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ORIGINAL ARTICLE

The effect of rate of force development on maximal force production: acute and training-related aspects

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Abstract The force generated during a maximal voluntary contraction (MVC) is known to increase by resistance training. Although this increase cannot be solely attributed to changes in the muscle itself, many studies examining muscle activation at peak force failed to detect neural adaptations with resistance training. However, the activation prior to peak force can have an impact on maximal force generation. This study aims at investigating the role of rate of force development (RFD) on maximal force during resistance training. Fourteen subjects carried out 5 days of isometric resistance training with dorsiflexion of the ankle with the instruction to generate maximal force. In a second experiment, 18 subjects performed the same task with the verbal instruction to generate maximal force (instruction I) and to generate force as fast and forcefully as possible (instruction II). The main findings were that RFD increased twice as much as the 16% increase in maximal force with training, with a positive association between RFD and force within the last session of training and between training sessions. Instruction II generated a higher RFD than instruction I, with no difference in maximal force. These findings suggest that the positive association between RFD and maximal force is not causal, but is mediated by a third factor. In the discussion, we argue for the third factor to be physiological changes affecting both aspects of a MVC or different processes affecting RFD and maximal force separately, rather than a voluntary strategic change of both aspects of MVC.

Keywords Rate of force development · Resistance training · Neural adaptation · Instruction · Maximal voluntary contraction

Introduction

Several resistance training studies have observed increased maximal force without being able to specify the physiological processes or mechanisms providing the improvement (Cannon and Cafarelli 1987; Herbert et al. 1998; Holtermann et al. 2005; Jones and Rutherford 1987; Rutherford and Jones 1986; Thorstensson et al. 1976). Many of these studies have focused on muscle activation at the short time period of peak force during a maximal voluntary contraction (MVC). However, this state of maximal tension is not instantaneously reached, and muscle activation prior to maximal force, like doublet discharges and initial firing rate (Burke et al. 1976; Miller et al. 1981), could affect the MVC performance.

The rate of force development (RFD) prior to peak force has been well examined because of its impact on several human movements, e.g., explosive sports (Moritani 2002) and postural balance in elderly (Pijnappels et al. 2005; Thelen et al. 1996). The RFD is known to increase after explosive resistance training (Aagaard et al. 2002; Behm and Sale 1993a; Hakkinen et al. 1985; Hakkinen and Komi 1986; Van Cutsem et al. 1998), and is often attributed to neural factors like increased doublet discharges (Van Cutsem et al. 1998) and firing rate (Patten et al. 2001). However,

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RFD can also be influenced by other physiological factors like muscle cross-sectional area (Narici et al. 1996), muscle fiber type (Burke et al. 1971; Harridge et al. 1996), and properties of the muscle-tendon system (Bojsen-Moller et al. 2005).

A positive association exists between the RFD and maximal force (Mirkov et al. 2004), especially the RFD recorded in the later phase of the MVC (Andersen and Aagaard 2006). In addition, the many studies that observed increases in both maximal force and RFD with resistance training (Aagaard et al. 2002; Behm and Sale 1993a, b; Häkkinen et al. 1985; Häkkinen and Komi 1986; Rich and Cafarelli 2000; Thorstensson et al. 1976; Van Cutsem et al. 1998) have let several researchers to question whether a direct association between maximal force and RFD exists during resistance training (Andersen and Aagaard 2006; Griffin and Cafarelli 2005; Haff et al. 2005). In accordance with this assumption, maximum voluntary contraction with increased RFD has been demonstrated to enhance maximal force generation (Bemben et al. 1990), whereas others failed to demonstrate this (Christ et al. 1993; Sahaly et al. 2001). In addition, the intention to perform an explosive MVC has been suggested to be of major importance to the outcome of resistance training (Behm and Sale 1993a, b). Accordingly, the increased RFD and maximal force induced by resistance training might be caused by a voluntary strategy to generate MVC with high RFD during resistance training.

