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Effects of fast-velocity eccentric resistance training on early and late rate of force development

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Abstract
This study examined whether short-term maximal resistance training employing fast-velocity eccentric knee extensor actions would induce improvements in maximal isometric torque and rate of force development (RFD) at early (<100 ms) and late phases (>100 ms) of rising torque. Twenty healthy men were assigned to two experimental groups: eccentric resistance training (TG) or control (CG). Participants on the TG trained three days a week for a total of eight weeks. Training consisted of maximal unilateral eccentric knee extensors actions performed at 180°s-1. Maximal isometric knee extensor torque (MVC) and incremental RFD in successive 50 ms time-windows from the onset contraction were analysed in absolute terms (RFD_{INC}) or when normalised relative to MVC (RFD_{REL}). After eight weeks, TG demonstrated increases in MVC (28%), RFD_{INC} (0–50 ms: 30%; 50–100 ms: 31%) and RFD_{REL} (0–50 ms: 29%; 50–100 ms: 32%). Moreover, no changes in the late phase of incremental RFD were observed in TG. No changes were found in the CG. In summary, we have demonstrated, in active individuals, that a short period of resistance training performed with eccentric fast-velocity isokinetic muscle contractions is able to enhance RFD_{INC} and RFD_{REL} obtained at the early phase of rising joint torque.

Keywords: *Isometric, maximal torque, rate of force development, explosive strength, eccentric training*

Introduction

Training-induced increases in rapid force capacity (contractile rate of force development, RFD) and maximal muscle power output have essential implications within both sports medicine and athletic performance. Some benefits range from maintenance of joint health and reduced injury risks to enhanced post-exercise recovery and performance during recreational and competitive sports practice (Haskell et al., 2007). Resistance training plays a particularly essential role in sports by enhancing neural contributions to joint torque output during both the early and later phases of training. In addition, morphological adaptations within muscle fibres, such as increased content of contractile proteins due to myofilament hypertrophy also are observed following prolonged periods of training (Aagaard et al., 2001; Baroni et al., 2013; Roig et al., 2009).

Training protocols involving dynamic contractions are proven to increase joint torque output, accompanied by hypertrophic myofiber responses following both concentric-based and eccentric-based regimes of resistance training (Farthing & Chilibeck, 2003; Higbie, Cureton, Warren, & Prior, 1996). Training-induced increases in maximal muscle strength are most evident when assessed at the specific contraction modality used during training (Higbie et al., 1996; Roig et al., 2009), although gains may also be observed in other contraction modes (i.e., concentric training leading to gains in maximal eccentric strength) (Aagaard, Simonsen, Trolle, Bangsbo, & Klausen, 1996; Blazevich, Horne, Cannavan,

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Coleman, & Aagaard, 2008). For instance, Higbie et al. (1996) trained two groups, one concentrically and other eccentrically, demonstrating strength enhancement for both the groups, but with the best results observed for specifically trained contraction type (i.e., concentric group enhances mainly concentric strength and vice versa). Interestingly, eccentric resistance training elicits greater increases in maximal eccentric muscle strength compared to concentric strength gains (Baroni et al., 2013; Farthing & Chilibeck, 2003; Roig et al., 2009), which can be related to neural drive facilitation and altered reflex activity during maximal eccentric muscle contraction (Duclay, Martin, Robbe, & Pousson, 2008; Fang, Siemionow, Sahgal, Xiong, & Yue, 2004; Holtermann, Roeleveld, Engstrøm, & Sand, 2007). Additionally, muscle damage during eccentric exercise may play a significant role in eliciting morphological muscle fibre adaptation and enhance muscular strength (Roig et al., 2009).

