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Original research article

RELIABILITY AND GENERALIZABILITY OF CONSECUTIVE MAXIMUM CONTRACTIONS AS A TEST OF NEUROMUSCULAR FUNCTION

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Abstract. *The aim of the study was to explore the intra- and inter- session reliability, generalizability, as well as the factorial validity of the recently proposed novel test of neuromuscular function. Twelve participants took part in the first experiment, performing the standard strength test (SST) and a novel test based on consecutive maximum contractions (CMC) tests on the knee extensor muscle. Within the second experiment, additional 36 participants performed the SST and CMC tests on the knee and elbow flexor and extensor muscles.*
The obtained results for the SST and CMC revealed high day by day and test-retest reliability in most measured variables (ICC in the range of 0.80 - 0.92). The principal component analysis (PCA) applied on the SST variables revealed 3 factors that explained 81.2% of the non-normalized and 66.1% of the normalized data. The PCA applied on all 16 non-normalized variables of the CMC test revealed 3 factors that explained 80% of the total variance. Another PCA with the rate of force development and relaxation (RFD and RFR) normalized in regards to the PF revealed 4 factors that explained 70.9% of the total variance. Non-normalized factors were not loaded with different muscle groups, but with variables of the same muscle group. After the applied normalization, the individual factors were loaded with the variables recorded from individual muscles. The results of the CMC suggest that the ability of the RFD and RFR could be partially independent. The CMC may be a feasible alternative to SST since it could assess the same strength properties from muscles through a single trial, based on a relatively low and transient force.

Key words: *flexor, extensor, force, RFD, RFR.*

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INTRODUCTION

The assessment of neuromuscular function, as well as the determination of the ability to perform various functional movements is of profound importance in a number of clinical and non-clinical human movements related areas. The standard strength test (SST) has been the most commonly used test of muscle function in general, as well as the test for the assessment of functional movement abilities (Abernethy, Wilson, & Logan, 1995; Jaric, 2002; Wilson & Murphy, 1996). In particular, SST involves the maximum voluntary contraction of a muscle or muscle group performed under isometric or isokinetic conditions. The resulting force-time curve provides indices of the maximum force [F_{max}; (Abernethy et al., 1995; Jaric, 2002; Jaric, Mirkov, & Markovic, 2005; Sahaly, Vandewalle, Driss, & Monod, 2001)] and, less frequently, the maximum rate of force development (RFD_{max}). F_{max} is typically achieved after 3-5 s of a sustained maximum contraction. The face validity of F_{max} has been based on its presumed correspondence with the maximum force that the particular muscle can exert in various functional tasks. Among the various methods of calculation, RFD_{max} has been most frequently calculated as the maximum of the time derivative of the force recorded during a rapid maximum contraction (Andersen & Aagaard, 2006; Mirkov, Nedeljkovic, Milanovic, & Jaric, 2004). The face validity of RFD_{max} has presumably been based on the fact that the duration of a number of important functional tasks such as explosive and rapid cyclic movements, or postural corrections, is much shorter than the time needed for the exertion of F_{max} (Andersen & Aagaard, 2006; Holtermann, Roeleveld, Vereijken, & Ettema, 2007; Mirkov et al., 2004).

Although widely used, the SST is known to have several shortcomings. First, the patterns of neural activation for rapid (Desmedt & Godaux, 1977; Van Cutsem, Duchateau, & Hainaut, 1998) and sustained maximum contractions (Enoka & Fuglevand, 2001) could be different. Since the SST is based on sustained contractions, it may not capture the neural activation pattern typical for the rapid exertion of force that could be critical for functional tasks (Holtermann et al., 2007; Mirkov et al., 2004; Pijnappels, Bobbert, & van Dieen, 2005). Therefore, the validity of SST variables when used to assess the ability to perform rapid discrete and cyclic movements (e.g., correcting posture, jumping, running, cycling) could be questioned. Moreover, the instructions "to exert maximum force" and "to exert it rapidly" have profoundly different effects on the outcome of the SST assessed as F_{max} and RFD_{max} (Bemben, Clasey, & Massey, 1990; Sahaly et al., 2001). Thus, separate series of trials could be needed to record F_{max} and RFD_{max} which could also lead to a prolonged testing procedure associated with muscle fatigue (Andersen & Aagaard, 2006; Wilson & Murphy, 1996). The total number of trials may be even greater due to a longer familiarization needed for rapid exertion than for the maximum exertion of force (Sahaly et al., 2001; Wilson & Murphy, 1996), exacerbating further the fatigue issue.

An additional problem with the application of the SST tests is related to the phase after the maximal force has been achieved. Although the rate of force relaxation (RFR) calculated from the force time curve in the part where after sustained contraction, relaxation occurs, could be equally important as RFD for the success of rapid consecutive actions of antagonistic muscles, it has been almost completely neglected in SST procedures (Andersen & Aagaard, 2006). Finally, note that the exertion of a maximum sustained contraction typical for SST could be painful or inappropriate for some individuals, such as the frail elderly or injured/recovering persons (Wilson & Murphy, 1996). The discussed relatively large number of trials needed for the assessment of both F_{max} and RFD_{max} could intensify the unsuitableness of SST in this particular population.

