Influence of maximal muscle strength and intrinsic muscle contractile properties on contractile rate of force development

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2 authors:


Lars Louis Andersen
National Research Centre for the Working Environment


Per Aagaard
University of Southern Denmark

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ORIGINAL ARTICLE

Lars L. Andersen · Per Aagaard

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Abstract 'Explosive' muscle strength or contractile rate of force development (RFD) is a term to describe the ability to rapidly develop muscular force, and can be measured as the slope of the torque–time curve obtained during isometric conditions. Previously, conflicting results have been reported regarding the relationship between contractile RFD and various physiological parameters. One reason for this discrepancy may be that RFD in various time intervals from the onset of contraction is affected by different physiological parameters. The aim of the present study was to investigate the relationship between voluntary contractile RFD in time intervals of 0–10, 0–20,..., 0–250 ms from the onset of contraction and two main parameters: (1) voluntary maximal muscle strength and (2) electrically evoked muscle twitch contractile properties. The main finding was that voluntary RFD became increasingly more dependent on MVC and less dependent on muscle twitch contractile properties as time from the onset of contraction increased. At time intervals later than 90 ms from the onset of contraction maximal muscle strength could account for 52–81% of the variance in voluntary RFD. In the very early time interval (< 40 ms from the onset of contraction) voluntary RFD was moderately correlated to the twitch contractile properties of the muscle and was to a less extent related to MVC. The present results suggest that explosive movements with different time spans are influenced by different physiological parameters. This may have important practical implications when designing resistance training programs for specific sports.

L. L. Andersen (✉) · P. Aagaard
Institute of Sports Medicine Copenhagen/Team Danmark
Testcenter, Bispebjerg University Hospital, Build. 8,
2nd floor, DK-2400 Copenhagen, Denmark
E-mail: ll_andersen@yahoo.dk
Tel.: +45-3531-6086
Fax: +45-3531-6097

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Introduction

'Explosive' muscle strength or contractile rate of force development (RFD) is a term to describe the ability to rapidly develop muscular force (Aagaard et al. 2002). In vivo contractile RFD can be defined as the slope of the torque–time curve (Δtorque/Δtime) obtained during isometric conditions. In a range of sports involving explosive movements (e.g. sprint running, karate, jumping), the time allowed to exert force is typically very limited (∼50–250 ms). In contrast, longer time is needed to reach the maximum muscular force (> 300 ms) (Thorstensson et al. 1976). Thus, in certain sports a high contractile RFD exerted during the initial phase of muscular contraction may be of vital importance for successful performance. Among the physiological factors that can affect RFD are muscle fiber type and myosin heavy chain (MHC) composition (Harridge et al. 1996), muscle cross sectional area (Aagaard and Thorstensson 2003), maximal muscle strength (Schmidtbleicher 1992), visco-elastic properties of the muscle–tendon complex (Bojsen-Moller et al. 2005; Wilkie 1949) and neural drive to the muscle (Aagaard et al. 2002; Grimby et al. 1981). It can be speculated that RFD in various time intervals from the onset of contraction may be affected differently by these parameters. Cross bridge cycling rate of type IIA and particularly type IIX muscle fibers markedly exceeds that of type I muscle fibers (Bottinelli et al. 1996, 1999), which may be especially important in the very early phase of muscle contraction. Thus, a close association between muscle fiber type composition and peak RFD during electrically evoked tetanic contraction (20–40 ms from the onset of contraction) has been documented previously (Harridge et al. 1996). Further, maximal muscle strength and muscle size also influence RFD. For instance, some training studies have reported parallel changes in maximal muscle strength and contractile RFD measured in time intervals of 150–250 ms from the onset of contraction (Aagaard et al. 2002; Hakkinen et al. 1981, 1985a, b; Narici et al. 1996; Thorstensson et al. 1976). Thus it appears that two main physiological parameters, that is maximal muscle strength and the intrinsic contractile properties, are especially important with regard to voluntary contractile RFD. However, the relationship between these parameters and RFD in various time intervals from the onset of contraction has not been thoroughly investigated. It is important to investigate this since different types of explosive movements involve different time spans (e.g. unloaded kick ~80 ms vs. vertical jump ~250 ms), and may thus be affected by different physiological parameters. Based on the above studies it can be hypothesized that contractile RFD during the very early phase of muscle contraction (< 50 ms) would be related to the intrinsic contractile properties of the muscle, whereas RFD during later time intervals (i.e. 150–250 ms) would be related more closely to the maximum muscle strength.