Andersen and Aagaard (2006) have shown that RFD is influenced by different factors at early (<100 ms: neural drive and intrinsic muscle properties) and late phases (>100 ms: neural, muscle cross-sectional area and tendon/aponeurosis stiffness) from the onset of muscle contraction. Accordingly, several studies have reported that resistance training may elicit different adaptive responses between early and late phases of rising torque output (Aagaard, Simonsen, Andersen, Magnusson, & Dyhre-Poulsen, 2002a; Andersen, Andersen, Zebis, & Aagaard, 2010; Blazevich et al., 2008; de Oliveira, Rizatto, & Denadai, 2013). Recently, de Oliveira et al. (2013) found that a short period (six weeks) of resistance training performed with concentric fast-velocity isokinetic muscle contractions is able to enhance only RFD obtained at the early phase of rising joint torque. Blazevich et al. (2008) have shown similar data after five weeks of slow-speed resistance training involving concentric or eccentric single-joint muscle contractions. Thus, the effects of resistance training on early and late RFD seems to be independent of contraction mode (i.e., concentric *vs.* eccentric). However, fast-velocity dynamic training causes augmented firing frequency, synchronisation and earlier recruitment of large motor units, playing an important role in RFD (Häkkinen, Komi, & Alen, 1985). Thus, it is relevant to investigate the effects of fast-velocity eccentric isokinetic resistance training on early and late RFD.

The aim of the present study was to examine the effect of fast-velocity eccentric resistance training on maximal isometric strength and early and late RFD of the knee extensor muscles. Based on the studies cited above (Andersen & Aagaard, 2006; de Oliveira et al., 2013; Häkkinen et al., 1985; Roig et al., 2009), we hypothesised that the changes in RFD with short-term maximal eccentric training would be more likely to occur in the early phase of muscle contraction.

Material and methods

Subjects

Twenty physically active, though not specifically trained subjects, males (mean ± SD: 22 ± 2 y, 179.1 ± 6.2 cm and 80.1 ± 9.5 kg) gave their informed consent to participate in the study. These subjects were performing team sports, running, swimming or cycling at least three times/week at the time of the experiment. All subjects were healthy and free of cardiovascular, respiratory and neuromuscular disease. The study was approved by the Institutional Research Ethics Committee.

Experimental design

Subjects were randomly divided in two groups by simple raffle for training or control conditions. A training group (TG, 22 ± 3 y, 178 ± 6 cm, 77 ± 10 kg, n = 12) and a control group (CG, 23 ± 4 y, 182 ± 4 cm, 86 ± 7 kg, n = 8). Subjects were tested multiple times over a period of 11 weeks. In week 1 subjects were tested to become familiarised to the isokinetic and isometric assessment procedures. In week 2, subjects were baseline tested for maximal isometric strength (MVC) and RFD using a Biodex isokinetic dynamometer (Biodex System 3, Biodex Medical Systems, Shirley, N.Y.). The familiarisation sessions and the test sessions were identical (see: "MVC Testing") and only the knee extension of the dominant lower limb was tested and trained. For TG group, 24 sessions of an eccentric isokinetic training protocol were performed. These training sessions were performed 3·week^{-1}, separated by 48 hours, totalling eight weeks. During these eight weeks, the CG members were asked to maintain their normal daily activities. After the training or the control period, all groups performed the post-test session.

Training

Following baseline testing TG subjects participated in an eight-week maximal isokinetic training programme using the isokinetic dynamometer to perform maximal eccentric knee extensor contractions (knee angular velocity 180°·s^{-1}, ROM: 10–90° knee flexion). The programme consisted of 24 sessions, divided in 3·week^{-1}. The protocol was an adaptation of the original protocol from Farthing and Chilibeck (2003), during which two sets of 8 maximal repetitions were performed in training weeks 1 and 2. During training weeks 3 and 4 – 4 × 8 maximal repetitions; during training weeks 5 and 6, 6 × 8 maximal repetitions; and during training weeks 7–8, 3 × 8 maximal repetitions were performed. Recovery between sets was one minute.

Procedures

MVC testing

Prior the test, subjects performed a standardised warm-up consisting of five-min cycling at 70-W. An isokinetic dynamometer was used to measure maximal isometric knee extensor torque. Subjects were placed in a sitting position and securely strapped into the test chair. Extraneous movements of the upper body were limited by two cross-over shoulder harnesses and an abdominal belt. The trunk/thigh angle was 85° (0° = full extension). The axis of the dynamometer was lined up with the right knee flexion-extension axis, and the lever arm was attached to the shank by a strap. The subject was asked to relax his leg so that passive determination of the effects of gravity on the limb and lever arm could be carried out. The knee joint angle during isometric contractions was 75° (0° = full extension). Anatomical 90° knee angle was determined by manual measurement using a handheld goniometer. Subjects were instructed to perform maximal isometric knee extensions while increasing force production as rapidly as possible (i.e. at maximal RFD) and aiming at producing maximal torque in the dynamometer. Three 5-second isometric contractions were performed, separated by three-minute rest periods. All subjects were encouraged to give a maximal effort by both visual feedback and strong verbal encouragement. All recorded force signals were converted into torque (moment of force) and subsequently corrected for the gravitational pull on the shank and foot.

