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ORIGINAL ARTICLE

**Dragan M. Mirkov · Aleksandar Nedeljkovic
Sladjan Milanovic · Slobodan Jaric**

Muscle strength testing: evaluation of tests of explosive force production

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Abstract The purpose of the study was to evaluate four tests of explosive force production (EFP). Specifically, the main aims of the study were to assess the reliability of different EFP tests, to examine their relationship with maximum muscle strength, and to explore the relationship between EFP tests and functional movement performance. After an extensive preliminary familiarization with the tasks, subjects ($n=26$) were tested on maximum explosive strength of the elbow extensor and flexor muscle, as well as on rapid elbow extension and flexion movements performed in both an oscillatory and a discrete fashion. In addition to maximum force (F_{max}), four different EFP tests were assessed from the recorded force–time curves: the time interval elapsed between achieving 30% and 70% of F_{max} ($F_{30–70\%}$), the maximum rate of force development (RFD), the same value normalized with respect to F_{max} (RFD/F_{max}), and the force exerted 100 ms after the contraction initiation ($F_{100\ ms}$). Excluding $F_{30–70\%}$, all remaining EFP tests revealed either good or fair reliability (intraclass correlation coefficients being within 0.8–1 and 0.6–0.8 intervals, respectively) which was also comparable with the reliability of F_{max}. RFD and $F_{100\ ms}$ demonstrated a positive relationship with F_{max}, but not $T_{30–70\%}$ and RFD/F_{max}. Stronger elbow flexor muscles also demonstrated higher values of RFD and $F_{100\ ms}$ than weaker elbow extensor muscles, while no difference was observed between either $T_{30–70\%}$ or RFD/F_{max} recorded from two muscles. Despite the simplicity of the tested movement tasks, the relationship observed between the EFP tests and the peak movement velocity remained moderate and partly insignificant. It was concluded that most of the EFP tests could be reliable for assessing neuromuscular function in their muscle-force- (or, indirectly, muscle size) dependent (such as RFD and $F_{100\ ms}$), or muscle-force-independent ($T_{30–70\%}$ and RFD/ F_{max}) forms. However, their "external validity" when applied to assess the ability to perform rapid movements could be questioned.

Keywords Elbow · Force–time · Movement · Reliability · Validity

S. Jaric (✉)
Rm. 146, Human Performance Laboratory,
Department of Health,
Nutrition, and Exercise Sciences,
University of Delaware, 547 S. College Ave,
Rust Ice Arena, Newark, DE 19716, USA
E-mail: jaric@udel.edu
Tel.: +1-302-8316174
Fax: +1-302-8313693

D. M. Mirkov
Department of Biophysics,
School of Medicine, Belgrade University,
Dr. Subotica 8, 11 000 Belgrade,
Yugoslavia

A. Nedeljkovic
The Research Center,
Faculty for Sports and Physical Education,
Belgrade University, B. Parovica 156,
Yugoslavia

S. Milanovic
Institute for Medical Research,
PO Box 102, 11 129 Belgrade,
Yugoslavia

Introduction

Muscle strength usually refers to maximum force (recorded by a dynamometer) or torque (recorded by isokinetic apparatus) of the tested muscle group (Sale 1991). Muscle strength testing has been the most often applied approach in testing muscle function in general, as well as functional movement abilities (for review see Abernethy et al. 1995; Jaric 2002; Sale 1991). However, a number of studies have considered recording a muscle's ability for explosive force (or torque) production (EFP) as an additional class of strength tests (see Abernethy et al. 1995; Wilson and Murphy 1996 for reviews). In addition to general assessment of neuromuscular function, an important rationale for testing EFP has been the short time available for force production in various athletic and other activities (Paasuke 2001; Ugarkovic et al. 2002; Wilson and Murphy 1996).

Several tests of EFP have been used through the literature. The one most often applied is the rate of force development (RFD). In short, the subject is instructed to exert maximal force in an explosive way and RFD is assessed as the maximal slope of the recorded force–time curve (Haff et al. 1997; Murphy and Wilson 1996; Sleivert and Wenger 1994), but sometimes also as the slope after a fixed time following the initiation of contraction (Aagaard et al. 2002). Taking implicitly into account the possible effects of muscle size, some authors also present RFD per unit of the recorded muscle strength (Aagaard et al. 2002; Sahaly et al. 2001). In addition to the RFD, a number of studies have provided alternative assessments of EFP. For example, some authors assess ability for EFP by the time intervals needed to achieve certain levels of muscle force. The most often applied is the time interval between two force levels relative to maximal force (Bobbert and van Zandwijk 1999; Gorostiaga et al. 1999; Sleivert and Wenger 1994; Viitasalo and Komi 1978; Zhou et al. 1996). Other authors measure either the time required to achieve a prescribed level of force starting from the zero level (Hakkinen et al. 1985; see Wilson and Murphy 1996 for review), or force exerted after a fixed interval of time (Izquierdo et al. 1999).