This study intends to investigate the role of RFD on maximal force during resistance training. The main aim of this study is to examine whether the parallel increase in RFD and maximal force is (a) due to a causal relation, (b) due to a voluntary strategy to increase RFD to gain force, or alternatively, (c) caused by separate physiological factors that increase RFD and maximal force with resistance training. Therefore, in the present study changes in RFD and maximal force of all performed MVC during resistance training were studied to examine the improvement in maximal force generation. Although 4–6 weeks of training is considered to be required to change structural characteristics of a muscle (Akima et al. 1999; Staron et al. 1994), recent studies have indicated that structural changes can occur in shorter time following resistance training (Bickel et al. 2005; Haddad and Adams 2002). Accordingly, the duration of the resistance training was only 5 days with together a total of nine sessions. A second experiment, applying different verbal instructions (i.e., “maximal force” and “as fast and forcefully as possible”), was conducted to evaluate the association between RFD and maximal force in a MVC.

Methods

Training experiment

Fourteen male university students (age 22.0 ± 2.4) volunteered to participate in the training experiment. All subjects were familiar with resistance training in general, but not with the specific training of the dorsiflexors of the ankle. The experiment was approved by the Local Ethics Committee and conducted with in the Declaration of Helsinki.

Prior to training, the subjects received standardized information about the task and performed some practice contractions. Before each training session, the subjects warmed up on a bicycle for 10 min at 50 W. The subject was positioned in a chair with the right foot in a device that fixed the ankle and knee joints at 105°. The hip was strapped to the chair preventing motion at the ankle, knee, and hip joints. Nine training sessions of maximal isometric dorsiflexion of the ankle were carried out during 5 days. In each session, the subject performed five series, each consisting of five trials. In each trial, the subject performed a 4-s maximal isometric dorsiflexion of the ankle. A 15-s rest period was allowed between trials, and 5-min rest periods between series. The instruction to the subjects was to generate maximal force in each trial. On-line information about the generated dorsiflexion torque was provided on an oscilloscope.

Force was recorded during all 225 trials of training. The force data was sampled at 1,000 Hz (Bioware Version 3.21, Kistler Instrument Corp., Amherst, NY, USA). A custom-built device was used in the present study. It consisted of a pedal of which the center of rotation could be aligned with the center of rotation of the talocrural joint in the ankle. The foot was tightly fitted in a shoe attached to the pedal. The force cell was attached with 90° alignment to the pedal recording dorsiflexion torque of the ankle joint only. Parts of these data related to maximal force with training were reported previously (Holtermann et al. 2005).

Instruction experiment

Eighteen male university students (age 23.0 ± 2.7) volunteered to participate in the instruction experiment. They signed an informed written consent prior to participation, and the experiment was conducted within the Declaration of Helsinki. All subjects were familiar with resistance training in general, but not with MVC of the dorsiflexors of the ankle.

The subject was seated in a dynamometer (BIODEX System 3 Pro, Biodex Medical Systems, Shirley,

Table 1 Mean (±SD) and percentage change in Fmax, RFDabs, RFDnorm, and RFDnorm in different time epochs calculated from trials with average values from the first and the ninth session of the training experiment

	Session 1	Session 9	Change (%)
Fmax (Nm)	53.6 (7.23)	62.4 (7.34)	16.9**
RFDabs (Nm s^{-1})	262.0 (60)	408.0 (88)	62.6**
RFDnorm (%Fmax s^{-1})	495.1 (122.0)	653.2 (95.2)	31.9**
RFDnorm 0–50 ms (%Fmax s^{-1})	203.3 (87.7)	260.6 (73.5)	28.2**
RFDnorm 0–100 ms (%Fmax s^{-1})	269.8 (71.5)	380.6 (60.8)	41.1**
RFDnorm 100–200 ms (%Fmax s^{-1})	310.8 (54.1)	402.9 (44.8)	29.6**
RFDnorm 200–300 ms (%Fmax s^{-1})	172.6 (51.8)	123.8 (51.7)	−28.3*
RFDnorm 300–400 ms (%Fmax s^{-1})	88.8 (43.2)	53.9 (21.8)	−39.3*