To investigate this hypothesis we determined the relationship between voluntary contractile RFD in various time intervals from the onset of contraction and two main parameters: (1) voluntary maximal muscle strength and (2) electrically evoked muscle twitch contractile properties.

Methods

Subjects

Twenty-five healthy sedentary male subjects (23 ± 3 years, 181 ± 7 cm, 75.7 ± 7.9 kg, mean ± SD) with no previous history of knee injuries participated in the present study. Most subjects were students at the University of Copenhagen. All subjects gave written informed consent to participate in the study, which was approved by the local Ethics Committee.

Force sampling

Voluntary and evoked muscle force was measured in a custom made setup where the subjects were seated in an upright position with back support and the hip and knee flexed 90°. A steel cuff was strapped around the lower leg, approximately 2 cm above the medial malleoli and was connected via a rigid steel bar to a strain gauge load cell (Bofors KRG-4, Bofors, Sweden), which was connected to a pre-amplifier (BK15, Nobel Elektronik, Denmark) and an amplifier (Gould 5900, Gould Inc. Valley View, OH, USA). The strain gauge signal was sampled at 1,000 Hz into a stationary computer using an external A/D-converter (DT9804, Data Translation, Marlboro).

Evoked muscle contractile properties

Electrically evoked contractile properties of the vastus lateralis muscle were determined when the subjects were at rest. Surface stimulation electrodes (Bioflex, model PE3590) were placed over the distal and proximal part of the vastus lateralis muscle. Twitch contractions were evoked on the passive muscle using electrical stimulation consisting of single square wave pulses of 0.1 ms duration delivered by a direct current stimulator (Digitimer Electronics, model DS7). Stepwise increments in the current were delivered, separated by rest periods of 30 s, until no further increase in twitch amplitude was seen (Harridge et al. 1996), and then three maximal twitches were obtained. Offline analysis was performed in Excel using custom made macros developed in Visual Basic (Microsoft Corp.). The twitch force signal was multiplied by the lever arm length to obtain the knee joint torque. The lever arm length was determined as the distance from the lateral femur epicondyle to the middle of the steel cuff. The signal was digitally lowpass filtered at 20 Hz, using a fourth-order zero phase lag Butterworth filter (Winter 1990). The following twitch characteristics were determined (Fig. 1): (1) peak twitch rate of force development (tRFD) which was determined as the peak slope of the rising part of the twitch curve derived in successive 2 ms intervals, (2) twitch time to peak torque (TPT) defined as the time elapsed from onset (1% of twitch amplitude) to the peak torque (PT), (3) half relaxation time (1/2RT) defined as the time elapsed from the peak twitch torque to 50% peak twitch torque and (4) twitch PT defined as the baseline-to-peak twitch amplitude. The average value of three maximal twitches was used for the correlation analysis.

Voluntary RFD and MVC

After a few submaximal habituation trials, four maximal attempts were performed at a static knee joint angle of 90°. The subjects were instructed to extend their knee "as fast and hard as possible" (Bemben et al. 1990; Sahaly et al. 2001). Each maximal voluntary isometric contraction was sustained for approximately 3 s with a rest period of 60 s in between. Strong verbal encouragement was given by the test leader in each trial. Online visual feedback of the strain gauge signal was provided to the subjects on a computer screen. Trials with an initial counter movement were discarded and an extra trial was performed (Grabiner 1994). Offline analysis was performed in Excel using custom made macros developed in Visual Basic (Microsoft Corp.). The force signal was multiplied by the lever arm length to obtain the knee joint torque, and was subsequently digitally lowpass filtered at 20 Hz, using a fourth-order zero phase lag Butterworth filter (Winter 1990). MVC was defined as the highest PT value of the