However a literature review reveals several potential problems related to the tests of EFP. Although both the reliability and validity of EFP tests have been generally questioned (Abernethy et al. 1995; Wilson and Murphy 1996), other than for the RFD (Sleivert and Wenger 1994) the reliability of other EFP tests has not been either tested or compared. More importantly, neither the relationships among different tests of EFP nor their relationship with the maximum force have been evaluated. In particular, although maximal force and EFP are routinely recorded as presumably independent abilities of the muscle groups being tested, it remains possible that some tests of EFP could be closely related to the maximum strength. Finally, muscle strength has often been tested in order to assess the ability for particular functional movement performance in ergonomy, physical medicine and rehabilitation, or athletic activity (see Jaric 2002; Wilson and Murphy 1996 for reviews). No-one has evaluated which tests of EFP provide the strongest relationship with particular movement performance.

In order to address the problems discussed, we designed a study that involved both various EFP tests of selected muscles and the assessment of performance of simple movements performed by the muscles being tested. The main aims of the study were: (1) to assess the reliability of different EFP tests, (2) to examine their relationship with maximum strength, and (3) to explore the relationship between EFP tests and movement performance.

Methods

Subjects

The subjects were 26 male university students aged 19–36 years, mean (SD) 21 (3) years. Their body mass was 76.3 (8.6) kg, while their body height was 1.81 (8.6) m. Most of them were physically active and none of them reported either neurological disorders or recent injuries. Subjects received a complete explanation of the purpose and procedures of the study and gave their written consent. The study was approved by the Ethical Committee of the School of Medicine.

Familiarization and testing procedure

The testing session was preceded by three identical familiarization sessions performed with 1–3 days of rest between them. The main aim of the familiarization sessions was to allow subjects to practise performing rapid elbow movements and, in particular, to familiarize subjects with the explosive force production of the tested muscles. Within the familiarization sessions subjects performed in total 180 pairs of rapid discrete extension and flexion movements, 180 extension-flexion cycles of rapid oscillatory movements, and 30 elbow extension and 30 elbow flexion explosive exertions of maximum force.

The collection of the experimental data was completed within a single experimental session. The sequence of tests was the same for all subjects. Subjects performed rapid discrete and, subsequently, oscillatory single joint movements (movement tests). Thereafter, subjects were tested on explosive exertion of maximal isometric voluntary force of elbow extensors and elbow flexors (muscle strength tests).

Movement tests

Subjects sat in a rigid chair with their right arm abducted at 90º. The forearm was placed on a light (moment of inertia 0.16 kg m^2) and almost frictionless manipulandum which permitted rotation about the elbow joint in a horizontal plane. The elbow axis was aligned with the axis of rotation of the manipulandum. Subjects viewed a rigid arrow attached to the distal end of the manipulandum. Two narrow external targets indicated elbow joint angles of 65º and 115º (full extension being 180º). The subjects were instructed to perform two blocks of consecutive elbow flexion and elbow extension movements over the 50º interval between two targets. The first block consisted of discrete movements since the consecutive flexions and extensions were performed with a 5-s rest in between. The second block consisted of oscillatory movements since the subjects were instructed to move between two targets in an oscillatory fashion. In each movement block the subjects were instructed to move as fast as possible. Blocks of discrete movements consisted of ten pairs of consecutive flexions and extensions, and the first two pairs of trials were rejected from further analysis. Blocks of oscillatory movements consisted of 12 pairs of flexions and extensions and the first and last two pairs were rejected. Therefore, eight elbow flexions and eight elbow extensions of each block were taken for further analysis. The elbow joint angle was measured by an optical decoder (HohnerTM, resolution 0.25°) mounted on the axis of the manipulandum. The signal was low-pass filtered (20 Hz) and differentiated in order to compute angular velocity.

