **(Table 1; Figure 7; Figure 8).**

There was a significant PRE-POST increase in PO ($p<0.001$) and FT ($p<0.001$) for UNTRAINED. There was also a significant increase MID-POST [PO ($p=0.005$); FT ($p=0.007$)]; however, no significant difference was seen PRE-MID. No significant differences were found in CONTROL for either variable **(Table 1; Figure 7; Figure 8).**

The combined mean increase in PO and FT was 18.7% (95% CI 13.2, 24.2) in TRAINED and 18.3% (95% CI 13.7, 22.9) in UNTRAINED. Applying the Goodwill et al. formula, the CE effect for power in this study was 14.6%[9].

In UNTRAINED, a Pearson's correlation calculation showed no significant correlation between the magnitude of strength and PO **(r=0.351, p=0.129),** strength and FT **(r= 0.262, p=0.264),** nor strength and combined PO and FT **(r=0.297, p=0.204).**

DISCUSSION

Our primary finding is that **eight weeks** of unilateral home-based training significantly increase bilateral plantar flexor strength, EMG amplitude and power. To our knowledge, this the first study to explore the CE of strength, EMG and muscle power in the lower-limb[19].

Our study discovered novel findings relating to the timeframe of CE and the relationship between the CE of strength and power. Currently there is no established timeframe to establish a CE effect, however Carr et al. have shown significant CE of strength and power in the upper limb in two to three weeks (22.3% and 32.6%, $p<0.05$, respectively)[27]. Our study found a significant strength increase in the untrained limb in the first four weeks of training (PRE-MID), however, the increase from MID-POST was not statistically significant. Conversely for the CE of power, a dose-response relationship was shown with power increase reaching significance in the final four weeks (MID-POST). Our findings were consistent with Lepley et al. and Latella et al who showed CE strength gains predominantly occurring within the first four weeks of their lab-based interventions[22,25].

Additionally, this the first study to show a dose-response effect for the CE of power in the lower limb.

The specificity principle may explain these findings. Since a strength training protocol was implemented, the motor plans associated with muscle power may have required a longer time to develop than those for muscle strength[1,5]. Our findings support this principle, with strength gains occurring before power, whilst outlining a degree of synergism between the CE of strength and power gains. Future studies with additional early phase testing intervals should be conducted to further explore the timeframe of CE.

Effects of training on strength

The CE effect for strength in this study was 23.4%. This is higher than the CE effect in the home-based upper limb study conducted by Magnus et al. (9.6 and 16.6%, for internal and external rotation respectively)[19]. **Our study's GROUP x TIME effect sizes (0.25-0.31) are comparable to Magnus et. al (0.29-0.40) and suggest a large effect size for strength gain. Our higher CE effect may be explained by the longer duration of training and the previously found larger CE effect seen in lower limb musculature compared to upper limb lab studies[25].**

Our study has demonstrated that untrained limb strength gain can be higher using home-based training than lab-based training. **Using similar testing protocols of concentric and eccentric strength at 30°/s and 120°/s, Uh et. al reported a significant GROUP x LEG x TIME effect (p=0.0142) and CE effect of 1.5% in the dominant and 3.5% in the non-dominant limb following an eight week unilateral ankle lab intervention[12]. The higher CE in our study may be attributable to the intervention specifically targeting plantar flexors, the largest ankle muscle. Uh et. al did not distinguish CE effect by ankle movement, hence it is possible that the pooled strength gain is influenced by lower strength gain in smaller ankle muscles[12].**

Shima et. al reported a 7.8% (p<0.05) CE effect using calf raises of 3 sets 10-12 reps at 70-75% 1RM, mirroring the protocol in this study, with the addition of weights[16]. The higher CE effect in our study may again be explained by the longer training duration, the exercise intensity of 70-80% MVC, and the training-testing specificity which has been shown to have higher CE effects[16].