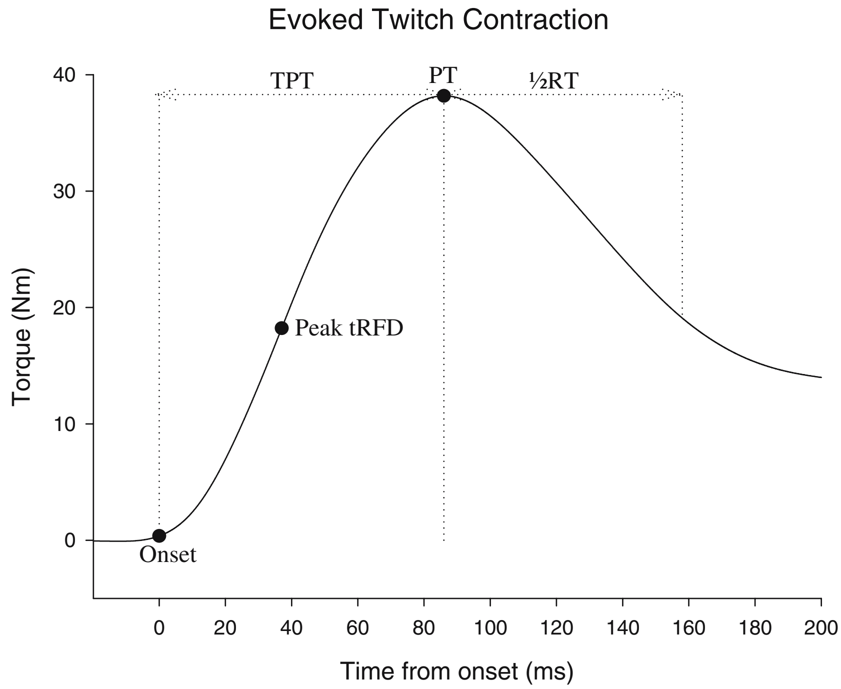

Fig. 1 A twitch recording from one of the subjects. The twitch time to peak torque (*TPT*), peak torque (*PT*), half relaxation time (*1/2RT*) and peak twitch rate of force development (*peak tRFD*) were determined

four maximal attempts (Fig. 2). Contractile RFD was defined as the slope of the torque–time curve (i.e. Δtorque/Δtime) in incrementing time periods of 0–10, 0–20, 0–30,..., 0–250 ms from the onset of contraction (Fig. 2). Onset of contraction was defined as the instant when the knee extensor torque exceeded the baseline by 7 1/2 Nm to obtain a robust onset of force (Aagaard et al. 2002).

Statistics

Pearson's product moment correlation coefficient (r) was calculated to determine the association between main parameters. For correlation analysis MVC and RFD were normalized relative to bodyweight to avoid the opinion that the results merely reflected differences in body size between the subjects. The explained variance