Although it is presumed that F_{max} and RFD_{max} represent independent indices of neuromuscular function, their relationship remains questionable. Namely, although several studies demonstrated a positive relation between them (see Abernethy et al., 1995; Wilson & Murphy, 1996 for a review), particularly for the *RFD* recorded in a later phase of force development (Haff et al., 1997; Murphy & Wilson, 1996; Sleivert & Wenger, 1994), the available results are mainly inconsistent (Holtermann et al., 2007; Wilson & Murphy, 1996). As a consequence, it remains unclear to which extent F_{max} and RFD_{max} obtained from the SST represent independent abilities of the tested muscle. Some authors suggest the normalization of RFD_{max} with respect to F_{max} (Andersen & Aagaard, 2006; Mirkov et al., 2004; Sahaly et al., 2001), since F_{max} affects the steepness of the force-time slope. As a result, RFD_{max} might be force-dependent, questioning the assumption that these two measures represent the independent indices of neuromuscular function.

To address the above mentioned shortcomings of SST we recently evaluated consecutive maximum contractions (CMC) as a possible candidate for a strength test complementary to SST (Suzovic, Nedeljkovic, Pazin, Planic, & Jaric, 2008). In short, the participants performed externally paced isometric contractions (i.e., a series of consecutive maximum force exertions and relaxations) of the quadriceps muscle. The peak force and the rates of force development and relaxation demonstrated relatively stable values within the frequency interval of 0.67-2.67 Hz. More importantly, the same variables revealed moderate-to-high intra-trial reliability, while their predictive power regarding the performance of the maximum vertical jump was systematically higher than those of the SST variables. Finally, the peak force revealed a strong relationship with the Fmax of SST, despite being considerably lower. Therefore, we concluded that the CMC could be developed into an independent test of muscle strength or, alternatively, into a test that could be complementary to SST.

Within the present study we extended our previous research in order to properly assess (1) intra- and inter-session reliability, and (2) generalizability and factorial validity of CMC variables. Specifically, a definitive test of the reliability was conducted on the quadriceps muscle whereas CMC were performed at different externally paced frequencies (i.e., 1.0, 1.5, 2.0 Hz), as well as at the ‘self-selected’ one (i.e., without external pacing). In addition, the test of CMC was conducted on four different muscle groups (i.e., the knee flexor and extensor, as well as the elbow flexor and extensor) in order to generalize previous findings. Finally, the principal component analysis was applied to both the non-normalized and properly normalized data in order to assess the relationship among the measured variables of SST and CMC.

THE METHOD

The sample of participants

Forty-eight male students of the Faculty of Sport and Physical Education participated in two experiments. Although they were not active athletes, they all participated in courses of physical activities on a daily basis through their standard academic curriculum. They were randomly assigned into two groups. Twelve of them participated in Experiment 1. Their mean age was 20.0 (1.4) years, body mass and height were 79.9 (9.2) kg, and 184 (8.6) cm, respectively, while their body mass index was 23.4 (1.5) ranging between 20.7 and 25.9. Another 36 students participated in Experiment 2. Their mean age was 21 (2) years, body mass and height were 77.5 (7.8) kg, and 182 (7) cm, respectively, while the body mass index was 23.4 (1.4) ranging between 20.2 and 26.4. None of the participants had health problems or recent injuries. They were already familiar with the standard strength tests (SST; see the further text) due to the regular semi-annual testing of physical abilities, as well as due to their participation in various athletic activities through their academic curriculum. The measurement procedures and potential risks were verbally explained to each participant prior to obtaining an institutionally approved informed consent according to the Helsinki Declaration.

The measuring instrument

The subjects were sitting on a rigid home-made chair specifically designed for this set of experiments (see Figure 1 for illustration). Their thighs, trunk and upper arms were tightly fixed to the chair and limbs supports with wide belts. Depending on the tested muscle group, a calibrated strain-gauge force transducer (Hottinger, Type S9, range 10 kN; linearity better than 1%, tensile/compressive force sensitivity 2mV/N) was repositioned to fix either the lower leg or lower arm to the chair through a rigid belt positioned just above the wrist or lateral malleolus, respectively. Both the elbow and knee angle were fixed at 120º of extension. Therefore, the experimental setup allowed for testing the strength of four muscle groups (i.e., elbow flexors and extensors, and knee flexors and extensors) under isometric conditions. Only the dominant limb was tested.

