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Are early and late rate of force development differently influenced by fast-velocity resistance training?

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Summary

This study examined the effect of fast-velocity concentric isokinetic resistance training (FV) on the rate of force development (RFD) at early (<100 ms) and late phases (>100 ms) of rising muscle force. Nine men participated in a 6-week resistance training intervention for the lower body, and nine matched subjects participated as controls (CON). During concentric isokinetic ($180°s^{-1}$) knee extension training, subjects were instructed to do each contraction 'as fast and forcefully as possible'. Maximal muscle strength (MVC) and RFD (0–10, 0–20, …, 0–250 ms from the onset of contraction) were measured during maximal voluntary isometric contraction of the knee extensors (KE). There were no significant changes in MVC of KE in both groups after intervention (FV = 314·2 ± 101·1 versus 338·7 ± 88·0 N·m, P>0·05; CON = 293·3 ± 94·8 versus 280·0 ± 72·2 N·m, P>0·05). The RFD increased 39–71% at time intervals up to 90 ms from the onset of the contraction (P<0·05), whereas no change occurred at later time intervals. Similarly, relative RFD (i.e.%$MVC{\cdot}s^{-1}$) (RFDr) increased 33–56% at time intervals up to 70 ms from the onset of the contraction (P<0·05). It can be concluded that a short period of resistance training performed with concentric fast-velocity isokinetic muscle contractions is able to enhance RFD and RFDr obtained at the early phase of rising muscle force.

Introduction

The neuromuscular capacity to rapidly generate muscular force, also known as 'explosive' muscle action, can be represented by the rate of force development (RFD). The RFD can be defined as the slope of the moment (force)-time curve obtained under isometric conditions (Aagaard *et al.*, 2002). Andersen & Aagaard (2006) have shown that RFD is influenced by different factors at early (<100 ms) and late phases (>100 ms) from the onset of muscle contraction. The early phase was influenced by neural drive (Gruber & Gollhofer, 2004) and intrinsic muscle properties (e.g. fibre-type and myosin heavy chain composition) (Andersen *et al.*, 2010). However, the late phase was closely related to factors that promote gains in maximal muscle strength (MVC) (Andersen *et al.*, 2010), as neural drive (Andersen & Aagaard, 2006) and peripheral muscle properties (i.e. muscle cross-sectional area and tendon/aponeurosis stiffness) (Suetta *et al.*, 2004; Bojsen-Møller *et al.*, 2005). Thus, analyzing early and late RDF may provide insight into the physiological mechanisms underlying the neuromuscular adaptation to resistance training (Gruber & Gollhofer, 2004; Bojsen-Møller *et al.*, 2005; Andersen & Aagaard, 2006; Andersen *et al.*, 2010; Cheng *et al.*, 2012).

Studies have investigated the effects of several resistance trainings on RFD obtained at different time intervals from the onset of muscle contraction and demonstrated different adaptive responses between early and late phases of rising muscle force (Hakkinen *et al.*, 1985; Aagaard *et al.*, 2002; Suetta *et al.*, 2004; Barry *et al.*, 2005; Holterman *et al.*, 2007; Blazevich *et al.*, 2008; Geertsen *et al.*, 2008; Andersen *et al.*, 2010; Tillin *et al.*, 2011, 2012). Interestingly, resistance training performed under isometric conditions can enhance RFD after both short (4 weeks) and long (>12 weeks) periods of training (Barry *et al.*, 2005; Behm & Sale, 1993; Kubo *et al.*, 2001; Tillin *et al.*, 2012). It is important to note that the strategy used during MVC seems to modulate the effects of resistance training on RFD. Geertsen *et al.* (2008) and Tillin *et al.* (2012) have found that ballistic-intended isometric training can improve both early and late RFD. In contrast, Tillin *et al.* (2011) did not find increases in RFD at any contraction time after isometric training without ballistic-intended contraction. Moreover, the utilization of an intended ballistic effort seems to be more important for inducing increases in RFD than the type of contraction actually performed (Behm & Sale, 1993). However, using electrically evoked tetanic contractions, Duchateaus & Hainaut (1984) found that peak RFD gains were greater after fast ballistic training rather than isometric training (31 versus 18%).