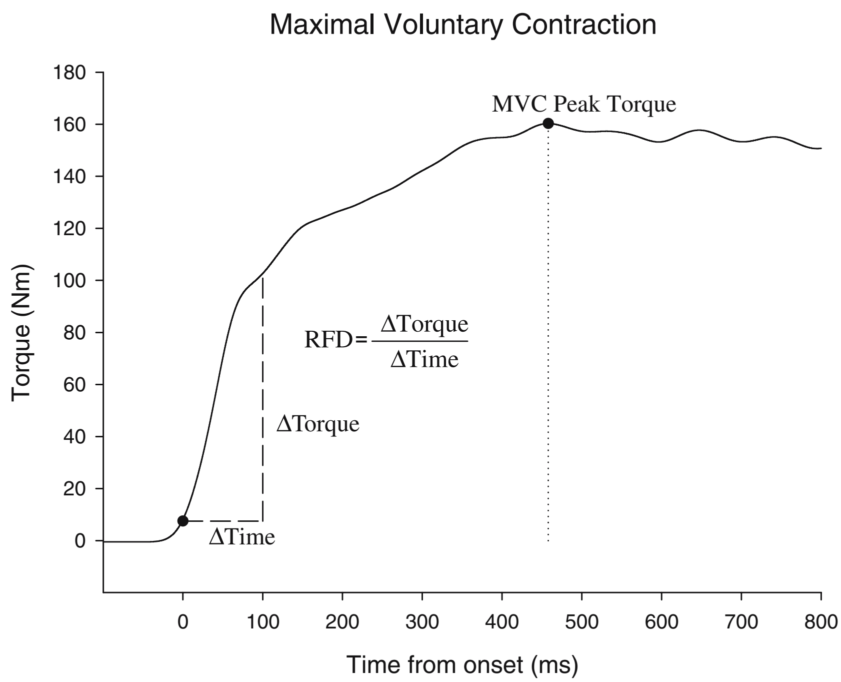

Fig. 2 A maximal voluntary contraction from one of the subjects. Maximal muscle strength was determined as the PT and rate of force development (*RFD*) was determined as the slope of the torque–time curve in intervals of 0–10, 0–20,..., 0–250 ms from the onset of contraction (shown here for RFD at 0–100 ms)

was calculated as the correlation coefficient raised to the second power (r^2).

Results

Examples of correlations between the main parameters are given in Figs. 3 and 4. Mean values of the main parameters are reported in Table 1.

In general a moderate to strong relationship was found between voluntary RFD and MVC. The correlation coefficient between these parameters increased as the time from the onset of contraction increased (Fig. 5). A strong correlation between these variables was obtained when voluntary RFD was determined in time intervals later than 90 ms from onset (Fig. 5) where the explained variance exceeded 50% (Fig. 6).

A moderate relationship was found between twitch RFD and voluntary RFD in the very early phase of contraction (up to 50 ms). The correlation coefficients between these parameters decreased as the time from onset increased and was non-significant when RFD was determined in time intervals later than 50 ms from the onset (Fig. 5).

In the time interval up to 40 ms from the onset of contraction the relationship between voluntary RFD and twitch RFD was stronger than between voluntary RFD and MVC, whereas at longer contraction times this relationship was reversed (Fig. 5).

Twitch TPT, (1/2)RT and PT did not show any significant correlation with voluntary RFD (r = −0.26–0.11 (n.s.), r = −0.10–0.01 (n.s.) and r = 0.01–0.14 (n.s.), respectively).

Discussion

In the present study we investigated the relationship between voluntary contractile RFD at different time intervals relative to the onset of contraction and maximal muscle strength (MVC) as well as electrically evoked muscle twitch contractile properties. The main finding was that voluntary RFD became increasingly more dependent on MVC and less dependent on twitch RFD as the time from the onset of contraction increased (Fig. 5). At time intervals later than 90 ms from contraction onset maximal muscle strength could account for 52–81% of the variance in voluntary RFD (Fig. 6).

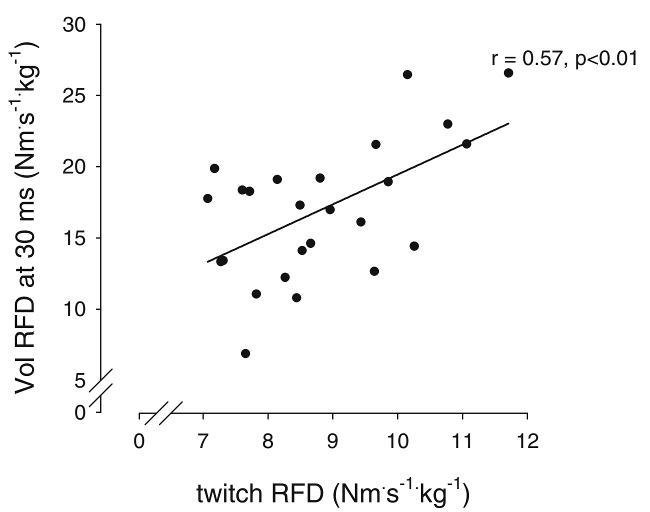

Fig. 3 Relationship between voluntary RFD at 30 ms from the onset of contraction and twitch RFD

