

Unilateral leg resistance training improves time to task failure of the contralateral untrained leg

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Background: Cross-training is the process whereby training of one limb gives rise to enhancements in the performance of the opposite, untrained limb, most likely due to neural adaptations at the level of the motor cortex and/or spinal cord. **Objective:** To investigate whether unilateral resistance training can affect the ability of untrained homologous muscle in the contralateral limb to maintain force output over a sustained contraction. **Methods:** Fifteen healthy subjects completed 12 weeks of resistance training consisting of 36 sessions, using the unilateral leg press exercise. Sustained isometric knee extension performed at 50% of maximal force until task failure on both the ipsilateral trained leg and contralateral untrained leg. Surface electromyography (EMG) signals were recorded from the trained and contralateral untrained quadriceps (vastus medialis, rectus femoris, and vastus lateralis). **Results:** Time to task failure of the contralateral untrained leg was significantly increased after 12 weeks of unilateral resistance training ($p < .05$). Moreover, the EMG amplitude of the contralateral untrained quadriceps was significantly higher during the post training sustained contractions with respect to pre training condition ($p < .05$). **Conclusions:** Unilateral resistance training of the quadriceps can increase the ability of homologous muscle in the contralateral limb to maintain force output.

Keywords: EMG, cross training, sustained contraction

Introduction

Muscular endurance is defined as the ability of muscle to sustain a continuous contraction over an extended period of time. Task failure during a sustained sub-maximal contraction is thought to be largely related to impaired motor drive (Hedayatpour, Arendt-Nielsen, & Farina, 2007, 2008; Place, Bruton, & Westerblad, 2009) as evidenced by twitch interpolation and transcranial magnetic stimulation technique for the upper and lower limb muscles (Ljubisavljević et al., 1996; Löscher, Cresswell, & Thorstensson, 1996a, 1996b; Zijdewind, Zwarts, & Kernell, 1998). Previous studies have also shown that time to task failure was prolonged following resistance training, most likely due to neural adaptations at the level of the motor cortex and/or spinal cord (Vila-Chã, Falla, & Farina, 2010). Cross-training is the process whereby training of one

limb gives rise to enhancements in the performance of the opposite, untrained limb (Carroll, Herbert, Munn, Lee, & Gandevia, 2006). For this reason, unilateral leg training has received a great deal of attention for injury prevention, rehabilitation and performance enhancement training programs in recent times and is commonly used in physiotherapy programs for knee and ankle injuries (Uh, Beynon, Helie, Alosa, & Rensstrom, 2000).

It has been reported that the cross-training process is primarily caused by adaptations in the central nervous system for the untrained limb following exercise training (Bezerra, Zhou, Crowley, Brooks, & Hooper, 2009; Dragert & Zehr, 2011; Everaert, Thompson, Chong, & Stein, 2010) and this may also affect the ability of homologous muscle in the untrained limb to sustain a continuous contraction over the extended period of time.

Thus, it is expected that unilateral resistance exercise training result in an increased time to task failure not only in the exercised muscle, but also in the untrained homologous muscle in the contralateral limb. However, there are no studies that have investigated time to task failure in homologous muscle in the contralateral limb

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after unilateral exercise training. This knowledge may be useful for exercise training and/or a rehabilitation program. It has been hypothesized, that 12 weeks of unilateral resistance training may affect the time to task failure and associated EMG activity in homologous muscle of the opposite limb. Surface EMG signals and time to task failure were recorded from the contralateral quadriceps muscle before and after 12 weeks of unilateral resistance training.

Methods

Subjects

Fifteen healthy male volunteers (mean \pm SD: age 25.6 \pm 3.6 yrs, body mass 70.4 \pm 12.9 kg, height 1.77 \pm 0.09 m) with no history of knee injury or trauma participated in this experimental study. All subjects were right leg dominant and had no experience in resistance training and were not involved in regular exercise of their knee extensor muscles for at least 6 months before the experiment. The study was conducted in accordance with the Declaration of Helsinki, approved by the local Ethics Committee (BOJ 13950701), and written informed consent was obtained from all subjects prior to inclusion. The number of participants was based on previous studies examining the effects of exercise on neuromuscular activity of same muscle (vastus medialis, rectus femoris, vastus lateralis), which showed that 10 subjects were sufficient to show a difference (Hedayatpour, Arendt-Nielsen, & Farina, 2008; Hedayatpour, Falla, Arendt-Nielsen, & Farina, 2008).