The RFD is derived from the peak slope in successive 2 ms intervals. The presented RFDnorm in different time epochs was calculated from the mean slope within each time epoch

Statistically significant differences between the first and the last session of training: *$P < 0.05$ and **$P < 0.01$

NY, USA). The right foot of the subject was strapped to a pedal with a broad non-elastic band pulled tightly across the foot, just below the metatarsal-phalangeal joints. As even small divergences between the two devices (e.g., the mechanical stiffness) might have an impact on the RFD recordings in the two experiments, the construction and use of the devices used in the training and the instruction experiments was as similar as possible. The subject was positioned with similar angles in the hip, knee, and ankle as in the training experiment. To get familiar with the experimental task, the subject followed a standardized sinus target of dorsiflexion force followed by a maximal dorsiflexion contraction. Subsequently, the subject was given the instruction to generate three trials of maximal dorsi-flexion force (instruction I). Finally, the subject was given the instruction to generate three trials of maximal dorsi-flexion force "as fast and forcefully as possible" (instruction II). The duration of the MVC with both instructions was 3 s. The subjects were given at least 3 min rest between subsequent contractions and 10 min rest between the instructions.

Data analyses

The force data of all trials from both experiments were analyzed using Matlab software (The MathWorks, Natick, MA, USA) Version 7.0. The force data was low-pass filtered at 20 Hz with an eighth order zero phase lag Butterworth filter. The maximal dorsi-flexion force (Fmax) was calculated as the average value of a period of 0.25 s around the recorded peak force to avoid possible effects of biological jerks in the force data. The RFD was calculated from the peak steepness of the force-time slope in successive 2 ms intervals (+df/dt) from contraction onset to peak force, defined as absolute RFD (RFDabs) (Nm s^{-1}). Examination of a possible physiological association between RFD and maximal force requires that the force and time aspects of a MVC are calculated independently of each other. Therefore, RFD was also calculated from the force-time slope normalized with respect to maximal force for each trial, respectively, defined as normalized RFD (RFDnorm) (%Fmax s^{-1}). Thus, RFDnorm provides information of only the "time-related aspect" of the force slope, whereas RFDabs provides information of both changes in absolute force and in time of the MVC. In addition, step-wise RFD was calculated from 0 to 50 ms, and in 100 ms time epochs from 0 to 400 ms. The contraction onset was set to the sample when the force exceeded a pre-defined baseline of 2.5 Nm (for RFDabs) or by 2.5% of the difference between baseline and maximal force (for RFDnorm) (cf. Aagaard et al. 2002). The changes in strength with training were derived from the trial with the highest Fmax of each session. The changes in RFD with training were derived from the trial with the highest RFD of each session. The changes in Fmax and RFD with different instructions were derived from average values from the three performed contractions of each instruction. Therefore, to be able to compare data from the training and instruction experiments and to illustrate changes in performance of all trials with training, both average strength and average RFD were calculated from all 25 trials of each session and presented in Tables 1 and 2. To examine the association between Fmax and RFDnorm normalized to maximal values of each subject, linear regression lines for each subject were obtained for all trials within each session, and between the trials with the maximal force of each session of training.

Statistical analysis

The statistical analyses were carried out to test changes in force and RFD with training and with different instructions, differences in RFD between the two

Table 2 Mean (±SD) and difference in Fmax, RFDabs, RFDnorm, and RFDnorm in different time epochs calculated from trials with average values of instruction I and instruction II