Muscle strength tests

Muscle strength of the elbow flexor and extensor muscles was tested using the same experimental set-up as applied in the movement tests. The forearm was placed on the manipulandum (see previous section) and additionally strapped with wide tight belts in order to prevent relative movements of the forearm with respect to the manipulandum during rapid force exertions. The centre of the elbow joint was aligned with the axis of rotation of the manipulandum. The distal end of the manipulandum was connected to the force transducer by a light and rigid belt and fixed at the position corresponding to 90º of the elbow angle. The subjects were instructed to "achieve the maximal force against the belt as soon as possible and to retain it". The total time of force exertion lasted 4 s and a digital display provided feedback information about the achieved force.

The force–time curve (see Fig. 1 for illustration) was recorded using a calibrated strain-gauge dynamometer with a digital display (KKM-1, AB Bofors, Stockholm, Sweden; the linearity and reliability better than 0.4% and 0.5%, respectively). The signal was recorded at a rate of 200 s^{-1}, low-pass filtered (5 Hz) and stored on a computer disc for off-line analysis. The curve provided the maximum voluntary force (F_{max}) and four indices of explosive force (EFP) production by the muscles being tested. F_{max} was assessed as the highest force level recorded during each contraction. The indices of EFP included the time interval elapsed between achieving 30% and 70% of F_{max} ($T_{30–70\%}$), the maximum rate of force development (RFD; assessed as the maximum of the first derivative of the recorded force–time curve, see Fig. 1 for illustration), the same value normalized with respect to F_{max} (RFD/F_{max}), as well as the force exerted 100 ms after the contraction initiation ($F_{100\ ms}$). The time interval of 100 ms was selected because it closely corresponded to one-half of the movement time of the tested elbow flexion and extension movements. The initiation of $F_{100\ ms}$ was assessed by the first sustained rise of the recorded force above the baseline. Each test trial was repeated four times with a 2-min rest between them. The first trial served as a practice trial, while the remaining three trials were recorded for further analysis. All three trials were used for the assessment of reliability, while the trial with the highest F_{max} served for all other purposes.

Statistical analysis

Means and standard deviations were calculated for all tested variables. Reliability was assessed by intraclass correlation coefficients (ICC) calculated for all three consecutive strength test trials, as well as by the corresponding 95% confidence intervals. One-way ANOVA was applied in order to assess the differences among the means of three consecutive trials. Thereafter, the trial with the highest value of recorded force was taken for further analysis. Differences between the results obtained from the elbow flexor and extensor muscles were tested by paired Student's *t*-test and corresponding confidence intervals. The relationships among muscle strength tests (i.e. F_{max} and of four tests of EFP) were assessed by Pearson's correlation coefficients. Each strength test was correlated with the maximum velocity of the tested movement tasks. Thereafter, Z-transformation and 3-way ANOVA with main factors "muscle" (elbow extensor and elbow flexor), "movement" (oscillatory and discrete) and "test" (F_{max}, $T_{30–70\%}$, RFD, RFD/F_{max} and $F_{100\ ms}$) were applied. The statistical significance was set at $p < 0.05$. Note that for 26 subjects the statistical power of 0.75 gives the correlation coefficient $r = 0.54$.

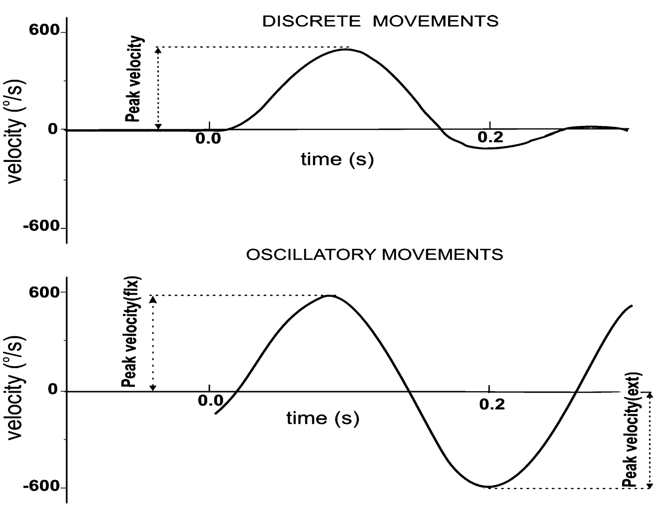

Fig. 1 Force–time curve (*full line*) recorded from a representative subject. *Dashed line* represents the first derivative of the force that was used to assess the rate of force development (*RFD*). Methods for assessing maximum force (F_{max}), the time interval elapsed between reaching 30% and 70% of F_{max} ($T_{30–70\%}$), and the force exerted 100 ms after the contraction initiation ($F_{100\ ms}$) are also illustrated

Results

Figure 1 represents a typical force–time curve recorded within the strength tests. Methods of assessment of both F_{max} and four tests of explosive force production (RFP) are also illustrated.