Exercise training

All subjects completed 12 weeks of resistance training using the unilateral leg press exercise to increase muscular endurance. Moderate workload training group consisted of 3 sets \times 15 reps using 60% one repetition maximum (1-RM). Three minutes of rest was considered between sets. The unilateral leg press exercise was performed with 90° of knee flexion to 0° of knee extension. Timing of the lifting, lowering and lockout phases of the exercise was established using a metronome. The metronome emitted an audible stimulus at a frequency of 1 Hz. Subjects were asked to maintain a cadence of 2 during the lifting phase, 1 during the lockout and 3 during the lowering phase, in time with the metronome. 1-RM was evaluated for each subject every week and the weights were adjusted accordingly. Progressive increase in resistance training was determined based on 1-RM testing performed every week. Because the weights were adjusted every week, the number of repetitions was also adjusted so that the total weight lifted by each subject could be equated. The workloads were

determined for the subject based on their 1-RM. One repetition maximum is defined as the heaviest load that can be moved over a specific range of motion, one time, and with correct performance (Pereira & Gomes, 2003).

Procedures

The dynamic 1-RM was determined by having the subjects perform 1-RM at each successive load using a weight-training machine (Model: FM014, S & T Welcare Equipments Private Limited, Chennai, India). The load was increased in 1- to 5-kg increments with a 30-s break between each attempt. Each subject was required to be able to lift his maximum load in a smooth, controlled motion (Hortobágyi et al., 1998).

For muscle function testing the subject sat comfortably on a chair fixed with a belt at the hip with the right knee flexed 90°. A strap connected by a chain to a load cell was attached to the ankle to measure knee extension isometric force. The subject performed six 5-second maximal voluntary contractions (MVC) by trained and untrained leg (three MVC for each leg) separated by 2-min rest. During each MVC contraction, verbal encouragement was provided. MVCs were performed in random order for trained and untrained leg. The highest MVC was considered as the representative value to determine submaximal sustained contraction at 50% MVC.

Participants also performed isometric knee extension contraction at 50% MVC with the trained and untrained leg sustained until task failure, with the participant in the same position as in the maximal voluntary contractions. Visual feedback of force was provided on a screen positioned in front of the subject. The submaximal force was relative to the highest MVC measured on the same day of the test. Task failure was defined as a drop in torque $>$ 5% MVC for more than 5 s after strong verbal encouragement to the subject to maintain the target torque (Hedayatpour, Falla, Arendt-Nielsen, & Farina, 2010). Surface EMG signals were simultaneously recorded from vastus medialis (VM) rectus femoris (RF) and vastus lateralis (VL) muscles of the trained and contralateral untrained leg during isometric knee extension contraction at 50% MVC, which was sustained until task failure, see Figure 1.

For surface EMG recordings six pairs of circular (Ag-AgCl surface electrodes Ambu Neuroline, Ambu A/S, Ballerup, Denmark; conductive area = 28 mm²) were placed in bipolar configuration (interelectrode distance = 2 cm) over the quadriceps femoris muscle of the trained and untrained leg. Electrodes were placed over the quadriceps components at 10% of the distance between medial border, superior border and lateral border of the patella (for vastus medialis, rectus femoris