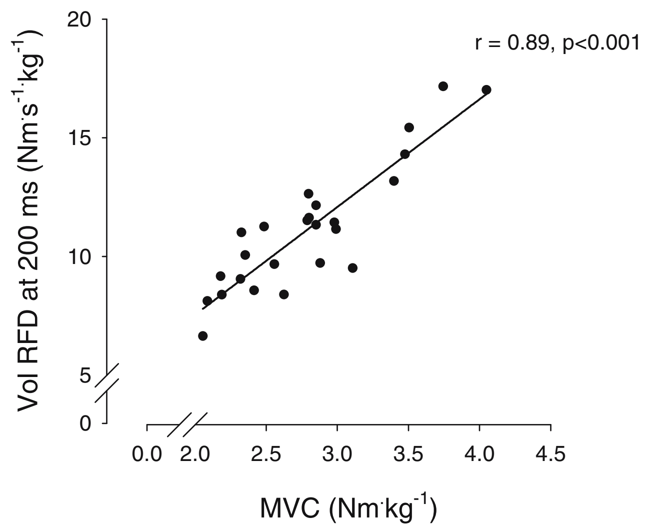

Fig. 4 Relationship between voluntary RFD at 200 ms from the onset of contraction and MVC

Relationship between maximal muscle strength and RFD

Numerous previous studies have investigated the relationship between maximal muscle strength and measures of explosive muscle strength. Muscular power was found to be moderately to strongly related to maximal muscle strength (Bell et al. 1989; Jensen et al. 1996; Stone et al. 2003). Also, functional measures of explosive muscle performance such as maximal jumping ability (Birch et al. 1994; Paasuke et al. 2001) and 100 m sprint time (Meckel et al. 1995) have been positively associated with maximal muscle strength. However, yet other studies have found poor correlations between maximal muscle strength and functional performance (Kukolj et al. 1999; Pincivero et al. 1997). Moderate to strong correlations have been demonstrated between maximal muscle

Table 1 Group mean values ± SD (n=25)

Twitch peak RFD (Nm s^{-1})	661 ± 102
TPT (ms)	88 ± 6
PT (Nm)	41 ± 11
1/2RT (ms)	75 ± 16
MVC (Nm)	211 ± 49
Vol RFD 0–50 ms (Nm s^{-1})	1,519 ± 380
Vol RFD 0–100 ms (Nm s^{-1})	1,316 ± 275
Vol RFD 0–200 ms (Nm s^{-1})	842 ± 224

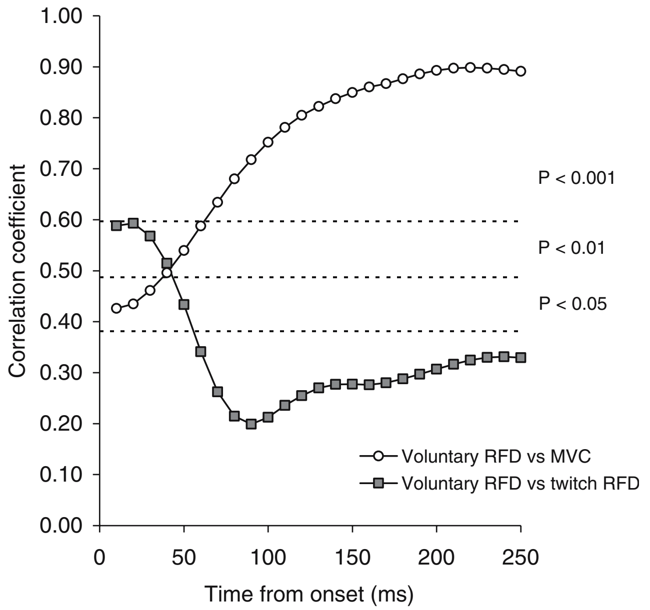

Fig. 5 Correlation coefficients between voluntary RFD and MVC (*open circles*), and between voluntary RFD and twitch RFD (*filled squares*), with voluntary RFD measured in time intervals of 0–10, 0–20,..., 0–250 ms from the onset of contraction. *Dotted lines* indicate the levels of significance

strength and voluntary isometric RFD (Driss et al. 2002; Mirkov et al. 2004). Likewise, resistance training studies that reported increases in maximal muscle strength also found increases in RFD measured in time intervals of 150–250 ms from the onset of contraction (Aagaard et al. 2002; Hakkinen et al. 1981, 1985a, b; Narici et al. 1996; Thorstensson et al. 1976). In contrast, the majority