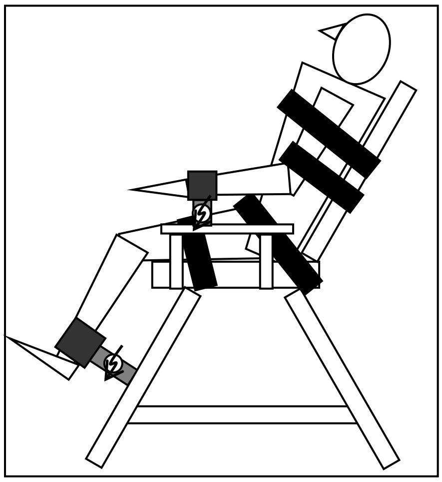

Fig. 1 Subject in a seated position on the chair

Testing procedure

The following two tests were applied to each muscle group:

Standard strength test (SST). We selected the maximum isometric exertion of muscle force as the most frequently applied strength test ((Abernethy et al., 1995; Jaric, 2002); see also Introduction). The subjects were instructed to “achieve the maximal force against the band as soon as possible and to retain it” (Wilson & Murphy, 1996). The duration of the force exertion was 4 s. The feedback regarding the current force was showed on a computer monitor positioned in front of the subject and verbal encouragement was also provided. The rest intervals between two consecutive trials were 2 min.

Consecutive maximum contractions (CMC). The test selection was based on its presumed similarity with various rapid and cyclical movements regarding both the kinetic and neural activation pattern of the muscle force exertion (see the Introduction for details). The subjects were specifically instructed to "achieve the maximum quadriceps force against the band as soon as possible and, thereafter, to relax, as when performing consecutive kicks". The frequency of force exertion was either paced with a metronome or self-selected (see further text for details). The same computer monitor was used to provide feedback information and verbal encouragement was also used. The trial duration covered 8 full cycles of CMC. The experimental trials were repeated when the contractions showed inconsistent force profiles and/or force timing, as well as when the exerted force did not sufficiently relax to drop within the interval of ±5% of the peak force.

Each experimental session was preceded by a standard 10-min warm up and stretching procedure. The rest intervals between two consecutive trials in all the tests were 2 min.

Experiment 1

The experiment was performed on 12 participants with the aim of assessing the reliability of the variables of CMC and SST within and between sessions, as well as evaluating the possible differences between the externally paced and self-selected CMC. The experiment consisted of three sessions, the second and the third one performed 2 days and 6 weeks following the first one, respectively. Only the knee extensor muscle was tested.

Within Session 1, the subjects performed 4 consecutive trials at each of the three frequencies paced by a metronome set to 1.0, 1.5, 2.0 Hz, as well at a the 'self-selected frequency' (i.e., without external pacing) in a random sequence. The instruction for the self-selected frequency was to perform the CMC "with as much force and speed as possible". The last 3 trials were recorded for further analysis. Thereafter, the subjects performed 3 trials of the SST and the last 2 were selected for further analysis. Sessions 2 and 3 represented a repetition of Session 1. However, only two trials executed at each frequency of CMC and two trials of SST were performed and the second ones were taken for further analysis.

Experiment 2

Another 36 participants were tested within a single session of Experiment 2 with the aim of generalizing the relationship between the variables depicting the maximum forces and the rates of their change across different muscle groups. Specifically, the participants performed two trials of CMC and, thereafter, the SST of the knee flexors and extensors and elbow flexors and extensors. Based on the findings of Experiment 1 (see the Results section for details) only the CMC at the self-selected frequency was performed. The sequence of muscle group tests was randomized, as was the sequence of the CMC and SST applied to each muscle. The second trial of each test was recorded for further analysis.

Data processing and analysis

A custom-made Lab View program was used for data acquisition and processing. The force-time curve of the muscle was recorded at a rate of 500 s^{-1} and low-pass filtered (10 Hz) using a fourth-order (zero-phase lag) Butterworth filter. The force maxima provided the *peak force* of CMC (*PF*), and the *maximum force* of SST (F_{max}). Thereafter, a derivative of the force-time curve was calculated and averaged within a 20 ms moving window. The maximum and minimum values of the calculated curve provided the *rate of force development* (*RFD*) and the *rate of force relaxation* (*RFR*), respectively. The CMC variables were calculated as average values obtained from the last three cycles of the recorded force averaged across a trial. The same Lab View program also provided on-line force profiles for visual inspection, as well as a warning if the CMC frequency differed from the prescribed one, or if the recorded muscle force did not relax below 5% of the preceding maximum.

Descriptive statistics were calculated for all the experimental data. To assess the within-day and between-day reliability of each of the dependent variables obtained from the SST (i.e., F_{max} and RFD_{max}) and CMC (*PF*, *RFD*, and *RFR*) performed within Experiment 1, the intra-class correlation coefficients (ICC) were calculated among the three trials of Session 1, as well as among three consecutive sessions. In addition, one-way repeated measures ANOVA was applied to detect systematic bias among the trials and sessions (Weir, 2005). Absolute (i.e., within-individual) variability was assessed by typical error of measurement as well as by coefficient of variations (CV)(Hopkins, 2000). The SEM was used as an indication of the precision of a score, and to allow the construction of confidence intervals for scores (Weir, 2005).

The data obtained in Experiment 2 were used to calculate the correlation coefficients among CMC and SST variables of four tested muscle groups. Note also that both the theoretical models and experimental findings suggest that the results of the rate of force changes are force-dependent and therefore should be normalized relative to maximal force.