Data processing and analyses

The isometric strength data (joint torque and RFD) were sampled at 2000 Hz via an analog-to-digital converter using an external system (EMG System800, São José dos Campos, Brazil) and were analysed using specific algorithms written in MatLab (The MathWorks, Natick, MA, USA). Torque curves were smoothed by using a Butterworth fourth-order zero-lag low-pass filter with a 10 Hz cut-off frequency (Aagaard et al., 2002a; Thorlund, Michalsik, Madsen, & Aagaard, 2008). Maximal voluntary contraction (MVC) strength was calculated as average torque exerted over a 1-s period around the torque-plateau level. The highest torque value measured across the isometric trials was considered as the MVC. The calculation of RFD was performed according to previous reports (Aagaard et al., 2002a). In brief, the onset of contraction was considered when the torque level reached 8 Nm above the baseline level. Throughout the whole contraction, RFD was derived as the tangential slope of the moment-time curve (Δtorque/Δtime) calculated by time-differentiation. Maximum RFD was defined as the peak tangential slope (RFD_{PEAK}), and the time to achieve this RFD_{PEAK} was defined as $RFD_{PEAK\text{-}TIME}$. In addition, RFD was also described in successive 50 ms time-windows (0–50, 50–100, 100–150, 150–200 and 200–250 ms, respectively), hence in the latter time intervals representing a measure of incremental RFD (Tillin, Jimenez-Reyes, Pain, & Folland, 2010). We are reporting the RFD values averaged in each of these time windows (RFD_{INC}), and also by normalising these averaged RFD values by the MVC (RFD_{REL}).

Statistical analyses

Data are presented as mean ± standard deviation. Normality (by a Kolmogorov–Smirnov test) and homogeneity (by Levene Statistic test) of distribution were assessed for the dependent variables (MVC, RFD_{PEAK}, RFD_{TIME}, RFD_{INC} and RFD_{REL}) before (PRE) and after the eccentric training period (POST). The effects of the training on these above mentioned dependent variables were evaluated by two-way analysis of variance (ANOVA) for repeated measures (two groups [TG × CG], two times [PRE × POST] as repeated measure). All tests were carried out using a two-tailed test design and a level of statistical significance of $p \leq 0.05$.

Results

Figure 1 shows representative curves for isometric torque and RFD. As can be seen, this representative subject demonstrated increased maximal torque and RFD after eight weeks of eccentric knee extensor training.

MVC increased 28% ($p < 0.01$) in the TG, whereas no change occurred in the CG (Figure 2A). The TG increased significantly RFD_{PEAK} after training (~48%, $p < 0.01$) while no changes were observed in CG (Figure 2B). No changes in RFD_{TIME} were observed pre-to-post training (Figure 2C), and no differences emerged between TG and CG.

RFD_{INC} and RFD_{REL} extracted from successive 50-ms time windows increased during the first two time intervals (0–50 and 50–100 ms) in TG (~30–32%, $p < 0.05$, Figure 3A and 3B). No changes in RFD_{INC} and RFD_{REL} were observed in CG (Figure 3C and 3D).

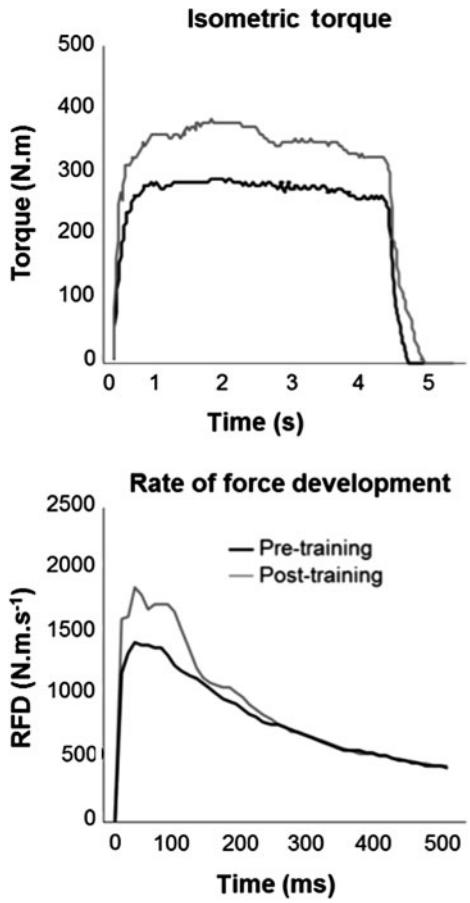

Figure 1. Representative isometric knee extensor torque (top) and rate of force development curves (bottom) obtained before and after 8 weeks (24 sessions) of eccentric resistance training.