Indeed, it has been proposed that the greater power outputs that can be generated by ballistic movements appear to offer an ideal stimulus for muscle power development (Crewther *et al.*, 2005). Thus, light to moderate loads (e.g. 30–60% 1RM), at which the maximal power output values can be attained, have been considered important for improving explosive strength. Moreover, greater acceleration and velocity obtained during ballistic movements might optimize the transfer of training effects for athletic activities performed in such manner (Crewther *et al.*, 2005). Low resistance (30–40% 1RM) fast-velocity dynamic training causes augmented firing frequency, synchronization and earlier recruitment of large motor units, playing an important role in RFD, especially at early contraction phase (Cutsem *et al.*, 1998; Gruber *et al.*, 2007; Hakkinen *et al.*, 1985).

However, to the best of our knowledge, no studies have examined the changes in both early and late RFD in response to fast-velocity resistance training. Thus, the aim of this study was to examine the effect of fast-velocity concentric isokinetic resistance training (FV) on early and late RFD. Based on the studies cited above (Cutsem *et al.*, 1998; Gruber *et al.*, 2007; Hakkinen *et al.*, 1985), we hypothesized that the changes in RFD with FV would be more likely to occur in the early phase of muscle contraction.

Material and methods

Subjects

Eighteen healthy active men volunteered to participate in this study. The characteristics of the participants are shown in Table 1. The subjects did not have any knee joint problems and had not participated in any resistance training regimen six months previous to the study. All volunteers were textually and verbally informed about the experimental procedures and risks and signed an informed consent before being submitted to the tests. The research was approved by the University's Ethics Committee (019/2010).

Experimental design

Firstly, the volunteers were randomly assigned to control (CON) and fast-velocity training (FV) groups by means of a random numbers table. After the randomization, the research assistants were not blinded to group allocation at pre and post-training period. Participants completed three trials before (two familiarizations and one measurement trials, each trial was 2–3 days apart) and one measurement after a 6-week unilateral fast-velocity concentric isokinetic knee extensor resistance training programme. The familiarization sessions and the test sessions were identical (see: 'Maximal muscle strength Testing'), and only the knee extension of the dominant inferior limb was tested and trained. For FV group, 18 sessions of a concentric isokinetic training protocol were performed. These training sessions were performed 3 week^{-1}, separated by 48 h, totalling 6 weeks. During these 6 weeks, the CON group members were asked to maintain their normal daily activities. After the training or the control period, all groups performed the post-test session. All familiarizations, tests and training sessions were performed in an isokinetic dynamometer (Biodex System 3, Biodex Medical Systems, Shirley, N.Y.) (Fig. 1).

Table 1 Physical characteristics for fast-velocity (FV) and control group (CON).

	Age (yr)	Height (cm)	Body weight (kg)
FV (n = 9)	25·5 ± 3·4	178·2 ± 7·0	79·4 ± 11·5
CON (n = 9)	21·0 ± 1·5	176·7 ± 8·8	78·8 ± 12·2

Procedures

Maximal muscle strength testing

Before tests, the subjects completed 5 min of warm-up in a stationary cycle ergometer (Excalibur Sport, Lode B.V., Groningen, Nederland) with 50 W and 70 rpm. Three minutes later, they performed the neuromuscular tests. Subjects were accommodated on the dynamometer chair at the upright sitting position with 85º between the hip and thigh. The femoral lateral epicondyle was aligned to the dynamometer axis of rotation. The subjects were also firmly strapped to the dynamometer with two transversal shoulder to hip belts fixing the trunk, one hip belt and one belt at the distal thigh. The lower leg was fixed to the lever arm of the dynamometer right above the medial malleolus. The isometric test consisted of two maximal isometric contractions (knee extension). The angle between the thigh and leg was 75º (0 = full extension). The time under contraction was 5 s, with 30 s of rest between each contraction. During the tests, the subjects were instructed to do the contraction 'as fast and forcefully as possible'. Strong verbal encouragement was also given to the subjects during the trials.