	Instruction I	Instruction II	Difference (%)
Fmax (Nm)	46.1 (10.5)	45.3 (10.5)	−0.8
RFDabs (Nm s^{-1})	230.2 (70.5)	300.4 (110.3)	30.5**
RFDnorm (%Fmax s^{-1})	476.4 (97.6)	583.7 (109.0)	22.5*
RFDnorm 0–50 ms (%Fmax s^{-1})	210.0 (67.0)	253.0 (79.3)	20.5**
RFDnorm 0–100 ms (%Fmax s^{-1})	262.3 (81.3)	320.4 (89.3)	22.1**
RFDnorm 100–200 ms (%Fmax s^{-1})	298.8 (88.7)	314.9 (82.7)	5.4
RFDnorm 200–300 ms (%Fmax s^{-1})	159.4 (59.3)	109.2 (53.3)	−31.1**
RFDnorm 300–400 ms (%Fmax s^{-1})	72.0 (42.6)	33.4 (30.2)	−53.6**

The RFD and RFDnorm are derived from the peak slope in successive 2 ms intervals. The presented RFDnorm in different time epochs was calculated from the mean slope within the given time epochs

Differences between instructions: *$P < 0.05$ and **$P < 0.01$

experiments, the association between force and RFD within and between training sessions, and changes in RFD at different time epochs with training and different instructions. The difference in force, RFD, and RFD at different time epochs with training (session 1 versus session 9) and instructions (instruction I versus instruction II) were tested with Student's *t*-test for paired samples. Student's *t*-test for independent samples was used to test differences between the two experiments. The linear regression lines representing the association between RFD and force in each session and across training sessions were tested with Student's *t*-test for paired samples against zero. Pearson's correlation coefficient (r) was calculated between RFDnorm and force in each session and across training sessions. In addition, the test-retest reliability of Fmax, RFD, and RFD at different time epochs was estimated with intra-class correlation coefficient (R) from the trials with highest values from the first and second session of training and within-subject coefficient of variation (CV) from the first five trials from the first session of training, respectively. CV was defined as SD/mean × 100.

Results

Training experiment

Reliability, as estimated with intra-class correlation coefficients from the first and second session of training was $R = 0.97$ for Fmax, $R = 0.90$ for RFD, and $R > 0.91$ for RFD at the different time epochs. The within-subject CV of the first five trials from the first session of training was 2.7 (1.0)% for Fmax, 8.8 (3.9)% for RFD, and <7.9% for RFD at the different time epochs.

As shown in Fig. 1, the Fmax increased 15.7% from 59.6 Nm (SD ± 7.5) in the first session to 68.7 Nm (SD ± 7.7) in the last session of training ($P < 0.01$) (previously published in Holtermann et al. 2005).

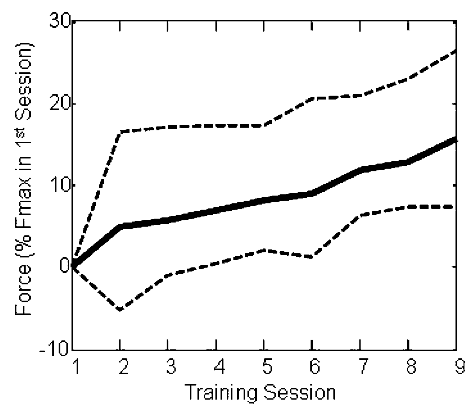

Fig. 1 **a** Change in Fmax with training, averaged across subjects per training session. The force is normalized to Fmax in session 1. *Solid line* represents mean value, *dotted lines* represent ±SD

Even though the instruction to the subjects during training was to generate maximal force, the RFDabs increased 53.2% with training from 369 Nm s^{-1} (SD ± 81) in the first session to 533 Nm s^{-1} (SD ± 136) in the last session ($P < 0.01$) (Fig. 2a). This cannot be solely explained by the increase in maximal force, as RFDnorm increased 20.6% with training ($P < 0.05$) (Fig. 2b). Figure 3 shows a typical example of the increased force and steepness of the force-time slope with training.

The increase in RFDnorm with resistance training was dependent on the time epoch during the MVC (Table 1). The RFDnorm increased in the early phase (prior to 200 ms) of the contraction ($P < 0.05$). However, it decreased in the late phase of the MVC (Table 1).