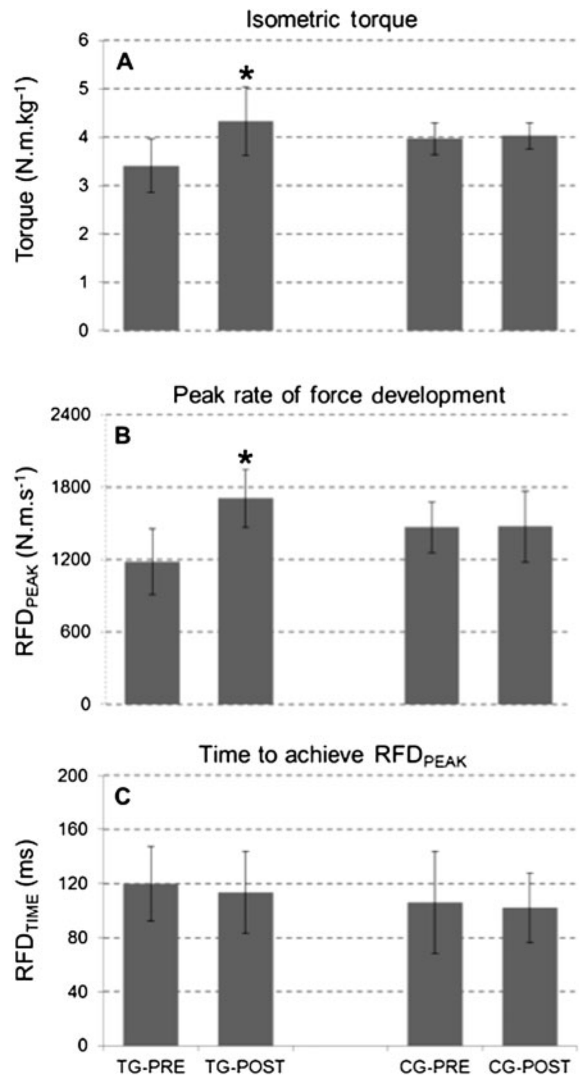

Figure 2. Mean (SD) isometric torque (A), peak rate of force development (B) and time to achieve the maximal rate of force development (C) for the training group (TG) and control group (CG) before (PRE) and after training period (POST). *denotes PRE-to-POST differences (p < 0.01).

Discussion

The main finding of the present study was that RFD_{INC} and RFD_{REL} at an early phase of rising joint torque can be improved by an exclusively short-term eccentric training protocol, whereas both late RFD_{INC} and late RFD_{REL} remained unchanged. As a measure of maximal explosive muscle strength, RFD_{PEAK} also was found to increase (+48%) following the regime of eccentric resistance training, suggesting a facilitation to produce explosive torque static contractions. These results suggest that the regime of eccentric resistance exercise elicited adaptations to perform explosive muscle actions in the very initial phase of muscle contraction, which are specific to the early phase of RFD production.

Previous investigations have reported transferred adaptations from dynamic to static muscle actions from long-term strength training regimens (12–14 weeks; Aagaard, Simonsen, Andersen, Magnusson, & Dyhre-Poulsen, 2002b; Andersen et al., 2010), which are influenced by both morphological and neural adaptations to training. It is suggested that shorter resistance training programmes (up to eight weeks) may induce less morphological adaptations such as muscle hypertrophy, changes in pennation angle and alterations in muscle-tendon unit stiffness (Roig et al., 2009). However, a few investigations have found steeper muscle fascicle pennation angles and increased anatomical muscle CSA following short-term (five weeks) eccentric resistance training (Norrbrand, Fluckey, Pozzo, & Tesch, 2008; Seynnes, de Boer, & Narici, 2007). Nonetheless, short-term resistance training can increase RFD (early RDF and RFD_{PEAK}) if muscle actions with maximal intended RFD (i.e. explosive-type resistance training) are performed in dynamic (Holtermann et al., 2007; de Oliveira et al., 2013; Vila-Chã, Falla, & Farina, 2010) and isometric conditions (Geertsen, Lundbye-Jensen, & Nielsen, 2008; Tillin, Pain, & Folland, 2012). Our data corroborate these