No significant difference was found in strength gain between 30°/s and 120°/s, suggesting a non-velocity specific CE effect. This is in line with Abazovic et al. who demonstrated a non-velocity specific CE effect in the knee, and may have important rehabilitation applications[28]. Training at a specific velocity may result in a bilateral strength increase at multiple velocities, hence allowing a faster return to full velocity of movement post-injury.

Effects of training on EMG

In UNTRAINED, there was a significant increase in peak EMG amplitude in GM but not GL. Increased contralateral EMG activity is in line with the results of Fimland et al., Shima et al. and Hortobagyi et al., although contrasts a recent review by Manca et al. on neurophysiological adaptions in CE[3,13,16,29]. Manca et al. found a non-significant increase in EMG activity during maximal voluntary isometric contractions (MVIC) of the untrained limb (p=0.26). Subgroup analysis revealed no significant difference after static (p=0.56) and dynamic (p=0.24) training. However, of the 11 studies included in the review, only four studies utilized dynamic training, none of which tested ankle plantar flexors.

A moderate correlation was found between the individual strength gains at 30°/s and changes in peak EMG amplitude values of GM after training (r=0.47), as well as between strength gains at 120°/s and changes in SOL (r=0.59). These correlations corroborate with Shima et al. who in a lab-based study found a positive correlation (r=0.734, p<0.05) between the changes in EMG values of the untrained calf muscles and individual percentage changes in MVC, supporting that central neural factors and neural drive play an important role in CE[16]. The utilization of a supervised **six week** lab-based strength training program with calf-raises and foot press exercises being performed four times a week each could explain the stronger correlation in their study. Our study shows that even without supervision, home-based strength training with resistance bands instead of exercise machines can elicit a CE effect with similar positive correlations. Specifically, our results suggest that the strength gains at 30°/s were associated with increased neural drive to GM, while strength gains at 120°/s were associated with an increased neural drive to SOL. We acknowledge however, that individual variations in exercise technique might also explain these findings.

Effects of training on Power

The CE of power in our study was 14.6%[9]. **The only other published study exploring the CE of power in the plantar flexors reported a higher value [18 (13)%, p<0.05][18].Tøien et al. reported greater power increase in the trained limb [35 (17)%, p<0.001], compared to the TRAINED group in our study [18.7 (17.7)%, p<0.001]. The aforementioned results demonstrate that laboratory-based interventions in the plantar flexors result in greater bilateral power increase, however the magnitude of power transfer from TRAINED to UNTRAINED was more substantial in our study (97.9 % compared to the 51.4% found by Tøien et al.)[18].** Thus, our study indicates that unilateral home-based strength training results in a significant and sizeable bilateral increase in plantar flexor power. It is also important to note that Tøien et al. conducted their study in an older male cohort [73 (4) years], had a smaller intervention group [n=11] and utilized a supervised lab-based training protocol which can maximize compliance and technique but is less applicable for wide use in rehabilitation[18].

The synergistic increase in strength and power following a strength training protocol has potential value in rehabilitation. Power has shown to be of crucial importance for functional ability across a variety of populations, from reducing the occurrence of slip-related falls in the elderly to athletic performance[30,31].

Training-testing specificity has been shown to maximize the CE effect[1]. Training movements form unique motor unit activations, and the matching of testing and training modalities may enhance motor plan recall, maximizing force production[1,29]. Jump-mat testing facilitates the matching of lower limb weight-bearing training and testing protocols. The significant power output gains measured in our study corroborate with Ben Othman et al, indicating that the jump-mat is a viable alternative to dynamometry in the measurement of lower limb power output following a weight-bearing intervention[1].

Limitations

The participants our study recruited were young adults with moderate activity levels. Hence, whilst our sample demographic offers translational validity in sporting or athletic population, it requires replication in elderly patient populations. Additionally, whilst an **eight week** intervention was implemented to achieve strength improvements in the absence of muscular hypertrophy, without cross-sectional area measurement it cannot be proven that the strength increase was solely due to neurological factors. Future studies could measure CSA throughout the intervention to further explore the CE time frame. Furthermore, surface EMG measurement alone is not sufficient to fully explore the neuromuscular mechanisms of cross-education; **additional variables such as voluntary activation or V-wave measurements could have been included.** Finally, our study did not assess whether the strength and power gains made were translated into increased functional ability. Future studies could assess this by utilizing tests such as 'sit to stand' performance, the 'Margaria-Ka-Lamen stair climb test' or the 'full squat'[31].