Data processing and analyses

Torque curves were smoothed by a digital fourth-order zero-lag Butterworth filter with a cut-off frequency of 20 Hz. The

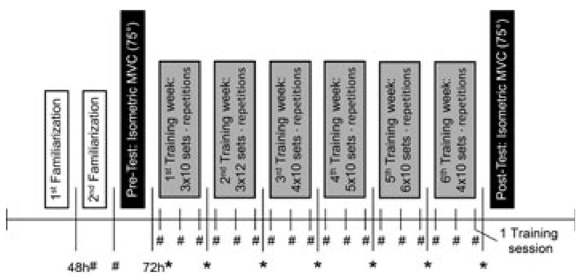

Figure 1 Tests and training protocol timeline. # 48 h interval. * 72 h interval.

contractions with the highest isometric (MVC) torque were chosen for further analysis. RFD was obtained by the isometric contraction slope of the moment–time curve (i.e. Δmoment/Δtime) across time intervals of 0–10, 0–20, …, 0–250 ms relative to the onset of contraction and its peak (RFD_{MAX}). The onset of muscle contraction was defined as the time point where the KE torque exceeded the baseline by 2·5% of the baseline-to-peak difference (Andersen *et al.*, 2010). RFD was also normalized (RFDr) by MVC (%MVC·s^{-1}) and calculated at the same time intervals from the onset of muscle contraction as used for RFD and its peak ($RFDr_{MAX}$).

Training

The training programme had 18 training sessions and was performed 3 · $week^{-1}$ for 6 weeks. Two consecutive or alternate absences were allowed without rescheduling the training session. During concentric isokinetic (180°s^{-1}) knee extension training, subjects were instructed to do each contraction 'as fast and forcefully as possible'. Anatomical 90° of knee flexion was determined by manual measurement using a goniometer, and the range of motion (ROM) determined was 70° (from 90° to 20° knee flexion [0° = full extension]). During the first training week, the sets versus repetitions were 3 × 10. In the second week, there was an increase in two repetitions per set (3 × 12). From the third to fifth week, there was an increase in one set per week, while the number of repetitions was maintained as in the first week (4 × 1s × 10 - 6 × 10). In the last week, the training was the same as in the third week (4 × 10), so the total volume was reduced aiming to generate a training tapering period. During all training sessions, two minutes of interval were adopted between each set.

Statistical analyses

Data are expressed as mean ± SD. Changes in main parameters were analyzed using multivariate analysis of variance with repeated measures. Factors included in model for RFD and RFDr were training period (pre- and post-intervention), group (resistance training and control group) and contraction time (0–10, 0–20, …, 0–250 ms from onset of muscle contraction). Factors included in model for MVC, RFD_{MAX} and $RFDr_{MAX}$ were training period (pre- and post-intervention) and group (resistance training and control group). When appropriate, *post hoc* comparisons were made with the Tukey test. The significance level was set at $P \leq 0{\cdot}05$.

Results

Maximal muscle strength

Figures 2a to 2d represent moment–time curves and relative moment-time curves at pre and post-training periods. There were no significant changes in MVC of knee extensors in both groups (Table 1).

RFD_{MAX} and $RFDr_{MAX}$

There was a significant main effect of training for RFD_{MAX} (F = 10·66, P = 0·004) and $RFDr_{MAX}$ (F = 6·92, P = 0·01). *Post hoc* test showed a significant increase in RFD_{MAX} (1787·2 ± 625·4 to 2899·1 ± 1247·2 N·m·s^{-1}, P = 0·0005) and $RFDr_{MAX}$ (575·6 ± 138·9 to 838·0 ± 259·6%MVC·s^{-1}, P = 0·001) in the resistance training group, whereas no change occurred in the control group (Table 2).