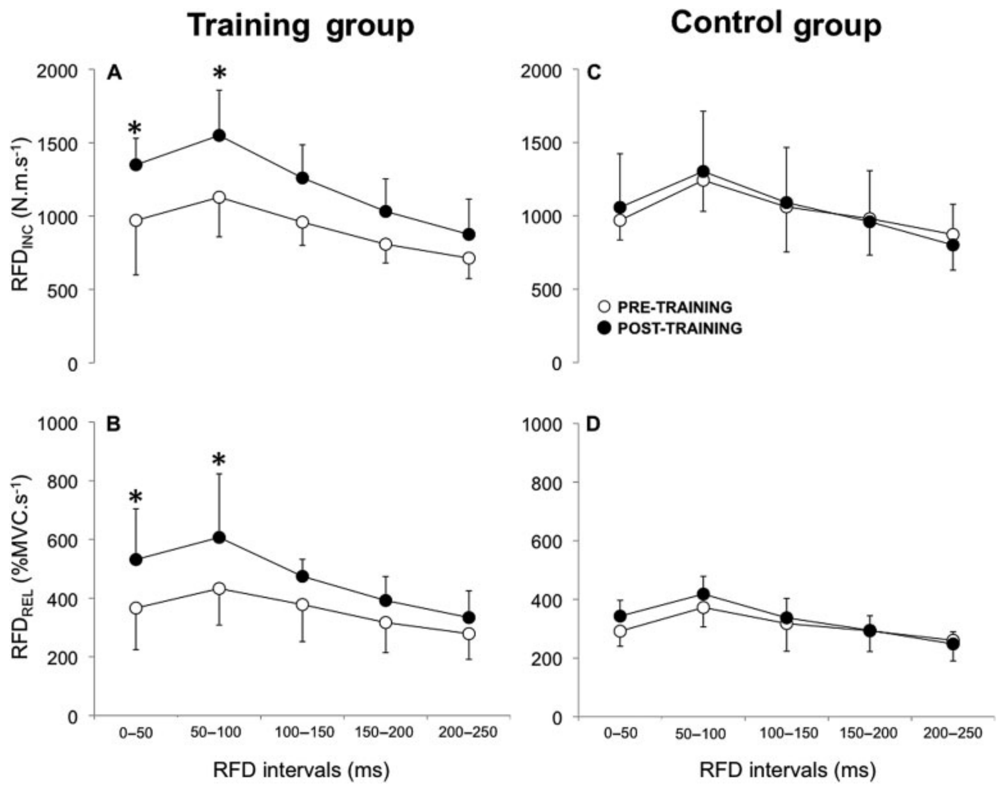

Figure 3. Mean (SD) non-normalised incremental rate of force development (RFDINC) and normalised rate of force development (RFDREL) calculated in successive 50-ms time windows in trained individuals (left panels) and untrained controls (right panels) before (white circles) and after (black circles) the period of training. *denotes significant training effect on RFD (p < 0.05).

previous studies and reinforce the suggestion that muscle actions of maximal intentional effort may allow positive adaptations on RFD (early RFD and RFD_{PEAK}) regardless the contraction type performed during training sessions.

In the case of short-term eccentric resistance training, adaptive increases in strength and RFD may be predominantly credited to reduced inhibition of neural drive, increased voluntary activation and improved efferent output of spinal motorneurones (MNs) reflected by an elevated V-wave response (Michaut, Babault, & Pousson, 2004; Pensini, Martin, & Maffiuletti, 2002). The latter finding further suggesting an increased central descending drive to the pool of spinal MNs and/or increased MN excitability or reduced pre/postsynaptic inhibition of Ia afferents (Aagaard et al., 2002b). Although in the present study we did not analyse EMG results, these previous investigations support the suggestion that improvements on isometric strength and RFD transferred from eccentric training may be predominantly induced by neural adaptations that enable enhanced ballistic muscle actions.