Clinical implications

Our results indicate that a home-based program incorporating common rehabilitative practices such as the use of resistance bands, progressive loading and high intensity exercise can elicit the CE of strength, EMG and power. In the COVID-19 era home-based exercise programmes are of increasing value. The cost-effectiveness, feasibility and convenience of home-based cross-education protocols enables its application by clinicians and physiotherapists in clinical and athletic populations alike. **Our study has demonstrated good adherence to training (80%), despite no regular follow up. The methods used to encourage adherence are simple for participants and easy to monitor for researchers. Our methods are scalable to clinical settings, and could be utilized in patients with unilateral injury or neuromuscular pathology as an adjunct to rehabilitation at home.**

CONCLUSION

Our unilateral home-based plantar flexor exercise protocol comprising progressive loading with resistance bands elicited a significant CE effect. The strength gains of 23.4% in the contralateral untrained plantar flexors were not velocity dependent. Functional power output gains were recorded bilaterally and were time-dependent. A positive Pearson correlation with EMG supports the link between strength gains and muscular excitation. Future studies should be replicated in patients, using more functionally relevant markers to quantify strength and power gains.

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TABLES

Table 1: Intervention group data for strength, electromyogram and power variables (mean ± SD). *Significant difference from PRE p<0.05 **Significant difference from PRE p<0.01 ***Significant difference from PRE p<0.001 #Significant difference from MID p<0.05 ##Significant difference from MID p<0.01

Group	Trained leg			Untrained leg		
	PRE	MID	POST	PRE	MID	POST
30°/s concentric, N·m	110.6±29.7	124.3±33.2	133.8±28.5**	110.7±24.5	128.7±24.6***	130.8±27.5***
30°/s eccentric, N·m	131.4±33.1	147.3±32.2**	153.8±30.4***	131.2±29.0	147.7±24.3**	148.7±31.3**
120°/s concentric, N·m	110.6±33.7	123.7±23.0	134.2±28.9**#	115.2±25.4	127.0±25.8**	133.5±28.4**
120°/s eccentric, N·m	139.4±39.1	154.7±31.6*	165.4±31.9**#	144.3±28.5	153.7±29.7*	163.0±31.0**
30°/s GM† EMG†, µV	74.1±35.1	99.2±41.2*	117.5±57.1*#	79.4±38.4	106.1±44.3*	101.6±48.1*
30°/s GL† EMG†, µV	71.6±30.9	85.5±30.1**	93.5±40.4*	72.1±34.5	79.0±27.7	81.5±24.7
30°/s SOL† EMG†, µV	167.6±52.3	174.8±60.8	186.0±65.2	153.8±57.0	161.8±50.2	165.2±48.6
120°/s GM† EMG†, µV	89.4±42.1	109.9±41.9	123.5±53.1*	88.9±38.6	108.2±43.7*	104.8±48.7*
120°/s GL† EMG†, µV	78.1±30.8	85.9±33.3	93.8±48.0	70±25.8	76.7±26.1	83.9±35.2
120°/s SOL† EMG†, µV	166.1±51.9	168.2±49.7	189.7±61.9	144.7±40.9	158.0±44.7	174.6±42.9*
FT† (seconds)	0.26 ±0.07	0.27 ±0.06*	0.29±0.05***##	0.25±0.07	0.27±0.06	0.29±0.06***##
PO† (Watts)	387.8±131.6	417.9±145.1*	449.1±128.6***##	384.6±141.5	409.8±141.1	443.7±137.8***##

† Abbreviations

Medial gastrocnemii, GM

Electromyogram, EMG

Lateral gastrocnemius, GL

Soleus, SOL

Flight Time, FT

Power, PO