Three consecutive trials of explosive exertions of maximum force provided three sets of data related to F_{max}, as well as to four different tests of EFP in each of the tested muscles. The descriptive statistics of the recorded data are depicted in Table 1, together with the intraclass correlation coefficients (ICC) calculated from all three trials. None of the tests demonstrated significant differences in averaged values among three trials. Note that most of the ICC were within the 0.8–1 interval. Only the $T_{30–70\%}$ of elbow extensors and the $F_{100\ ms}$ of elbow flexors provided ICCs within the 0.6–0.8 interval, while the $T_{30–70\%}$ of elbow flexors suggested an ICC of below 0.6. The associated confidence intervals suggest significantly higher reliability of F_{max} than of $T_{30–70\%}$ obtained from both muscles.

Table 2 shows the results of all five tests obtained from the elbow flexor and extensor muscles when the trial that demonstrated the highest muscle force was taken for further analysis. Note that the stronger elbow flexor muscle (i.e. higher F_{max}) also demonstrated higher values of RFD and $F_{100\ ms}$ than the weaker elbow extensor, while no differences were recorded in $T_{30–70\%}$, and RFD/F_{max}.

Table 3 depicts correlation coefficients among all five muscle strength tests observed in elbow extensors (upper part of the table) and elbow flexors (lower part of the table). Of particular importance are the relationships observed between F_{max} and each of the four EFP tests. One can notice that the results obtained from the elbow flexor and extensor muscles provided consistent results. Namely, both RFD and $F_{100\ ms}$ correlated significantly with F_{max}, while the same relationship for $T_{30–70\%}$ and RFD/F_{max} was insignificant. The confidence intervals suggested higher correlation coefficients for RFD than RFD/F_{max} in elbow extensors, while in elbow flexors the RFD suggested a higher correlation coefficient than either $T_{30–70\%}$ or RFD/F_{max}.

Figure 2 illustrates a typical velocity pattern of the discrete and oscillatory movements tested. When aver-

Table 1 Maximum force and four explosive force production tests of two muscles. Data represent mean (SD). (*ICC* Intraclass correlation coefficients)

		F_{max} (N)	$T_{30–70\%}$ (s)	RFD (N/s)	RFD/F_{max} (1/s)	$F_{100\ ms}$ (N)
Elbow extensor	Trial 1	113 (26)	0.68 (0.15)	125 (31)	1.10 (0.21)	7.4 (2.7)
	Trial 2	110 (30)	0.66 (0.17)	117 (31)	1.07 (0.22)	7.1 (2.5)
	Trial 3	107 (29)	0.69 (0.18)	114 (32)	1.09 (0.22)	7.4 (3.1)
	ICC	0.92	0.70	0.87	0.83	0.82
	Confidence intervals	0.86–0.96	0.52–0.84	0.77–0.93	0.71–0.91	0.69–0.91
Elbow flexor	Trial 1	149 (27)	0.62 (0.13)	181 (45)	1.21 (0.21)	11.8 (5.0)
	Trial 2	148 (24)	0.60 (0.11)	177 (42)	1.20 (0.20)	11.6 (4.6)
	Trial 3	148 (28)	0.60 (0.09)	180 (52)	1.21 (0.22)	11.3 (5.5)
	ICC	0.85	0.54	0.81	0.81	0.71
	Confidence intervals	0.74–0.93	0.31–0.74	0.67–0.90	0.67–0.90	0.53–0.85

Table 2 Maximum force and explosive force production tests recorded from the elbow extensor and flexor muscles. Data represent mean (SD)

	F_{max} (N)	$T_{30–70\%}$ (s)	RFD (N/s)	RFD/F_{max} (1/s)	$F_{100\ ms}$ (N)
Elbow extensor	117 (22)	0.62 (0.11)	129 (25)	1.10 (0.17)	7.8 (2.5)
Elbow flexor	158 (32)	0.61 (0.09)	183 (52)	1.15 (0.20)	12.2 (5.3)
p	<0.01	>0.05	<0.01	>0.05	<0.01

Table 3 Relationships among different muscle strength tests of elbow extensors (*upper part of the table*) and elbow flexors (*lower part of the table*). Data depict correlation coefficients