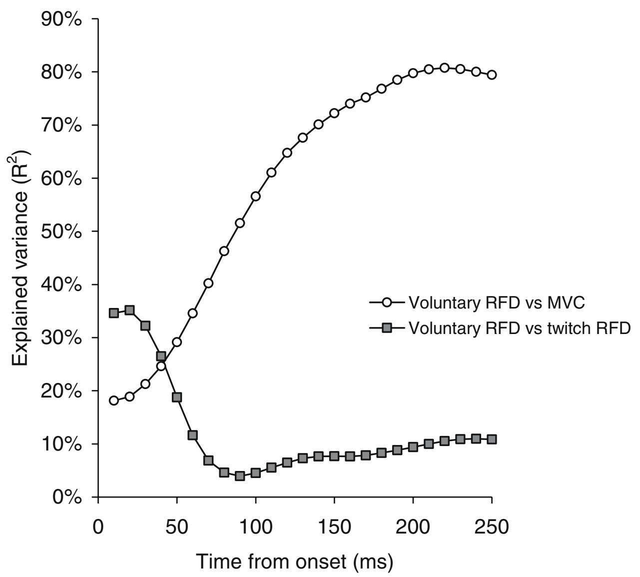

Fig. 6 Explained variance between voluntary RFD and MVC (*open circles*), and between voluntary RFD and twitch RFD (*filled squares*), with voluntary RFD measured in time intervals of 0–10, 0–20,..., 0–250 ms from the onset of contraction

of resistance training studies that found increases in maximal muscle strength found no change in RFD in the very initial phase of contraction (20–40 ms from onset) (Hakkinen et al. 1985a, 1998), although one study did (Aagaard et al. 2002). Likewise, a recent study demonstrated that peak velocity and acceleration of maximal unloaded knee extension (which is achieved in approximately 80–90 and 30–35 ms, respectively) remained unchanged in response to resistance training in spite of increased maximal muscle strength (Andersen et al. 2005). The present results suggest that the discrepant findings mentioned above regarding the association between maximal and explosive muscle strength could at least in part be explained by the different methods of analyzing RFD, i.e. the time interval in which RFD is determined. Thus, while maximal muscle strength in the present study accounted for approximately 80% of the total variance in voluntary RFD during the later phase of contraction (150–250 ms), RFD during the very early phase of contraction (< 50 ms) was moderately related to both the evoked muscle contractile properties and MVC (Figs. 5, 6). The two main physiological factors that influence maximal muscle strength are muscle cross sectional area (Close 1972; Schantz et al. 1983) and neural drive to the muscle fibers (Hakkinen et al. 1985a). Based on the present results it is therefore likely that RFD during the later phase of contraction (150–250 ms) is also highly influenced by these factors. Furthermore, a recent study showed that stiffness of the tendon–aponeurosis complex may account for up to 30% of the variance in voluntary RFD in this phase of contraction (Bojsen-Moller et al. 2005).

Relationship between functional performance and RFD

Correlations between voluntary RFD and functional muscle performance has been reported in some studies (Jaric et al. 1989; Viitasalo and Aura 1984), whereas others did not establish a relationship (Mero et al. 1981; Young and Bilby 1993). These conflicting results may to some extent be related to the time interval in which RFD is determined. For instance, during a vertical jump a relatively long time is allowed to develop force (~300 ms) (Bosco and Komi 1979; Hakkinen and Komi 1983). During isometric muscle contraction approximately 300 ms or more is needed to reach the maximum muscular force (Narici et al. 1996; Thorstensson et al. 1976). Therefore, vertical jump performance would be expected to depend on RFD during the later phase of contraction or MVC. In contrast, during other types of rapid movement, e.g. unloaded kicking, the peak angular velocity is reached in less time (~80–90 ms; Andersen et al. 2005). This may explain the findings of Saliba and Hrysomallis that reported that maximal muscle strength was significantly related to vertical jump but not to the kicking performance in a group of Australian footballers (Saliba and Hrysomallis 2001). The present results indicate that RFD in different time intervals from the onset of contraction is influenced by different physiological parameters. Thus, when relating functional performance to isometric measurements of explosive muscle strength the time interval from the onset of contraction should be equivalent to the time span of the functional movement.