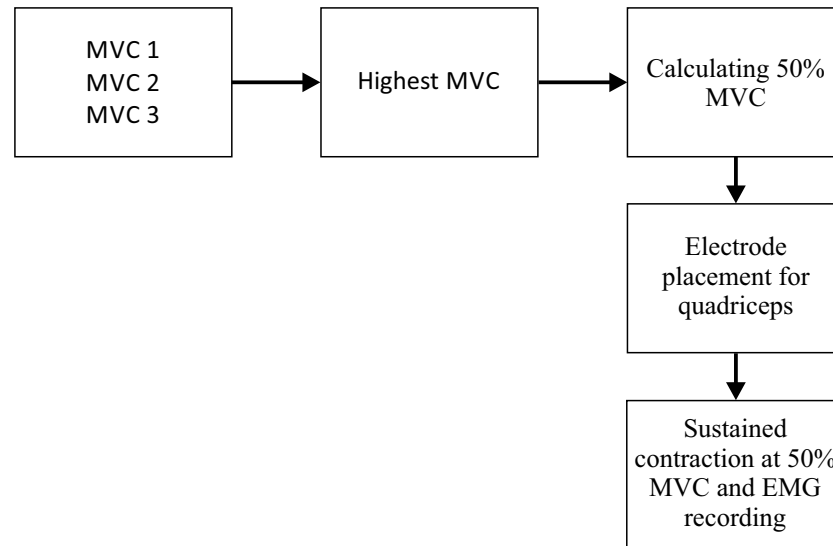


Figure 1. The procedure of the experiment.

and vastus lateralis respectively) and anterior superior iliac spine (Hedayatpour, Falla, et al., 2008). Before electrode placement, the skin was shaved and lightly abraded at the selected locations. Surface EMG signals were amplified bipolarly (EMG amplifier, EMG-16, LISiN - OT Bioelettronica, Torino, Italy; bandwidth 10–500 Hz), sampled at 2048 Hz, and stored after 12 bit A/D conversion.

Signal analysis

Average rectified value (ARV) was estimated from the EMG signals for time interval of 1 s using the Matlab code developed by Dario Farina (Hedayatpour, Falla, et al., 2008). The values obtained from 1 s long time interval in intervals of 10% of the time to task failure were averaged to obtain one representative value for each 10% interval. This was done to compare subjects that had different times to task failure. To compare changes across sessions, differences in ARV for post training with respect to pre training were calculated.

Statistical analysis

All statistical analyses were performed using SPSS (Version 18; IBM Corp., Armonk, NY, USA). Normality of data distribution was verified by Kolmogorov-Smirnov test. One-way repeated measures ANOVA was applied to analyze time to task failure during pre- and post- training session with leg (trained and untrained) as independent factor. Three-way repeated-measures ANOVA was also used to assess change in ARV across the sustained contraction at 50% MVC before and after training, with muscle (VM, RF, VL), time interval (initial and last 10% interval of the time to task failure) and leg (trained and untrained leg) as factors. Pairwise comparisons were performed with the

Student-Newman-Keuls post hoc test when ANOVA was significant. The effect size was assessed by η^2 .

Results

Time to task failure of the trained and untrained leg were significantly increased after concentric eccentric resistance training ($F = 10.2$; $p = .012$; $\eta^2 = .39$). A significant interaction was also observed between time to task failure and trained/untrained leg. Trained leg resulted in a greater increase in time to task failure compared to untrained leg ($p = .028$), see Figure 2.

In both the trained and untrained leg ARV of EMG significantly increased over time during sustained contraction at 50% MVC ($F = 9.6$; $p = .001$; $\eta^2 = .59$). EMG

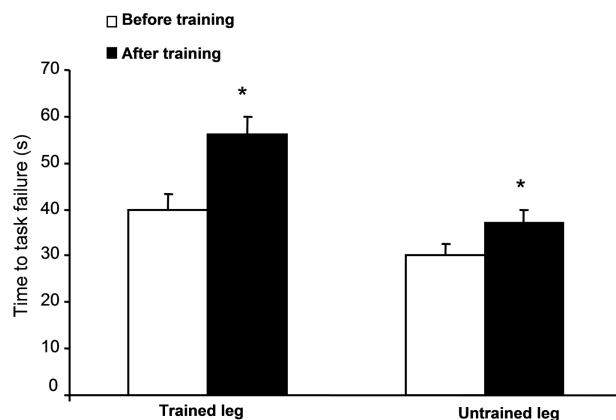


Figure 2. Time to task failure in the trained and untrained leg (mean \pm SE, $N = 15$) during sustained isometric knee extension at 50% of the maximal voluntary contraction measured before and after 12 weeks resistance training. $*p \leq .05$.