	F_{max}	$T_{30–70\%}$	RFD	RFD/F_{max}	$F_{100\ ms}$
F_{max}	–	0.22 (−0.18–0.56)	0.62** (0.30–0.81)	−0.28 (−0.60–0.12)	0.42* (0.03–0.69)
$T_{30–70\%}$	−0.00 (−0.39–0.39)	–	−0.17 (−0.50–0.23)	−0.45* (−0.71 to −0.08)	0.45* (0.07–0.71)
RFD	0.82** (0.62–0.91)	−0.66** (−0.83 to −0.36)	–	0.53** (0.18–0.76)	−0.76** (−0.89 to −0.52)
RFD/F_{max}	0.22 (−0.18–0.56)	−0.58** (−0.79 to −0.25)	0.74** (0.50–0.87)	–	−0.38 (−0.64–0.08)
$F_{100\ ms}$	0.52** (0.17–0.76)	0.28 (−0.12 to 0.60)	−0.66** (−0.91 to −0.63)	−0.52** (−0.76 to −0.17)	–

*$p<0.05$; **$p<0.01$; confidence intervals are in*parentheses*

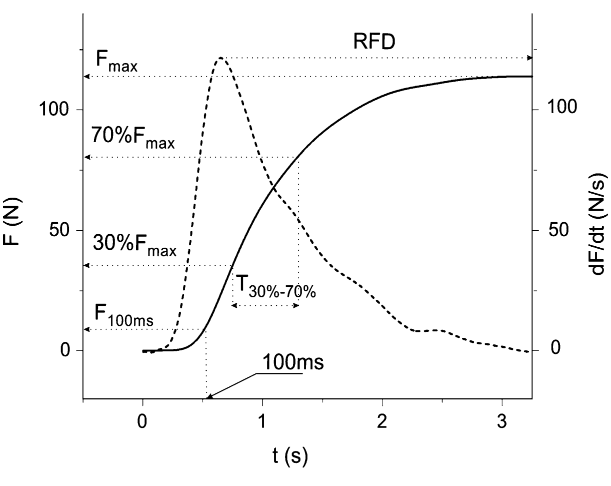

Fig. 2 Elbow angular velocity recorded in a typical discrete (*upper figure*) and oscillatory (*lower figure*) trial

aged across the subjects and trials, the oscillatory movements suggested not only higher peak velocity, but also (when averaged across the subjects) higher variable errors than discrete movements (Student's *t*-test; $p<0.01$; see Table 4 for results).

The correlation coefficients obtained between various indices of muscle strength and the peak velocity of discrete and oscillatory movements are depicted in Table 5. *Z*-values of the depicted correlation coefficients were tested by means of 3-way ANOVA. The results revealed a significant effect of "muscle" (higher values obtained for elbow flexor than for elbow extensors; $F=96$, $p<0.01$), "movement" (higher values obtained for oscillatory than for discrete movements; $F=25$, $p<0.01$), and "test" ($F=19$; $p<0.01$), with a "movement–test" interaction ($F=3.7$, $p<0.05$). A Tukey HSD post-hoc test suggested higher *Z*-scores for RFD, RFD/F_{max} and $F_{100\ ms}$ than for F_{max} and $T_{30–70\%}$. All differences revealed $p<0.01$, except the difference between $F_{100\ ms}$ and $T_{30–70\%}$, which revealed $p<0.05$.

Discussion

The results obtained provided three groups of findings related to the specific aims of the present study (see Introduction) that need to be discussed. The first group refers to the unexpectedly high reliability of most of the tests of EFP. The second group of findings is related to a strong relationship obtained between two out of four

Table 4 Accuracy and velocity recorded in movement performance tests. Data represent mean (SD)

	Variable error (°)		Constant error (°)		Peak velocity (°/s)	
	Extension	Flexion	Extension	Flexion	Extension	Flexion
Oscillatory	9.3 (1.0)	8.9 (1.3)	1.9 (9.3)	1.5 (8.9)	603 (75)	604 (77)
Discrete	1.2 (0.7)	1.2 (0.4)	−0.1 (1.2)	−1.5 (1.2)	485 (66)	484 (68)
p	<0.01	<0.01	>0.05	>0.05	<0.01	<0.01

Table 5 Correlation coefficients recorded between the peak velocity of the tested movements and strength tests of active muscles