To account for possible force impact on the rate of force changes of various muscle groups, all further calculations were performed on both non-normalized (RFD_{max}, *RFD*) and normalized (RFD_{max}/F_{max}, *RFD*/*PF* and *RFR/PF*) rates of force changes (Andersen & Aagaard, 2006; Mirkov et al., 2004; Sahaly et al., 2001). Thereafter, the correlation coefficients were factorized using a principal components factor analysis [PCA (Nunnaly & Bernstein, 1994)]. The data were analyzed using the Statistical Package for Social Sciences (SPSS, version 12.0). The number of significant principal components in the factor pattern matrix extracted by the PCA was determined by the Kaiser-Guttman criterion (Nunnaly & Bernstein, 1994), which retains the principal components with eigenvalues greater than 1. The original factor pattern matrix was rotated to improve the simple structure of the matrix. This rotation was orthogonal and used a Varimax criterion with Kaiser Normalization. The final outcomes of each PCA were commonalities and factor loadings for each manifest variable, eigenvalues, and percentage of variance explained by each rotated principal component. The level of statistical significance was set to $p = 0.05$.

RESULTS

Experiment 1:

Experiment 1 has been conducted in order to determine within- and between-day reliability of both the standard strength test (SST) and test of consecutive maximum contractions (CMC) performed at different frequencies [e.g., 1 Hz, 1.5 Hz, 2 Hz and self-selected frequency (SS)]. Table 1 depicts the results of both evaluated tests averaged across the subjects for each recorded trial. In addition, the corresponding measures of reliability as well as the corresponding results of repeated measures ANOVA are presented. The within-day reliability as depicted by ICC calculated for three consecutive trials within the same session (upper part of Table 1) for all variables of both evaluated tests was high and exceeded 0.90. The only exception was the RFR in the CMC test performed at 1.5Hz (ICC = 0.89). The maximum force (F_{max}) recorded in SST revealed considerably lower within-subject variation expressed as either CV (%) or SEM (1.8% or 15, respectively), than the variation obtained from the maximum rate of force development (RFD_{max}; 5.6% or 272, respectively) recorded within the same contraction. Similarly, the CVs (%) and SEMs of peak forces (*PF*) recorded in the CMC performed at different frequencies were considerably lower (2.6 – 4.7% and 20 – 31, respectively), than the corresponding parameters of variation obtained from either rate of force development (RFD; 3.6 – 8.0% and 183 – 357, respectively) or rate of force relaxation (RFR; 3.7 – 8.1% and 233 – 418, respectively). When applied to each particular variable recorded in both tests, the repeated measures ANOVAs revealed $F_{[2,11]} = 0.43 – 3.92$ ($P > 0.05$) suggesting that the differences between consecutive trials proved to be small and inconsistent.

The high ICC (0.80 – 0.92, respectively) calculated for three consecutive sessions revealed high between-day reliability for both SST and CMC, albeit the within-subject variation were slightly higher across all measured variables, than the corresponding variation obtained from three consecutive trials within the same session (see Table 1 for details). Repeated measures ANOVAs applied on both F_{max} and RFD_{max} recorded in SST revealed $F_{[2,11]} = 2.26$ and 3.92, respectively ($P > 0.05$) suggesting no significant differences among three consecutive sessions. On the other hand, no significant differences among three consecutive sessions for all three variables derived from CMC (*PF*, *RFD* and *RFR*) are obtained only for self-selected frequency [$F_{[2,11]} = 2.87$, 0.54 and 2.58, respectively ($P > 0.05$)].

The effect of frequency was assessed for all three variables derived from the CMC. The repeated measures ANOVAs revealed a significant effect for all three derived variables [*PF* - $F_{[2,11]} = 6.60$ ($P < 0.01$); *RFD* - $F_{[2,11]} = 5.15$ ($P < 0.01$); *RFR* - $F_{[2,11]} = 5.38$ ($P < 0.01$)]. A post-hoc analysis of the *PF* revealed significant differences between 1 – 2 Hz and 2 Hz - SS ($P < 0.05$ and $P < 0.01$, respectively), while the post-hoc tests of both *RFD* and *RFR* revealed significant differences between 1 - 2 Hz and 1 Hz – SS ($P < 0.05$ and $P < 0.01$, respectively).

Table 1 Within- (upper part) and between-day reliability (lower part) of both the standard strength test and the test of consecutive maximum contractions performed at different frequencies (N = 12).