ARV for both trained and untrained leg in the last 10% interval of the time to task failure was significantly larger than the initial 10% interval ($p = .022$). Moreover, the ARV of EMG during post training sustained contraction of both trained and untrained leg was significantly larger than pre training condition ($F = 19.6$; $p < .001$; $\eta^2 = .67$). A significant interaction was also observed between EMG ARV and leg, in which, EMG ARV rate of increase in the trained leg was significantly larger than the untrained leg ($p = .042$). Change in EMG ARV was not significantly different between three muscles ($p = .063$), see Figures 3 and 4.

The pre-post reliability of each value of EMG for quadriceps muscle (averaged for all muscle in the trained and untrained leg) was examined using linear regression,

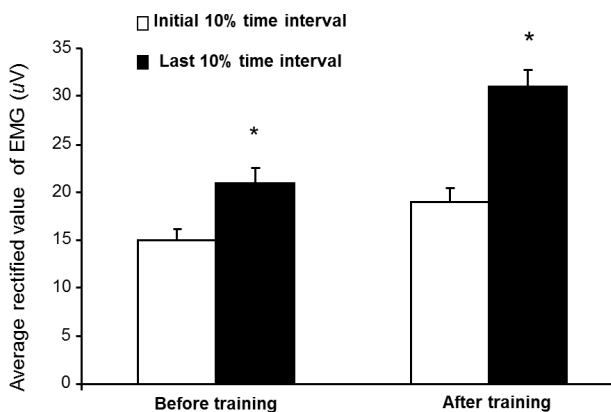


Figure 3. Average rectified value of EMG obtained from the initial and last 10% interval of the time to task failure of the trained leg (average for the VM, RF and VL muscles) during sustained isometric knee extension at 50% of MVC measured before and after 12 weeks resistance training. * $p \leq .05$.

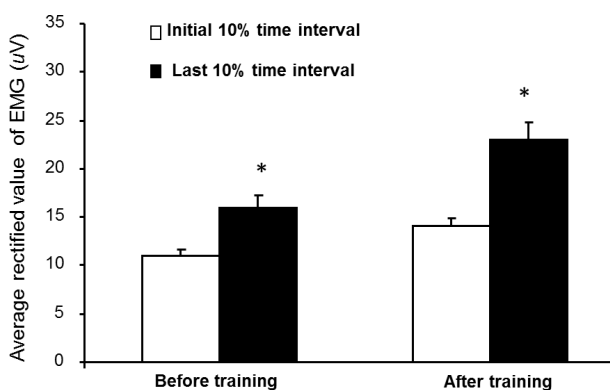


Figure 4. Average rectified value of EMG obtained from the initial and last 10% interval of the time to task failure of the untrained leg (average for the VM, RF and VL muscles) during sustained isometric knee extension at 50% of MVC measured before and after 12 weeks resistance training. * $p \leq .05$.

interclass correlation. A significant correlation ($p = .014$, $\eta^2 = .59$) was observed for the magnitude of EMG ARV as a function of time (pre- and post-training). Moreover, the raw EMG signals during pre- and post- training session were recorded from the same muscle location and from the same amplifier channel.

Discussion

The result of this study demonstrated a significant increase in the time to task failure of the contralateral untrained leg following 12 weeks dynamic resistance training. Moreover the EMG amplitude of quadriceps muscle in the contralateral untrained leg increased significantly more over time during post training sustained contraction as compared with pre training. A greater increase in EMG amplitude over time observed for the untrained limb may be related to increasing motor unit recruitment and/or discharge rate required to maintain force (Kirsch & Rymer, 1992).

Sustained contraction of the untrained leg before unilateral resistance training

EMG amplitude of the quadriceps muscle in the untrained leg progressively increased over time during submaximal sustained contraction at 50% MVC to maintain force output. Previous studies have also reported, a longer duration of a submaximal task was associated with an increase in EMG activity over time (Kirsch & Rymer, 1992; Lind & Petrofsky, 1979). These studies suggested that the increased EMG amplitude is related to the enhanced neural drive from higher motor center to muscle fibers to increase motor unit recruitment and/or discharge rate required to compensate for contractile failure caused by fatigue (Kirsch & Rymer, 1992; Petrofsky & Phillips, 1985).