Muscle	Elbow extensor				Elbow flexor			
movement fashion	Oscillatory		Discrete		Oscillatory		Discrete	
Movement direction	Flexion	Extension	Flexion	Extension	Flexion	Extension	Flexion	Extension
F_{max}	0.290	0.195	0.154	−0.036	0.413*	0.391*	0.271	0.154
$T_{30–70\%}$	−0.171	−0.258	−0.084	−0.177	−0.361	−0.294	−0.321	−0.335
RFD	0.473*	0.377	0.334	0.188	0.653**	0.582**	0.477*	0.352
RFD/F_{max}	0.247	0.258	0.297	0.360	0.621**	0.529**	0.525**	0.482*
$F_{100\ ms}$	−0.309	−0.229	−0.292	−0.220	−0.553**	−0.478*	−0.431*	−0.382

*$p<0.05$; **$p<0.01$

EFP tests (specifically, RFD and $F_{100\ ms}$) and F_{max}. The correlations of the remaining two tests of EFP (i.e. $T_{30–70\%}$, and RFD/F_{max}) proved to be insignificant. In line with these findings were significantly higher values of RFD and $F_{100\ ms}$ recorded in stronger elbow flexors that in elbow extensors, while no differences were recorded in $T_{30–70\%}$, and RFD/F_{max}. The third group of findings refers to the relationship between muscle strength and movement performance tests. Despite the relatively weak relationships obtained in general, some differences related to both the movement fashion and the selected EFP tests deserve to be discussed.

Reliability of the tests of EFP

There are several possible approaches when interpreting reliability based on consecutive tests repetitions. One of them could be based on particular intervals of ICC (Sleivert and Wenger 1994), while the other takes into account both differences between means obtained in consecutive tests and the related confidence intervals (Hopkins 2000). According to the first approach, it should be noted that most of the ICC obtained in four tests of EFP were within the interval 0.8–1.0. This interval is generally regarded to provide "good" reliability of the applied tests (Sleivert and Wenger 1994). The exceptions were $T_{30–70\%}$ (recorded from elbow extensors) and $F_{100\ ms}$ (recorded from elbow flexors) that were within the "fair" reliability interval of 0.6–0.8, while only the ICC of $T_{30–70\%}$ of elbow flexors was below the acceptable level of 0.6. From the prospective of the second approach, it should be noted that there were no differences among means obtained in three consecutive trials in any of the applied tests, while the confidence intervals only suggest higher reliability of F_{max} than of $T_{30–70\%}$.

Taken together, these findings generally contradict the low reliability of EFP tests suggested by Slievert and Wenger (1994) although it should be taken into account that these authors tested lower limb muscles. Since most of the obtained values of ICC were also comparable with those obtained for F_{max}, the results also challenge the general inference of Abernethy and co-workers (1995) that the EFP tests are less reliable than the F_{max} test. The lack of literature does not allow for further elaboration of the discussed phenomenon. However, one could speculate that the extensive familiarization that our subjects had prior to the experimental session could play a role. It has been suggested that a rapid exertion of maximum force requires more practice than exerting maximum force per se (Abernethy et al. 1995). This suggestion has been indirectly supported by findings of Sahaly and co-workers (2001) implying that the recorded RFD values differ when subjects are asked to exert muscle force in a "rapid" and in a "rapid and strong" fashion.

Relationships among muscle strength tests

Maximum force (or torque) and EFP tests are generally considered to reflect two independent functional abilities of the tested muscle, while their relationships with various functional movements also differ (Paasuke et al. 2001; Pryor et al. 1994; Ugarkovic et al. 2002; see also Wilson and Murphy 1996 for review). The changes in muscle strength associated with athletic training have also been independently assessed by changes in maximum muscle force and changes in EFP (e.g. Gorostiaga et al. 1999; Haff et al. 1997; Matavulj et al. 2001; Zhou et al. 1996). However, our results suggest that some tests of EFP are related to F_{max}, while others are not. We believe that the observed phenomenon could be partly explained by taking into account the possible effect of muscle size, although one should also consider the relatively low reliability of some of the EFP tests.

Figure 3 illustrates a model of hypothetical behaviour of two muscles of different size while exerting the maximum force in an explosive fashion. The depicted force–time curves of the muscles are based on the presumption that muscle size positively affects maximum force, but not the underlying processes that influence the EFP. Since the latter presumption provides a preserved shape of the force–time curves, one should notice that, in addition to F_{max}, both the RFD and $F_{100\ ms}$ tests of the muscle bigger in size provide higher values. However, $T_{30–70\%}$ is not affected by muscle size, while it is conceivable that the RFD, after being normalized for F_{max}, also remains unchanged.