		Standard strength test		Consecutive maximum contractions												
				1 Hz			1.5 Hz			2 Hz			Self-selected frequency			
		F_{max} (N)	RFD_{max} (N/s)	*PF* (N)	*RFD* (N/s)	*RFR* (N/s)	*PF* (N)	*RFD* (N/s)	*RFR* (N/s)	*PF* (N)	*RFD* (N/s)	*RFR* (N/s)	*PF* (N)	*RFD* (N/s)	*RFR* (N/s)	f (Hz)
Sess. 1 (T1)	mean	894	5555	786 [b]	5226	-5621 [b]	755 [a,b]	5391 [b]	-5824 [a,b]	727 [a,b]	5709	-6276 [a,b]	797	5594	-6381	1.55
	SD	(79)	(697)	(52)	(606)	(805)	(70)	(698)	(917)	(79)	(689)	(895)	(87)	(717)	(1000)	(0.42)
Sess. 1 (T2)	mean	901	5336	779	5113	-5489	769	5391	-6055	746	5650	-6350	803	5671	-6431	1.55
	SD	(79)	(687)	(59)	(826)	(867)	(90)	(762)	(1050)	(81)	(647)	(830)	(96)	(700)	(1198)	(0.41)
Sess. 1 (T3)	mean			776	5039	-5661	760	5293	-5860	744	5673	-6422	793	5590	-6200	1.57
	SD			(70)	(740)	(882)	(67)	(5249	(702)	(85)	(539)	(942)	(90)	(652)	(1157)	(0.38)
ICC		0.98	0.92	0.93	0.93	0.93	0.93	0.93	0.89	0.95	0.96	0.97	0.98	0.97	0.97	0.98
95% CI		0.94-1.00	0.71-0.98	0.82-0.98	0.81-0.98	0.81-0.98	0.82-0.98	0.82-0.98	0.71-0.97	0.88-0.99	0.89-0.99	0.92-0.99	0.94-0.99	0.91-0.99	0.92-0.99	0.95-0.99
CV (%)		1.8	5.6	3.3	8.0	7.4	4.7	6.7	8.1	3.9	3.6	3.7	2.6	4.0	4.8	7.2
SEM		15	272	26	357	370	31	298	418	27	183	233	20	213	294	0
	F(2, 11)	1.10	3.92	0.43	1.05	0.70	0.61	0.48	0.85	1.53	0.24	0.99	0.63	0.54	1.62	0.12
	p	0.31	0.07	0.65	0.36	0.5	0.55	0.62	0.44	0.24	0.79	0.39	0.54	0.59	0.22	0.9
Sess. 2	mean	884	5400	792 [b]	5103	-6153	804 [b]	5568	-6625	786	5804	-7044 [b]	810	5533	-6591	1.47
	SD	(82)	(1032)	(81)	(866)	(991)	(86)	(692)	(851)	(89)	(639)	(1040)	(92)	(903)	(1076)	(0.41)
Sess. 3	mean	915	5609	848	5335	-6486	848	5861	-6876	817	6003	-7508	844	5727	-6975	1.46
	SD	(67)	(749)	(60)	(995)	(1049)	(64)	(847)	(900)	(52)	(638)	(828)	(66)	(679)	(1130)	(0.37)
ICC		0.92	0.91	0.80	0.90	0.80	0.90	0.90	0.86	0.89	0.90	0.94	0.85	0.84	0.84	0.94
95% CI		0.78-0.97	0.75-0.97	0.47-0.94	0.73-0.97	0.46-0.94	0.73-0.97	0.74-0.97	0.64-0.96	0.72-0.97	0.75-0.97	0.83-0.98	0.59-0.95	0.57-0.95	0.57-0.95	0.83-0.98
CV (%)		4.1	9.7	6.1	7.9	11.3	4.9	6.5	7.4	5.2	5.2	6.5	7.1	9.1	12.3	11.3
SEM		36	453	46	375	667	37	341	466	38	283	427	53	446	764	0
	F(2,11)	2.26	0.85	7.61*	0.92	5.79*	18.60*	4.92*	14.2*	16.6*	1.62	34.01*	2.87	0.54	2.58	1.12
	p	0.13	0.44	<0.05	0.41	<0.01	<0.01	<0.05	<0.01	<0.01	0.22	<0.01	0.08	0.59	0.09	0.35

F_{max} and RFD_{max} – maximum force and the rate of force development of the standard strength test; PF, RFD and RFR – peak force, and the rates of force development and relaxation of the consecutive maximum contractions; f – frequency; T – trials within Session; CC – intra class correlation coefficient; 95% CI – confidence intervals; CV- coefficients of variation; SEM – standard error of measurement; [a] – significantly different from sess.2; [b] - significantly different from sess.3; 95% CI – 95% confidence intervals.

Experiment 2:

Experiment 2 was conducted in order to assess the relationship among the variables obtained from the same test as well as to assess the generalizability of these relations across different muscle groups. In addition, the effect of normalization was evaluated for both SST and CMC tests. Namely, RFD_{max} in SST as well as RFD and RFR in CMC were normalized for the corresponding maximum force (e.g., Fmax and PF, respectively). Note that the CMC was performed only at the self-selected frequency since high reliability as well as no significant difference with 1.5 Hz and only slight differences with the other two frequencies (e.g., 1 Hz and 2 Hz) were shown in Experiment 1 (see the previous paragraph). Regarding SST, the correlation coefficients between F_{max} and RFD_{max} across different muscle groups were 0.72 – 0.84 ($P < 0.01$) suggesting a moderate to high relationship. Similarly, the CMC performed on different muscle groups revealed moderate to high correlation coefficients between the PF and both RFD and RFR [0.76 – 0.87 ($P < 0.01$) and (-0.79) – (-0.87) ($P < 0.01$), respectively].