Figure 4 shows, with a typical example from one subject, force against RFD for all performed trials during the period of resistance training. This figure shows

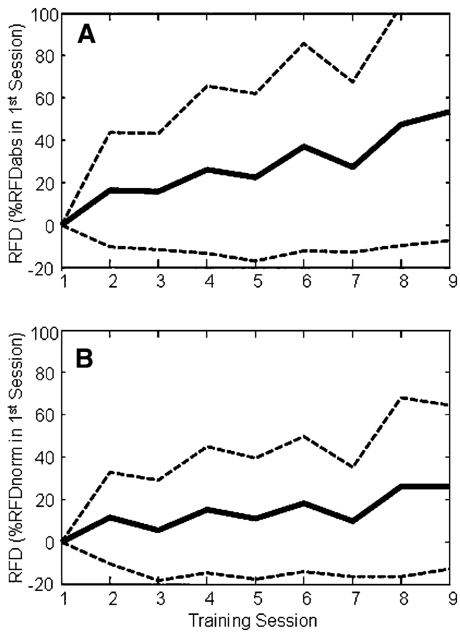

Fig. 2 **a** Change in RFDabs with training, averaged across subjects per training session. **b** Change in RFDnorm with training, averaged across subjects per training session. Both RFD variables are normalized to the trial with maximal RFD in session 1. *Solid line* represents mean value, *dotted lines* represent ±SD

how the relation between these two variables changes during the nine sessions of training. Taking all subjects into account, the association between RFDnorm and Fmax in the first session of training was not significant [mean $r = 0.04$ (SD 0.38), $P = 0.64$]. There was, however, a low but significant positive association between RFDnorm and Fmax in the last session of training [mean $r = 0.36$ (SD 0.31), $P < 0.05$].

When only the trial with Fmax from each of the nine sessions of all subjects was included in the regression analysis, the association between Fmax and RFDnorm was positive and significant [mean $r = 0.48$ (SD 0.33), $P < 0.05$].

Instruction experiment

When the subjects were instructed to first generate three trials of maximal force (instruction I) and subsequently generate three trials as fast and forcefully as possible (instruction II), there was no significant influence of the instructions on the Fmax ($P = 0.8$) (Table 2). In contrast, instruction II caused a significantly higher RFDabs ($P < 0.01$) and RFDnorm ($P < 0.05$) compared to instruction I. However, instruction II only showed increased RFDnorm in the early phase (the first 100 ms) of the contraction, whereas instruction I provided the highest RFDnorm in the later phase of the MVC (after 200 ms) (Table 2).