Previous studies have underpinned that eccentric muscle actions are uniquely modulated by the central nervous system (Duclay et al., 2008; Enoka, 1996; Grabiner & Owings, 2002). There are distinct and greater areas of the brain involved in executing eccentric actions (Fang et al., 2004), which can modulate differently eccentric contraction prior to the movement onset (Grabiner & Owings, 2002). Moreover, eccentric training protocols can induce specific adaptations on reflex excitability that may be directly responsible for increases in RFD (Holtermann et al., 2007). Indeed, using evoked spinal V-wave recordings Duclay et al. (2008) have shown that increases in voluntary isometric torque following short-term eccentric resistance training may be ascribed to increased volitional drive from supraspinal centres. Moreover, the observed adaptations may have included elevated spinal reflex responses, from neural adaptations at the spinal level (Duclay et al., 2008; Enoka, 1996; Grabiner & Owings, 2002). Thus, the present results on isometric strength and RFD improvements determined by eccentric resistance training may suggest the involvement of supraspinal and spinal adaptations to maximise neural drive during maximal isometric contractions. However, due to the present lack of neuromuscular measurements such as surface electromyography and H-reflex recordings we can only speculate on the underlying neuronal mechanism involved in the observed improvements in MVC and RFD. Recent investigation on the time-course of neural adaptations to eccentric training has suggested that both neural and morphological adaptations are related to increases in maximal isometric torque between 4–8 weeks (Baroni et al., 2013). However, measurements of the RFD were not reported in this investigation (Baroni et al., 2013), and therefore a definitive statement on the underlying mechanisms for RFD improvements remains speculative.

RFD has been used to describe the ability to generate steep rises in joint torque within fractions of a second (Aagaard et al., 2002a; Andersen et al., 2010; Thorlund, Aagaard, & Madsen, 2009), which is an essential parameter for sports performance and various functional tasks (Aagaard et al., 2002a; Thorlund et al., 2009). Recent investigations have demonstrated that the initial phase of explosive-type muscle actions (<100 ms) are more sensitive to ballistic resistance training stimuli, where joint torque development essentially is enhanced by means of neural adaptations (de Oliveira et al., 2013; Van Cutsem, Duchateau, & Hainaut, 1998). The present results suggest that eccentric stimulus can elicit neural adaptations that optimise RFD generation at the early time phase of isometric contractions. Both RFD_{INC} and RFD_{REL} were positively influenced by the present eccentric training protocol, and the effects on RFD_{REL} are indicative of adaptations to produce explosive strength regardless the maximal torque achieved at later stages of muscle contraction (de Oliveira et al., 2013; Tillin et al., 2012). Additional support to predominant neural adaptations is provided by the lack of changes in later phase of rising joint torque (>100 ms), especially for RFD_{REL} (Andersen et al., 2010). However, our results must be interpreted with caution, since no measurements related to morphological adaptations such as muscle hypertrophy, sarcomere numbers, pennation angle and others were conducted.

Recently, de Oliveira et al. (2013) have found that fast-velocity concentric isokinetic resistance training did not influence both late RFD and MVC. Other studies have also observed that RFD_{PEAK} increased in response to short-term ballistic resistance training (4 × 10 at 30–40% 1RM), with no changes in MVC (Gruber et al., 2007). Interestingly, we have found that fast-velocity eccentric isokinetic resistance training has improved both early RFD and MVC. Similar results were found by Tillin et al. (2012), following 4 weeks of resistance training performed with explosive isometric contractions (1 s "fast and hard"). In this study, Tillin et al. (2012) suggested that peripheral adaptations (hypertrophy and increased muscle-tendon unit stiffness) were the primary mechanism for improving MVC after resistance training. These adaptations would explain the optimised transfer of adaptation from isometric or eccentric resistance training based on explosive contractions in comparison to traditional and fast-velocity concentric isokinetic resistance training.

In summary, we have demonstrated, in active individuals, that eight weeks of maximal eccentric resistance training of the knee extensors led to marked gains in maximal isometric muscle torque production. Moreover, the early and late phase of rising joint torque measured by the contractile RFD responded differently to the eccentric training programme, demonstrating adaptations only at the very initial phase of rising joint torque (<100 ms). The latter findings suggest that neural improvements from eccentric training are transferrable to isometric contraction conditions, independently of the maximal torque improvements that may be caused by both neural and morphological adaptations.

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