Table 2 Strength and rate of force changes and the correlation coefficients (R) between them, obtained in SST and CMC
(all correlation coefficients significant at $p< 0.01$)

	Standard strength test		Consecutive maximum contractions (self-selected frequency)		
	F_{max}	RFD_{max}	*PF*	*RFD*	*RFR*
Knee Ext	847.1 (130.2)	4167.8 (790.0) $R_{Fmax}=0.79$	788.3 (146.1)	4560.3 (921.1) $R_{PF}=0.82$	-5274.0 (1208.3) $R_{PF}=-0.86$
Knee Flx	300.4 (62.5)	1612.3 (381.8) $R_{Fmax}=0.84$	239.8 (48.7)	1562.7 (333.8) $R_{PF}=0.76$	-1296.1 (326.5) $R_{PF}=-0.79$
Elb Ext	283.4 (41.5)	1671.4 (341.5) $R_{Fmax}=0.72$	255.9 (40.1)	1726.9 (407.0) $R_{PF}=0.76$	-1450.2 (335.7) $R_{PF}=-0.86$
Elb Flx	404.9 (63.0)	2284.7 (390.2) $R_{Fmax}=0.82$	355.1 (56.8)	2366.2 (440.0) $R_{PF}=0.87$	-2067.0 (445.1) $R_{PF}=-0.87$

The main finding of this study is related to the differences between the outcomes of two PCAs performed separately on the variables derived from both the SST and CMC. Namely, these two PCAs were applied prior to and following the appropriate normalization of the derived variables. Regarding SST, prior to normalization (the left part of Table 3) the PCA revealed three principal components or factors which accounted for 81.2% of the variance of all the selected manifest variables. The highest correlations (i.e., 'factor loading') with the first principal component (see Table 3) were demonstrated by F_{max} and RFD_{max} recorded in the knee and elbow flexors. The second principal component was loaded by F_{max} and RFD_{max} of the knee extensors, while the third principal component was loaded by F_{max} and RFD_{max} of the elbow extensors. The second PCA was applied to the same set of data where RFD_{max} was normalized for F_{max} (the right part of Table 3). The results also revealed three principal components which explained 66.1% of the variance of all selected manifest variables. The first component was loaded by F_{max} recorded in three different muscle groups (e.g., knee and elbow extensors and elbow flexors). Note that the correlations of the remaining F_{max} (e.g., knee flexors) with this principal component are very close to the highest one. The second principal component was loaded by the RFD_{max} recorded in three different muscle groups (e.g., the knee and elbow extensors and elbow flexors). The third principal component was loaded by the F_{max} and RFD_{max} recorded in the knee flexors.

Table 3 PCA conducted both prior to and following the normalization of the variables (F_{max} - maximum force; RFD_{max} - rate of force development) of standard strength test (SST) recorded on different muscle groups (N = 36).

SST variables	Non normalized data				Normalized data			
	Factor loadings			Communalities	Factor loadings			Communalities
	1	2	3		1	2	3	
Knee ext F_{max}	.214	**.866**	.203	.837	**.750**	.005	.172	.592
Knee ext RFD_{max}	.202	**.922**	.138	.909	-.073	**.816**	.031	.673
Knee flx F_{max}	**.886**	.000	.047	.787	.604	.157	**-.684**	.857
Knee flx RFD_{max}	**.876**	.166	.195	.834	.407	.187	**.752**	.766
Elb ext F_{max}	.154	.095	**.919**	.878	**.619**	-.076	.141	.409
Elb ext RFD_{max}	.153	.239	**.880**	.855	.218	**.595**	.336	.514
Elb flx F_{max}	**.738**	.306	.167	.666	**.802**	.026	-.106	.655
Elb flx RFD_{max}	**.756**	.376	.147	.734	-.089	**.898**	-.106	.826
Eigenvalue	4.037	1.387	1.076		2.259	1.851	1.182	
% of Variance	50.462	17.335	13.451		27.249	23.659	15.241	

Regarding CMC, prior to normalization (the left part of Table 4) the PCA revealed three principal components or factors, which accounted for 80.0% of the variance of all the selected manifest variables. The highest correlations (i.e., 'factor loading') with the first principal component (see Table 4) were demonstrated by *PF*, *RFD* and *RFR* recorded in the knee flexors and elbow extensors. The second principal component was loaded by *PF*, *RFD* and *RFR* of the knee extensors, while the third principal component was loaded by the *PF*, *RFD* and *RFR* of the elbow flexors. The second PCA was applied to the same set of data where the *RFD* and *RFR* were normalized for *PF* (the right part of Table 4). The results revealed four principal components which explained 70.9% of the variance of all the selected manifest variables. The first component was loaded by the *RFD* recorded

Table 4 PCA conducted both prior to and following the normalization of the variables (PF - maximum force; RFD - rate of force development; RFR – rate of force relaxation) of consecutive maximum contractions (CMC) recorded on different muscle groups (N = 36)