RFD at different times of contraction (0–10, 0–20, …, 0–250 ms)

Figures 3a to 3d represent RFD and RFDr time curves in different times of contraction at pre and post-training periods. There was a significant main effect of training for RFD (F = 2·68, P = 0·00004) and RFDr (F = 2·35, P = 0·0003). *Post hoc* test showed significant increase in RFD at 0–10 ms up

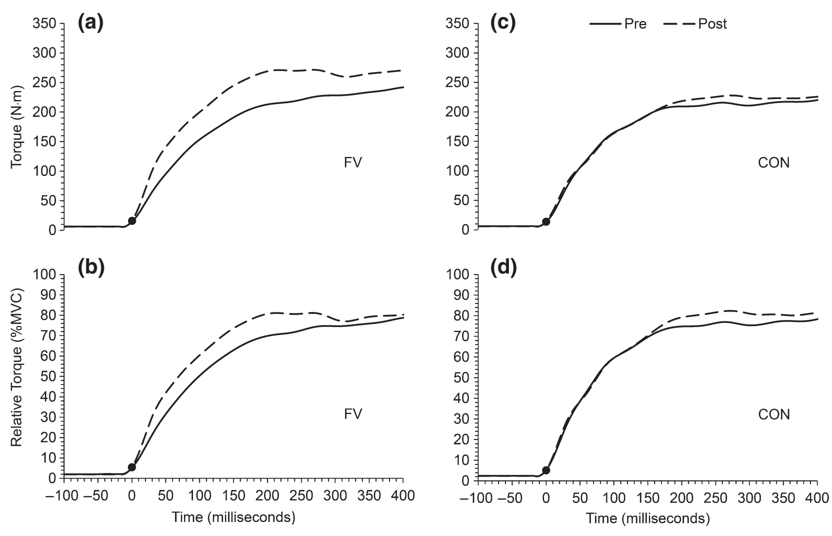

Figure 2 Group mean values of the isometric moment–time curve and relative moment–time curse of fast-velocity training (FV) and control (CON) groups at pre (black line) and post- (dashed line) training or daily activity periods, respectively. ● Onset of muscle contraction (2·5% baseline-to-peak difference).

Table 2 Mean ± SD values of isometric peak torque (MVC), maximum rate of force development (RFD_{MAX}) and maximum relative rate of force development ($RFDr_{MAX}$) for fast-velocity group (FV) and control group (CON) before (Pre) and after (Post) the training period.

	FV (*n* = 9)		CON (*n* = 9)	
	Pre	Post	Pre	Post
MVC (N·m)	314·2 ± 101·1	338·7 ± 88·0	293·9 ± 59·3	329·8 ± 60·4
RFD_{MAX} ($N{\cdot}m{\cdot}s^{-1}$)	1787·2 ± 625·4	2899·1 ± 1247·2*	2072·7 ± 516·4	2200·4 ± 712·6
$RFDr_{MAX}$ (%$MVC{\cdot}s^{-1}$)	575·6 ± 138·9	838·0 ± 259·6*	757·1 ± 218·5	803·0 ± 251·3

*P<0·01 in relation to pre.