The observed differences among the relationships between each of four individual EFP tests and F_{max} are in line with the behaviour of two hypothetical muscles. Specifically, the results suggest that RFD and $F_{100\ ms}$ tests recorded from both muscles are related to individual F_{max}, while $T_{30–70\%}$ and RFD/F_{max} are not. Moreover, stronger elbow flexors revealed higher values of RFD and $F_{100\ ms}$ than weaker elbow extensors, while the same difference in $T_{30–70\%}$ and RFD/F_{max} remained insignificant.

Although the presumption that muscle size does not influence EFP could be questioned from different aspects, it should be remembered that several studies have supported the concept that the RFD, as the most often applied test of EFP, could be related to muscle force or, indirectly, to muscle size. For example, Sleivert and coworkers (1995) reported a positive relationship between RFD knee extensors and both body mass and thigh volume. The conclusion that ''…ability to exert both isometric and dynamic peak force shares some structural and functional foundation with the ability to generate force rapidly'' (Haff et al. 1997; p 269) was based on the positive relationship observed between RFD and maximum force recorded under both isometric and dynamic conditions. F_{max} and RFD increase at a similar rate with maturation (Paasuke et al. 2001), but decrease with fatigue (Zhou et al. 1996) or aging (Paasuke et al. 2000). Finally, the well known differences in F_{max} observed between eccentric and isometric force production are also associated with similar differences in RFD (Pryor et al. 1994). On the basis of both the proposed model (Fig. 3) and the presented literature review, we believe that the distinction between ''absolute'' RFD (i.e. muscle-force-dependent) and ''relative'' RFD (i.e. muscle-force-independent; RFD/F_{max}) proposed by Sleivert and Wenger (1994) could be extended to $F_{100\ ms}$ and $T_{30–70\%}$ as muscle-force-dependent and muscle-force-independent (with respect to F_{max}) tests of EFP, respectively. The finding that muscles of very different size have similar rise times from 10% to 90% of maximum EMG level (Bobbert and van Zandwijk 1999) also speaks in favour of our conclusion.

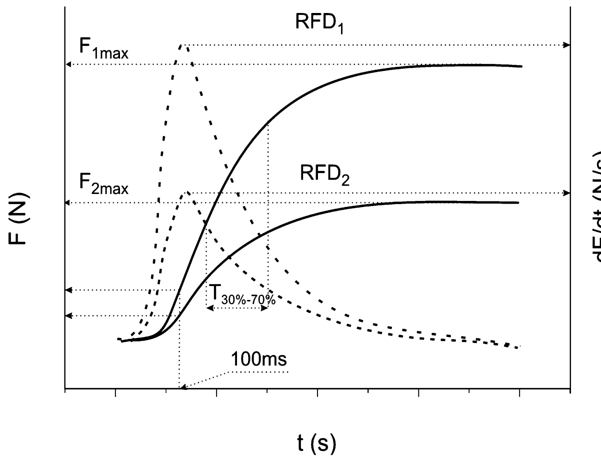

Fig. 3 Illustration of hypothetical force–time curves of two muscles that differ only in size and, therefore, in muscle force. The stronger muscle demonstrates higher values of both RFD and $F_{100\ ms}$, but not of $T_{30–70\%}$

Finally, the relationships among four EFP tests also deserve some attention. The negative relationship obtained between $T_{30–70\%}$ and both the RDF and RFD/F_{max} may be considered to be expected (see Table 3). A higher rate of force increase should lead to a shorter time lapsing between achieving two relative levels of force. However, a negative relationship observed between $F_{100\ ms}$ and both the RDF and RFD/F_{max} seems hard to interpret, since a steeper rise of the recorded force should generally lead to higher indices of all three tests. Therefore, additional research is needed in order to reveal whether the observed phenomenon is related to the method of assessment of the force initiation or, alternatively, whether the steepness of the ''initial'' and ''middle'' part of the force–time curves are unrelated and, therefore, represent two partly different properties of the neuromuscular system.