Sustained contraction of the untrained leg after unilateral resistance training

Time to task failure of the contralateral untrained leg was significantly prolonged after concentric eccentric resistance training. Accordingly, the EMG amplitude of quadriceps muscle in the contralateral untrained leg increased significantly more over time during post training sustained contraction as compared with pre training. The current study is the first to assess time to task failure in the contralateral untrained limb following unilateral dynamic resistance training. In the current study, 18.9% increase in time to task failure for the contralateral untrained leg observed after 12 weeks concentric eccentric resistance training. This corresponds to an increase of 28.5% in time to task failure of the ipsilateral training effect. These results are in

agreement with previous work suggesting an increased maximal force of the contralateral untrained limb following unilateral resistance training (Darcus & Salter, 1955; Hellebrandt & Houtz, 1956). For example, maximal muscle force increased at an average rate of 7% to 8% for the contralateral untrained homologous muscle group after 4 to 12 weeks of unilateral training (Carroll et al., 2006). Similarly, other studies have demonstrated that unilateral resistance training produces increased strength and neural activity in the contralateral resting muscle (Howatson, Zult, Farthing, Ziidewind, & Hortobágyi, 2013). A review of literature has shown that strength in the untrained limb may increase up to 22% with an average strength increase of about 8% (Munn, Herbert, & Gandevia, 2004). The increase in strength of the untrained limb is accompanied by greater EMG activity in that limb (Shima et al., 2002), thus suggesting that a central neural adaptations accounts for the majority of strength gains.

Cross-training effect has also been observed in different muscles groups after different mode of exercise training and at different levels of task complexity (Hortobágyi, Lambert, & Hill, 1997). These lines of evidence suggest that unilateral resistive exercise of a specific limb will also result in training effects in the untrained contralateral limb.

In the current study, an increase in time to task failure and associated EMG activity observed in the contralateral untrained leg after resistance training, which may be related to neural adaptations at the level of the motor cortex and/or spinal cord (Hedayatpour & Falla, 2015). It has been proposed that resistance training can changes the sensory receptors (i.e. Golgi tendon organs) and consequently lead to disinhibition and an increased neural expression at level of motor cortex (Gabriel, Kamen, & Frost, 2006). This enhances neural drive from higher motor center to muscle fibers to increase motor unit recruitment and/or discharge rate required to maintain muscle force (Kirsch & Rymer, 1992). These adaptations may be transferred to the opposite homologous limb by several potential mechanisms.

The mechanisms underlying cross education has been attributed to neural plasticity of motor pathways projecting to the contralateral untrained limb and or/ trained limb. It has been proposed that repeated unilateral muscle contractions can change the excitability of spinal and cortical motor pathways (Hortobágyi et al., 2011; Sotgiu, Brambilla, Valente, & Biella, 2004) that project to the contralateral untrained side and as consequence may increase neural derive and muscle strength in the untrained limb. Farthing, Borowsky, Chilibeck, Binsted, and Sarty (2007) reported after training, there was an enlarged region of activation in contralateral

sensorimotor cortex and left temporal lobe during muscle contractions with the untrained left arm.

The increased time to task failure of the contralateral untrained limb may also be explained by neural adaptations in hemisphere involved in execution of movements of the trained limb. The opposite hemisphere may access these modified circuits during voluntary contraction of the opposite untrained limb and enhance the ability of muscle to maintain force output (Hortobágyi et al., 1997).

Relevance for training prescription

Strengthening homologous muscle of the contralateral limb play an important role in the rehabilitation process, especially for those patients who have suffered limb injuries and/or require an amputation of the contralateral limb. The result of this study showed that time to task failure and neuromuscular activity of the contralateral untrained leg was significantly increased after unilateral resistance training. The knowledge gained from this study may be relevant to enhance recovery of specific muscle groups by utilizing contralateral therapy and cross-education principles. Further work is required to determine the effectiveness of contralateral therapy for specific clinical applications.

Conclusion

Time to task failure of the contralateral untrained leg was significantly increased after 12 weeks of unilateral concentric eccentric resistance training, most likely due to the neural plasticity of motor pathways projecting to the contralateral untrained limb. The results suggest that unilateral leg training can be used as a part of physiotherapy or rehabilitation programs to enhance muscle endurance in the injured leg.

Conflict of interest

There were no conflicts of interest.

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