SST variables	Non normalized data				Normalized data			
	Factor loadings			Communalities	Factor loadings			Communalities
	1	2	3		1	2	3	
Knee ext _PF	.092	**.891**	.205	.845	-.032	.176	**.843**	-.200
Knee ext _RFD	-.034	**.839**	.279	.783	**.649**	.196	-.263	-.256
Knee ext _RFR	-.018	**-.907**	-.144	.843	.177	**.682**	.018	-.445
Knee flx _PF	**.799**	-.223	.321	.845	-.033	.075	.244	**.878**
Knee flx _RFD	**.717**	-.113	.375	.667	**.789**	-.155	.133	-.364
Knee flx _RFR	**-.774**	.046	-.314	.700	.160	**.777**	-.046	.017
Elb ext _PF	**.707**	.489	.072	.745	-.015	.063	**.734**	.290
Elb ext _RFD	**.662**	.470	.300	.749	**.783**	.034	.354	.144
Eigenvalue	**-.750**	-.538	-.055	.855	.023	**.662**	.361	.039
% of Variance	.261	.261	**.868**	.889	.162	.045	**.681**	.363

in all four different muscle groups (e.g., the knee and elbow extensors and knee and elbow flexors). The second principal component was loaded by *RFR* recorded also in all four different muscle groups. The third principal component was loaded by the *PF* recorded in three different muscle groups (e.g., the knee and elbow extensors and elbow flexors). The forth principal component was loaded by the *PF* recorded in the knee flexors. However, of the utmost importance for the present study is that in both the SST and CMC the applied normalization caused the same variables recorded across different muscle groups to load the same principal components.

DISCUSSION

Within the present study we extended our previous research in order to additionally assess (1) intra- and inter-session reliability, and (2) generalizability and factorial validity of CMC variables. Specifically, we aimed to assess the reliability of the variables of CMC and SST within and between sessions, as well as to evaluate the possible differences between the externally paced and self-selected CMC. In addition, we assessed the relationship among the variables obtained from the same test as well as the generalizability of these relations across different muscle groups (the knee and elbow flexors and extensors). Finally, the principal component analysis was applied to both non-normalized and properly normalized data in order to assess the relationship among the measured variables of SST and CMC.

Although we hypothesized that the outcomes of the analysis (i.e., the factors), will discern both between the standard strength test (SST) and the test of consecutive maximum contractions (CMC), as well as between their *F* and *RFD*, the obtained factors mainly discerned among the muscle groups for non-normalized data, but also for neuromuscular characteristics for data normalized regarding to F_{max}.

Within the first experiment we evaluated the within and between day reliability of the applied measurements (Hopkins, Schabort et al. 2001) to test the repeatability of the novel test (i.e. the reliability of the obtained variables) in cases where the post-test is applied both shortly after the pretest, and after longer time intervals. Based on the data presented in Tables 1 and 2, it could be concluded that the results obtained in the SST and CMC revealed high within and between day reliability, which is consistent with the findings from earlier studies (for details see the review articles (Abernethy et al., 1995; Hopkins, Schabort, & Hawley, 2001; Wilson & Murphy, 1996). In both cases (within and between sessions), high intra-correlation coefficients (0.82 - 0.90) were obtained within the tested variables. In addition, all the measurements had small within measurement variation, with lower values regarding the maximum force (F_{max} and PF) compared to corresponding values for the rates of force change (RFD_{max}, *RFD* and *RFR*). Data obtained initially on different days, for the SST and CMC variables also revealed a high ICC at the range 0.80 - 0.92.

The limitation of the results obtained in the first experiment, could be that the reliability analysis was performed only for the data obtained on the single muscle group. As movement is governed and exerted by the number of muscles, the behavior of different muscle groups should additionally be explored. In the second experiment, the same neurophysiological characteristics were captured for four muscle groups (flexors and extensors of the knee and the elbow joint). As the muscle force is dependent on the cross sectional area it should not come as a surprise that F_{max} (Mirkov et al., 2004), and RFD (Aagaard, Simonsen, Andersen, Magnusson, & Dyhre-Poulsen, 2002), and RFD obtained for the knee extensors were higher when compared to the corresponding values obtained in the flexors (Table 3). The consistent results regarding the differences among the variables between antagonistic muscle groups were obtained in both the SST and CMC tests (Table 3). As expected, due to their anti-gravitational role, knee extensors and elbow flexors force as well as RFD were higher when compared to the corresponding values obtained for the knee flexors and the elbow extensors. The correlation coefficients among the variables in the CMC suggested a strong relationship between strength indices and rate of force changes regardless of the frequency on which the test were applied. Therefore, for the second experiment, the CMC were applied only on the self-selected frequency (Suzovic et al., 2008).

The main findings in the second experiment refer to the relationship among the variables prior to and after normalization. When the PCA was performed on non-normalized data, in both the SST and CMC, consistent results regarding grouping factors were obtained (the left columns of Table 3 and Table 4, respectively). Namely, in both tests, the PCA discerned three significant principal components explaining 81.2% and 80.0% of the variance of selected variables. These three factors correspond to the tested muscle groups rather than the possible different properties (forces and rate of force changes).