Relationship to movement performance

The relationship between muscle strength and functional movement performance has been often interpreted as ''external validity'' of muscle strength tests (Abernethy et al. 1995; Markora and Miller 2000). However, excluding very few examples that have provided exceptionally strong relationships, most of the studies suggested a moderate, if not insignificant, relation between movement performance and strength of active muscles (see Wilson and Murphy 1996; Jaric 2002 for review). Since one of the reasons could be a different level of skills while performing functional movement tests and/or a high number of body segments and muscles involved in task execution, we selected an exceptionally simple movement test and, thereafter, familiarized our subjects with the task. Nevertheless, the relationship obtained between movement performance and indices of the strength of active muscles proved to be moderate and partly insignificant. As a consequence, one could conclude that although the standard maximum force and EFP tests could be valid for general assessments of neuromuscular function, their external validity in terms of their relationships with various functional performance tests should be questioned. However, it remains possible that the difference in the contraction regime reduced the obtained relationship since the strength tests were performed under isometric conditions, while the tested movements were brief and rapid ones. Therefore, different indices of EFP could be affected by the changed muscle contraction regime differently. We do not have the data to support these claims, but the moderate relationship between isometric and "dynamic" strength test indices represent a well-known phenomenon.

Higher correlation coefficients of movement velocity with the muscle strength of the elbow extensor than with the elbow flexor muscles seem hard to explain since both muscles serve as agonists and antagonist in the tested movements. However, we believe some motor control findings could help to explain the stronger relationship observed between the tested muscle strength and the peak velocity of oscillatory movements, when compared with discrete ones. Rapid discrete movements performed from one to another position are usually associated with a well-known triphasic EMG activity of the agonist and antagonist muscle (Gottlieb et al. 1989; Wachholder and Alterburger 1926). Although the first agonist burst is assumed to provide the propelling force, while the antagonist burst provides the braking force (Lestienne 1979), most of the EMG data provide a relatively high level of muscle co-activation over most of the movement time (Yamazaki et al. 1994; see also Corcos et al. 1993; Gottlieb et al. 1989for illustration). As a consequence, one could conclude that movement velocity is partly sacrificed for the sake of movement accuracy through the mechanism of the agonist-antagonist co-activation. Rapid reversal or oscillatory movements, however, demonstrate well-defined consecutive EMG bursts of agonist and antagonist muscles, while the level of the antagonist co-activation is generally low (Gottlieb 1998; Schmidt et al. 1988). Thus it remains possible that the subject-specific strategy of controlling movement accuracy through muscle co-activation adds to the variability of performance of rapid discrete movements, while a similar mechanism does not play a role when performing rapid oscillatory movements. Although we do not have the data to support our claims, both the higher velocity and the higher variable error of oscillatory movements (as compared to the discrete ones) seem to speak in favour of our explanation. Specifically, reduced co-activation should contribute to the increased movement velocity, but could also negatively affect movement accuracy.

The last finding to be discussed is related to the relatively weak relationship of both F_{max} and $T_{30–70\%}$ with the movement performance when compared with the same relationship observed in RFD/F_{max}, $F_{100\ ms}$ and, in particular, RFD. With respect to F_{max}, comparison of Figs. 1 and 2 suggests that the available time for muscle action in movement tests corresponds to only a small fraction of the time needed to exert maximum muscle force. Therefore, it seems conceivable that the ability to exert the maximum muscle force is less important than the ability to exert this force in an explosive way when performing a rapid movement of a particularly short duration. With respect to other EFP tests, it should be taken into account that the moment of inertia of the manipulandum was several times higher than the moment of inertia of the system's lower arm-hand (with respect to the elbow joint). Thus the movement task could be considered as "exerting force against an external object" and the performance of these tasks should be assessed by the absolute (means non-normalized with respect to either body size or muscle force) strength of active muscles (see Jaric 2003). However, an exceptionally weak relationship observed between $T_{30–70\%}$ and movement performance could also be a consequence of a relatively low reliability of this particular EFP test.

Conclusions

The present study generally revealed a high reliability of the evaluated tests of EFP, although this result could be partly attributed to the extensive familiarization procedure performed prior to the testing. The exception could be the tests based on the time required to achieve certain levels of relative force, while all other tests demonstrated reliability comparable to the maximum force tests. The obtained results also support the concept of distinguishing "muscle-force-dependent" (i.e. related to muscle strength or, indirectly, muscle size) and "muscle-force-independent" tests of EFP. In particular, the maximum rate of force development and the level of force achieved after a fixed time interval could belong to the former group, while the time required to achieve a certain relative level of force and the rate of force development relative to maximum force could belong to the latter group. However, due to the moderate relationship obtained between these tests and the performance of rapid single-joint movement, the "external validity" of the EFP tests remains questionable. Future studies could address this problem by extending the EFP testing to dynamic conditions, as well as by involving a variety of functional movement tests including both single-joint and multi-joint movement tasks.

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