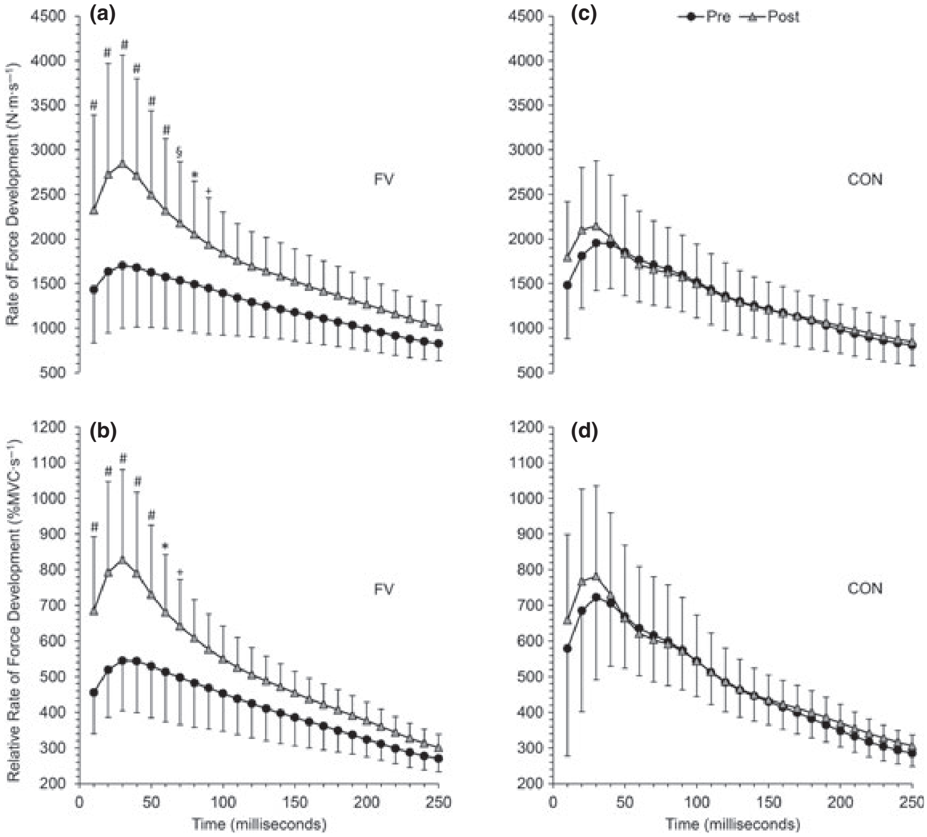

Figure 3 Group mean ± SD values of rate of force development (RFD) and relative rate of force development (RFDr) in different times of contraction rise of fast-velocity training (FV) and control (CON) groups obtained at pre (black circles line) and post- (grey triangles line) training or daily activity periods, respectively. # P<0·00005; § P<0·0001; * P = 0·001; + P<0·05 in relation to pretest.

to 0–90 ms (39·2 ± 22·2–71·3 ± 45·6%, P<0·05) and RFDr at 0–10 ms up to 0–70 ms (33·5 ± 25·5–56·2 ± 43·3%, P<0·05) in the resistance training group, whereas no change occurred in the control group.

Discussion

The principal and original finding of this investigation were the differential changes in early and late RFD after 6 weeks of fast-velocity concentric isokinetic resistance training. Specifically, we verified that RFD and RFDr at an early phase of rising muscle force increased in response to resistance training, whereas both late RFD and late RFDr remained unchanged. Moreover, consistent with previous research (Gruber *et al.*, 2007; Winchester *et al.*, 2008), short-term training for explosive strength (i.e. ballistic strength training) did not modify MVC.

Many studies have reported significant enhancements in RFD_{MAX} measured during KE maximal voluntary isometric contraction, after different resistance training protocols (e.g. traditional, explosive or isometric strength training) (Kubo *et al.*, 2001; Aagaard *et al.*, 2002; Hakkinen *et al.*, 2003). Studies using traditional and isometric strength training have found that RFD_{MAX} increased 28–33% after a relatively short period of time (3–6 weeks) (Holterman *et al.*, 2007; Vila-Chã *et al.*, 2010). It is important to note that in these studies, there was some specificity with respect to the training and testing exercises. In our study, with similar conditions (i.e. time duration and specificity of the test and training exercises), we have found that RFD_{MAX} increased 61%. Thus, fast-velocity concentric isokinetic resistance training, rather than a short period of traditional and isometric strength training, seems to elicit greater enhancement on RFD_{MAX}. Indeed, Duchateaus & Hainaut (1984) found that RFD_{MAX} was augmented to a greater extent by fast ballistic training than isometric training (31 versus 18%).

Our study reveals, for the first time, the differential changes in early and late RFD in response to 6 weeks of fast-velocity concentric isokinetic resistance training. In accordance with the present results, other research groups reported increased early-phase RFD/explosive force in response to both high-intensity (Aagaard *et al.*, 2002) and isometric resistance training (Tillin *et al.*, 2012). Thus, gains in early-phase RFD seem to involve exercises that were executed with maximal intentional acceleration effort regardless of the actual movement velocity (Behm & Sale, 1993; Cutsem *et al.*, 1998).