Relationship between intrinsic muscle contractile properties and RFD

With the technique of electrical myostimulation it is possible to obtain measurements of the intrinsic muscle contractile properties without the influence of the voluntary neural drive. During the very early phase of muscle contraction (<40 ms) a moderate relationship was found between voluntary RFD and electrically evoked twitch RFD. MVC and twitch RFD accounted for 18–21 and 32–35%, respectively, of the variance for voluntary RFD in this phase of contraction (Fig. 6). The present results suggest that twitch parameters such as TPT, 1/2RT and PT are not related to voluntary RFD. While PT and TPT are related to torque and the time characteristics of the twitch curve, respectively, twitch RFD is dependent on both these variables, i.e. changes in torque per time unit. Likewise, voluntary RFD expresses changes in torque per time. Therefore, the physiological factors that influence evoked and voluntary RFD may be related to a greater extent than the single twitch parameters (PT, TPT) and voluntary RFD, respectively. The rate of rise in force during tetanic electrical stimulation has been associated with the MHC composition of the muscle (Harridge et al. 1996). It is well known that the cross bridge cycling rate of muscle fibers that are dominated by type IIA and IIX MHC are roughly four- and nine-fold faster than that of type I fibers, respectively (Bottinelli et al. 1996; Larsson and Moss 1993). Thus, it is likely that the electrically evoked rate of rise in twitch force (i.e. twitch RFD) is strongly influenced by the cross bridge cycling rate. In addition, sarcoplasmic Ca^{2+}-kinetics could influence the mechanical muscle twitch parameters (Brody 1976; Kugelberg and Thornell 1983). Physiological factors besides maximal muscle strength and intrinsic muscle contractile properties could also influence the very early phase RFD. Measurements of electromyography (EMG) suggest that neural drive to the muscle may have a very important influence on voluntary RFD during this phase of contraction (Aagaard et al. 2002; Van Cutsem et al. 1998). In the present study we did not measure EMG, since the inherent variance associated with this type of measurement (De Luca 1997) makes it difficult to obtain meaningful correlations with mechanical measurements of muscle function. It is most likely that voluntary RFD in the very early phase of muscle contraction is a multifactorial phenomenon that is influenced by several physiological variables, amongst those intrinsic muscle contractile properties, maximal muscle strength and neural drive.

Practical implications

The present findings may have important practical implications. Thus, the time span of the movement should be considered for when designing resistance training programs for specific sports. The present results indicate that resistance training strategies to enhance maximal muscle strength should be employed when the time span of movement exceeds 90 ms. For instance, explosive movements such as jumping or sprinting, where the time span is in the range of 150–300 ms (Schmidtbleicher 1992), may be enhanced by training strategies that enhance maximal muscle strength. In contrast, certain types of unloaded movement with a shorter contraction time (Andersen et al. 2005; Houston et al. 1988) may depend on both the intrinsic muscle contractile properties and maximal muscle strength. A recent study demonstrated that detraining subsequent to resistance training induced faster intrinsic muscle contractile properties along with increased maximal unloaded movement speed in spite of decreased maximal muscle strength (Andersen et al. 2005).

In conclusion, voluntary RFD was increasingly related to MVC as the time from the onset of contraction increased and was strongly related to MVC in time intervals later than 90 ms from the onset of contraction. In contrast, voluntary RFD in the very early time interval (<40 ms from the onset of contraction) was moderately correlated to the intrinsic contractile properties of the muscle and was to a less extent related to MVC.

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