When the PCA was performed on the set of data where the rate of force changes were normalized (the right columns of Table 3 and Table 4), three factors were loaded and four factors were loaded for variables recorded in CCT, explaining 66.1% and 70.9% of the variance of selected variables, respectively. In the SST, the major components were discerned between F_{max} and RFD_{max} but without accounting for the muscle type as an additional differentiating factor. When the PCA was performed on CMC variables, the factors discerned between the *PF*, *RFD* and *RFR* in three out of four tested muscle groups (knee and elbow extensors and elbow flexors), while the latest component isolated the F_{max} of the knee flexors. Based on the findings obtained on the data where rate of force change indices were properly normalized, it could be concluded that the strength and rate of change indices partly represent the independent properties of muscles.

Although some authors have reported low to moderate correlations between the F_{max} and RFD_{max} (Holtermann et al., 2007; Wilson & Murphy, 1996), the high correlations between F_{max} and RFD_{max} obtained in SST for all four muscle groups are in agreement with the results obtained in some other studies (Aagaard et al., 2002; Mirkov et al., 2004). The correlations between the *RFD* and *RFR* obtained in CMC for all the studied muscle groups ($r = 0.76$ to $r = 0.87$) were higher than the corresponding values obtained in SST. This indicates that RFD and RFR describe each other with 40 - 86%. On the basis of a positive correlation between the *RFD* and *RFR* it could be proved that the indicators of *RFD* and *RFR* are inter-correlated.

CONCLUSION

The selected characteristics of the knee and elbow antagonistic muscles, included in the most everyday movements, and of importance for movements performed, were explored in the second experiment. The obtained results revealed a positive but moderate correlation between the observed neuromuscular characteristics, which lead us to the conclusion that measuring of the CMC for a muscle group could not lead us to argue with certainty that the results could be applied to all the muscle groups of the same person. This partially supports the claim that neuromuscular characteristics obtained from the CMC could be generalized to all muscle groups. However, our findings also suggest that the assessment of the neuromuscular system through muscle strength could require testing more than a single one or two antagonistic muscles acting in a single joint.

This study resolved several important methodological issues about the assessment of neuromuscular function. The SST and CMC tests differ in their measurement protocols of neuromuscular function as well as the number of attempts needed to determine all the required variables for a complete muscle function. The scheme of neural activation for fast and long-lasting muscle contraction is different. Standard tests are based on long-term contractions, which cannot record the neural activation pattern typical for rapid force exertion, which could be inappropriate for movements with restricted time to develop a relatively high force [walking, running, correcting the position (Holtermann et al., 2007; Mirkov et al., 2004; Pijnappels et al., 2005)]. CMC, as a novel test, enabled greater access and opportunity for easy assessment of neuromuscular function.

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POUZDANOST I GENERALIZACIJA UZASTOPNIH MAKSIMALNIH KONTRAKCIJA KAO TESTA NEUROMIŠIĆNIH FUNKCIJA

Cilj ovog istraživanja bio je da se ispitaju pouzdanost, generalizacija, kao i faktorska validnost unutar sesije i između sesija preporučenog novog testa neuromišićnih funkcija. U prvom eksperimentu učestvovalo je 12 ispitanika koji su izvodili standardni test jačine (STJ) i novi test zasnovan na uzastopnim maksimalnim kontrakcijama (UMK) primenjen na opružač u zglobu kolena. U okviru drugog eksperimenta učestvovalo je novih 36 ispitanika koji su izvodili testove STJ i UMK na opružačima i pregibačima u zglobu kolena i zglobu lakta. Dobijeni rezultati za STJ i UMK test pokazuju visoku povezanost između testa i retesta ostvarenih uzastopnim danima za većinu izmerenih varijabli (ICC u opsegu 0.80-0.92). Faktorska analiza primenjena na STJ izdvojene su 3 komponente koje objašnjavaju 81.2% za nenormalizovane i 66.1% za normalizovane podatke. Sa druge strane, faktorskom analizom primenjenom na svih 16 nenormalizovanih varijabli testa UMK izdvojena su 3 komponente koje objašnjavaju 80% varijanse. Sledeća faktorska analiza primenjena na brzinu razvoja sile i brzinu smanjenja sile (BRS i BSS), normalizovane u odnosu na maksimalnu silu izdvojila je 4 komponente koje objašnjavaju 70.9% varijanse. Nenormalizovane komponente nisu bile raspoređene prema različitim mišićnim grupama, već prema varijablama iste mišićne grupe. Posle normalizacije pojedini faktori su izdvojili varijable iste mišićne grupe. Rezultati UMK testa pokazali su da su BRS i BSS nezavisne varijable. Test UMK mogao bi da bude moguća alternativa STJ jer se njime mogu proceniti varijable jačine mišića na osnovu jednog pokušaja, zasnovanog na relativno manjim silama.

Ključne reči: *fleksori, ekstenzori, jačina, BRS, BSS.*