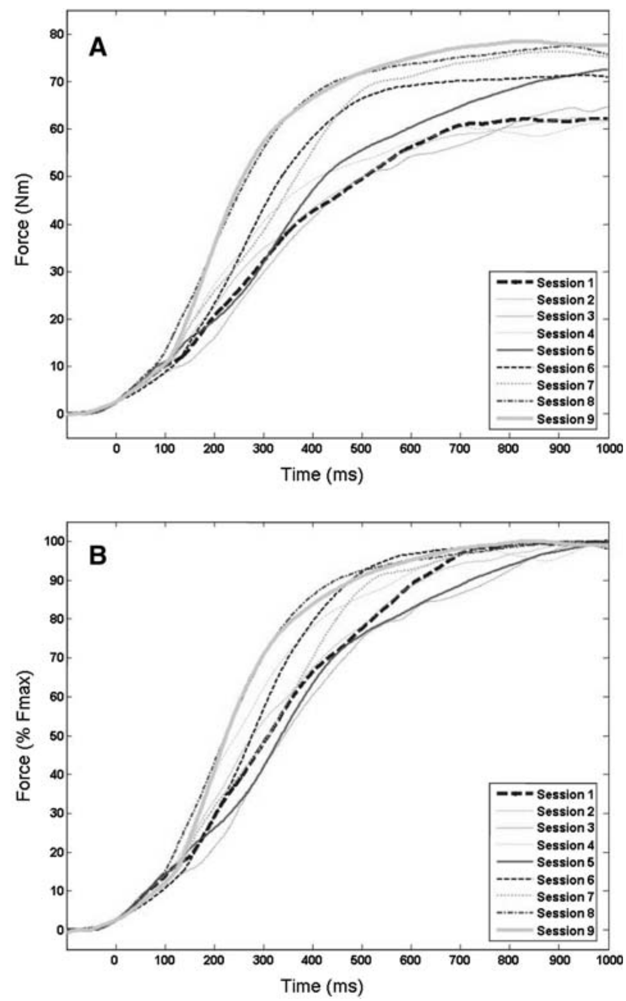

Fig. 3 A typical example from one subject of the trial with Fmax of each session. **a** Absolute force slopes, and **b** force slopes normalized to Fmax of each trial. The curves were aligned at the time epoch when the force exceeded the baseline by 2.5 Nm in the absolute force slopes and 2.5% MVC in the normalized force slopes

Comparison of training and instruction experiment

When comparing data from the first experiment involving 5 days of resistance training and the second experiment concerning acute effects of different verbal instructions on maximal force and RFD, neither the RFDnorm, nor the RFDnorm in the different time epochs from the first training session were significantly different from the RFDnorm of instruction I (Tables 1, 2). In contrast, the RFDnorm and the RFDnorm from 0 to 100 ms and from 100 to 200 ms of the last training session were significantly higher than the RFDnorm of instruction II ($P < 0.05$).

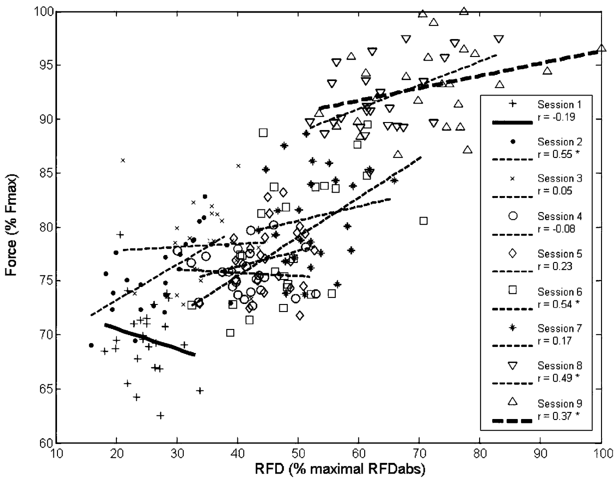

Fig. 4 A typical example from one subject of the association between force and RFD of all trials. The trials of each session are represented with *different symbols*, with a linear regression line for each respective session. The force was normalized to Fmax and RFD was normalized to maximal RFD. Pearson's correlation coefficient (r) between force and RFD is presented for each session. $*P < 0.05$

Discussion

The aim of this study was to investigate whether the muscle contraction prior to peak force could have an impact on the increased strength with short-term resistance training. Although the purpose of the resistance training was to improve maximal force, RFD increased to a larger extent (Figs. 1, 2, 3), consistent with previous reports (Hakkinen et al. 1985; Van Cutsem et al. 1998). In addition, there was a weak positive association between maximal force and RFDnorm across trials within the last training session, and across trials of maximal force from each training session, but not within the first session of training (Fig. 4). This association between RFD and maximal force can be (1) causal or (2) mediated by a third factor (confounder). More specifically, the third factor mediating the increased RFD and positive association between RFD and maximal force with resistance training can be (2a) a chosen strategy by the subjects that directly provides improved maximal force or indirectly enhances maximal force through optimization of the resistance training. Or, alternatively, (2b) the training event can cause physiological changes that increase both RFD and maximal force production. This can either be one group of physiological changes affecting both aspects of an MVC or different processes that affect RFD and maximal force production separately.