When normalized to MVC, we have verified that early RFD (i.e. RFDr) increased following training (33–56%), but late RFDr was unchanged. This change in relative RFD properties appears to have resulted from neural adaptations specific to explosive force production. Indeed, Tillin *et al.* (2012) has reported enhanced agonist neural drive in the early contraction phase, following short-term explosive strength training. Specific neural adaptations may include increased motoneuron recruitment and firing frequency and incidence of discharge doublets (Cutsem *et al.*, 1998). Moreover, our data cannot exclude the possible contribution from morphological adaptation induced by fast-velocity concentric isokinetic resistance training. In fact, contractile RFD at the onset of contraction is also influenced by muscle size and fibre-type (myosin heavy chain isoforms) composition (Andersen & Aagaard, 2006). However, Winchester *et al.* (2008) have observed that RFD_{MAX} increased after 8 weeks of ballistic strength training (26–48% 1RM), whereas both MVC and muscle fibre composition remained unchanged.

In the present study, we have found that fast-velocity concentric isokinetic resistance training did not modify both late RFD and MVC. Other studies have also observed that RFD_{MAX} increased in response to short-term explosive strength training (i.e. ballistic strength training), whereas MVC remained unchanged (Gruber *et al.*, 2007; Winchester *et al.*, 2008). In contrast, explosive force (early and late RFD) and MVC have previously been reported to increase in response to 4 weeks of resistance training performed with explosive isometric contractions (1 s 'fast and hard') (Tillin *et al.*, 2012). In this study (Tillin *et al.*, 2012), peripheral adaptations (hypertrophy and increased muscle-tendon unit stiffness) seem to explain the enhanced MVC after merely 4 weeks of training for explosive force production. It therefore appears that a short period of resistance training performed with explosive isometric contractions may provide a more effective stimulus for improving both explosive and maximal force than ballistic strength training. In whole, these results are consistent with previous studies that using different experimental designs (cross-sectional and longitudinal) have demonstrated that contractile RFD obtained in the later phase of rising muscle force was closely related to the magnitude of MVC (Andersen & Aagaard, 2006; Andersen *et al.*, 2010).

The findings of this study may have clinical relevance. Andersen *et al.* (2008) have recently verified that rapid muscle force capacity (i.e. RFD_{MAX}) is more severely impaired (~54%) than MVC (~18%) at conditions of chronic musculoskeletal pain. Thus, it can be interesting to perform resistance training protocols aiming to improve RFD through decreased pain, at painful conditions. Indeed, Andersen *et al.* (2009) have found that traditional strength training (3 × 8–12 RM) increased RFD of chronically painful muscles. Moreover, the pre- to post-intervention change in RFD was significantly correlated with the change in pain ($r = -0{\cdot}42$). Future prospective studies should evaluate the effects of fast-velocity concentric isokinetic resistance training on early and late RFD in rehabilitation settings.

Finally, the overall results of this study cannot necessarily be generalized to all health individuals, particularly for strength-trained athletes. Another limitation of the present study is that tests and training were performed on the same device, which might influence the results due to learning effects. However, the muscle action used during test (isometric) and training (concentric) was different, decreasing, at least in part, the learning effect. Further, RFD was obtained during standardized laboratory conditions. Although isometric RFD has been found to correlate with dynamic functional performance (Jaric *et al.*, 1989), the influence on human movements from the change in RFD can be dependent of the characteristics of the task (e.g. the available time span involved in the explosive movement).

It can be concluded that contractile RFD in the early and later phases of rising muscle force responded differently in response to short period of resistance training performed with concentric fast-velocity isokinetic muscle contractions. This training has induced gain in early RFD, whereas both late RFD and MVC remained unchanged.

Acknowledgments

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Conflict of interest

The authors have no conflicts of interest.

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