Direct causal relation

In accordance with previous studies (Sahaly et al. 2001), the instruction experiment revealed that the RFD can be increased by verbal instruction during an MVC (Table 2). This may lead one to suggest that the RFD can be enhanced by voluntary command throughout the training period as well. The early deficit in RFD when the verbal instruction focused on the generation of maximal force might partially explain the large increase in RFD with training. However, the increased RFD by verbal instruction did not have a positive effect on maximal force, a finding consistent with prior research (Christ et al. 1993; Sahaly et al. 2001). Therefore, the hypothesis of a direct causal relation between RFD and maximal force can be rejected.

Change in strategy

The finding that increased RFD by verbal instruction was not associated with an increase in maximal force also refutes the hypothesis that the increased RFD with training was caused by a change in strategy during MVC to directly obtain an increased maximal force. A second line of argumentation for increasing RFD in order to improve maximal force is that the intention to generate an explosive force might optimize the improvement in RFD due to the resistance training (Behm and Sale 1993a, b), and would thereby indirectly enhance maximal force throughout training. However, a change to this strategy requires a positive association between RFD and maximal force to enable the subjects to discover and exploit this association during resistance training. Since the variation in RFD was not related to maximal force in the first training session (Fig. 4), although no statistical comparison was made, the trend of increases in RFD already in the initial sessions of training (Fig. 2) is unlikely to be caused by a changed strategy during MVC. These findings argue against the hypothesis that the increased RFD with resistance training might have been due to a voluntary change in strategy during MVC.

Physiological changes

After nine training sessions with focus on maximal force generation, the RFD increased to significantly higher values than observed in non-trained subjects focussing on maximal RFD (Tables 1, 2). This suggests that the increased RFD was mainly due to physiological adaptations from the performed resistance training. The parallel increase in both RFD and maximal force with training (Figs. 1, 2), and the weak but positive association between RFD and maximal force across the sessions of training, suggest that the resistance training provided physiological adaptations that increased both RFD and maximal force production. In addition, the changes from no association in the first session to a significant positive relation in the last session of training indicate that physiological adaptations that affect both RFD and maximal force occurred with training. However, the experimental design of the present study precludes the conclusion as to whether it is a group of physiological changes that affect both aspects of a MVC, or different processes that affect RFD and maximal force production separately.

A wide range of physiological factors that change with resistance training might be underlying the increased RFD and maximal force with resistance training. However, the short duration of the training experiment eliminates all factors related to structural changes of the muscle, as there require at least 4–6 weeks of training (Akima et al. 1999; Staron et al. 1994). Furthermore, because the activation level of the involved muscles at peak force recorded with sEMG in this training experiment could not explain the improved strength (Holtermann et al. 2005), the increased force could not have been provided by neural adaptations causing modified surface EMG level, i.e., recruitment of motor units and increased firing rate.

The most plausible neural adaptations that could provide the increased RFD and maximal force in this study are doublet discharges (Burke et al. 1976), enhanced initial firing rate (Binder-Macleod and Barrish 1992), and decreased recruitment threshold of motor units (Keen et al. 1994). All of these physiological factors are likely candidates to enhance both RFD and maximal force generation (Buller and Lewis 1965; Burke et al. 1976; Grimby et al. 1981; Miller et al. 1981). Muscle contractions with high-initial motor unit firing rate (Desmedt and Godaux 1977) and presence of doublet discharges (Gurfinkel et al. 1972) have been shown to generate high-contractile RFD. Furthermore, it has been shown that resistance training provides increases in all of these physiological factors (Van Cutsem et al. 1998). This makes these three physiological factors likely candidates for the increased strength throughout the 5 days of resistance training. Another frequently mentioned neural factor that could contribute to increased strength with resistance training is synchronization of motor unit discharges (Behm and Sale 1993b; Enoka 1997; Semmler and Nordstrom 1998). However, although motor unit synchronization has been suggested to increase RFD (Semmler 2002), the only observed effect on RFD from synchronization is negative (Miller et al. 1981) and there is no documentation that motor unit synchronization can directly enhance RFD or maximal force.

Practical implications

As recordings and subsequent interpretation of the performance during resistance training are relatively rare, the findings from this study might have some practical implications regarding resistance training. In this study, both RFDabs (Nm s^{-1}) and RFDnorm (%Fmax s^{-1}) were calculated and presented as these two variables contain different information. The change in RFDabs contains information about both the force and time aspects of the MVC, and is an important parameter in explosive movements (Zatsiorsky 2002). The RFDnorm gives information about the time aspect of the force-time slope alone, and is useful to study physiological mechanisms influencing the maximal rate of tension independent of the maximal generated force. However, the RFDnorm cannot be applied directly to human movement. The approximately twice as high increase in percentage RFDabs compared with percentage RFDnorm (Table 1), caused by the approximately twice as high-relative increase in RFDabs compared with Fmax (Table 1) shows that change in maximal force is an important component to the enhanced RFD with resistance training. Therefore, contrary to other studies (Hakkinen et al. 1985), the findings from this study indicate that maximal resistance training is useful to improve RFD (e.g., Aagaard et al. 2002; Barry et al. 2005; Hakkinen et al. 1998; Suetta et al. 2004). However, the direct effect on human movements from the change in RFD depends on numerous characteristics of the task, e.g., the available time span to generate force (Zatsiorsky 2002).

Behm and Sale (1993a, b) suggested that the intention to generate an explosive force optimizes the gain in RFD induced by resistance training. This study cannot reject this hypothesis directly, but the findings show that subjects do not need instructions regarding the “explosiveness” of the performed resistance training to attain significant gains in both maximal force and RFD in the same task. In addition, even though the instruction during resistance training only referred to maximal force, the subjects increased RFD after a few sessions of training.

Methodological limitations

The training and instruction experiments were carried out on different experimental devices using different subjects. However, quite similar construction and fastening of the subject to the devices, and use of subjects with similar age, experience with resistance training, and body position during MVC, make it possible to compare the results from the two experiments.

A methodological limitation of the study is the lack of control group and familiarization prior to the pre-training test. Our results show a lack of causality between the increases in RFD and maximal force, but whether or not these increases are caused by training cannot be definitely concluded without a control group. However, because the subjects were experienced with resistance training in general, performed practice contraction prior to the pre-training test and attained good reproducibility of all performance variables makes the effect of lack of familiarization on the findings of this study very small. This is supported by the high ICC-values and low CV's seen from training sessions 1–2. Therefore, we trust our results and conclusions in that the changes in RFD and maximal force are due to training and not due to a lack of familiarization.

To be able to examine the influence of different strategies during MVC and compare the results between the experiments, the instruction given in the training experiment (instruction I) needed to be presented first in the instruction experiment as well. However, the long rest between contractions (3 min) and between instructions (10 min), in addition to the significant increase in RFD in instruction II, indicates that fatigue could only have a minor effect on MVC of instruction II, and not to such an extent that it significantly influenced the results.

Conclusion

Parallel increases in maximal force and RFD with resistance training have been reported before, but the association between these two aspects of an MVC during resistance training was unknown. The findings from this study indicate that the positive association between RFD and maximal force is not causal but mediated by a third factor. Although the instruction to produce maximal force during MVC affords the subject to vary RFD, the increased RFD with resistance training in this study is likely to be caused by factors also responsible for the gain in maximal force. Even though the experimental design of this study cannot provide definite conclusions as to whether the increased RFD and maximal force are mediated by one group of physiological changes affecting both aspects of a MVC, or by different processes that affect RFD and maximal force separately, changes in doublet discharge firing and/or initial MU firing rate seem to be the most likely candidates for the increase in RFD and maximal force with resistance training. In order to establish whether the gains in RFD and maximal force are due to common or separate physiological factors, we recommend a study that records several physiological factors that are known to adapt with resistance training, and examine the association between the change of each physiological factor with the change in RFD and maximal force with resistance training.

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