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Relationships among the muscle strength properties as assessed through various tests and variables

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Abstract

We tested the hypotheses that the individual strength properties depend on the applied test and the variable extracted, rather than on the muscle group tested. Flexor and extensor muscles acting in the knee and elbow joint were tested in 58 participants. The standard strength test (SST; based on sustained maximum contraction) and alternating consecutive maximum contractions (ACMC; alternating contractions of antagonistic muscles) performed under static conditions were separately applied to provide the maximum force (F) and the rate of force development (RFD) of each tested muscle. The principal component analysis applied on all 16 variables revealed 3 factors that explained 85.5% of the total variance. Contrary to our hypotheses, the individual factors were loaded with the variables recorded from individual muscles, rather than with either the particular variables or tests. The present findings suggest that recording both F and RFD in routine strength testing procedures could be redundant since they may assess the same strength property of the tested muscle. In addition, ACMC may be a feasible alternative to SST since it could assess the same strength properties from two antagonist muscles through a single trial, while being based on relatively low and transient forces.

Keywords

flexor; extensor; force; contraction; isometric

Introduction

The assessment of function of the neuromuscular system is of profound importance in human movement science. A large variety of routine procedures have been employed in both clinical and non-clinical assessments with purposes such as the exploration of intrinsic risk factors due to sport injury, identifying performance-limiting factors, monitoring the effects of training and rehabilitation programs, comparisons among the individuals and

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populations, and talent identification (Abernethy et al., 1995, Astrand, 1986, Jaric, 2002, Wilson and Murphy, 1996).

In addition to various tests of functional movements, the most frequent assessment of the neuromuscular function has been based on strength testing (Abernethy et al., 1995, Wilson and Murphy, 1996). Muscle strength usually refers either to maximum force (such as recorded by a dynamometer) or torque (recorded by isokinetic apparatus) exerted by the tested muscle group (Astrand, 1986, Sale, 1991). However, note that the routine strength testing procedures applied in athletic training and rehabilitation research have been usually focused upon individual muscle groups (Aagaard et al., 2002, Matavulj et al., 2001, Ugarkovic et al., 2002). Similarly, the routine batteries of physical fitness typically include a single test of muscle strength (e.g., the grip strength; (Eurofit, 1988, Suni et al., 2010)), while a few other test items may assess muscles' ability to overcome the load originating from the subject's own body (e.g., push-ups, chin-ups) which inevitably provides a body size dependent outcome (Jaric, 2003). That approach has been apparently based on an implicit presumption that the strength measures recorded from a single or several muscles can be generalized across the muscular system of the tested individual. However, that presumption remains questionable since a number of studies have revealed moderate relationships among the strength properties obtained from different muscles of the same individual (Bellumori et al., 2011, Jaric et al., 1989, Sahaly et al., 2001). Therefore, it still remains unclear whether one or, alternatively, several muscles acting around different joints need to be tested in order to assess the strength generating capacity of the entire neuromuscular system.

The most often applied test of muscle strength has been the *standard strength test* (SST) based on the sustained maximum voluntary contraction of a selected muscle performed under either isometric or concentric contraction conditions (Abernethy et al., 1995, Jaric, 2002, Wilson and Murphy, 1996). The regularly recorded SST variable has been the *maximum voluntary force* (F), typically achieved after 3–5 s of a sustained contraction (Sahaly et al., 2001, Wilson and Murphy, 1996). The face validity of F has not only been based on the presumed correspondence with the maximum force that the particular muscle exerts in various functional tasks, but also on the dependence of F on both the central (i.e., neural) and peripheral (muscular) factors. However, in addition to recording F, SST has also been frequently used to record the *maximum rate of force development* (RFD). RFD has been usually obtained from the recorded force–time curve, most frequently as the maximum of its derivative (i.e., the peak dF/dt ; (Aagaard et al., 2002, Izquierdo et al., 1999, Jaric et al., 1989, Matavulj et al., 2001, McLellan et al., 2011, Zebis et al., 2011)). RFD has been generally used to assess the explosive strength qualities of the neuromuscular system (Aagaard et al., 2002, Gruber and Gollhofer, 2004), the ability for executing high-performance movement tasks with limited duration (Aagaard et al., 2002, Gruber and Gollhofer, 2004, Hakkinen et al., 1985, Hakkinen et al., 1986, McLellan et al., 2011), and the effects of athletic training procedures (Matavulj et al., 2001). However, the relationship between F and RFD obtained from the same muscle still remains unclear. Several studies have suggested that the ability to develop high F and the ability to develop F rapidly (i.e., RFD) could be partly independent properties of the neuromuscular system (Izquierdo et al., 1999, Jaric et al., 1989, McGuigan et al., 2010, Sahaly et al., 2001), which may be selectively affected by the applied training and rehabilitation interventions (Holtermann et al., 2007, Zebis et al., 2011). Nevertheless, it is also known that both F and RFD are positively related with body size (Jaric, 2003) (Jaric et al., 2005) and, more specifically, muscle size (Bellumori et al., 2011). As a result, it is not surprising that several studies have revealed significant positive relationship between F and RFD obtained from the same muscle (Bozic et al., 2012, Holtermann et al., 2007, Mirkov et al., 2004). Therefore, it remains unknown to which extent F and RFD assess the same strength property of the tested muscle. From the practical point of view, the question is whether the routine strength tests

should record both F and RFD of each tested muscle or, alternatively, recording both of them is redundant.

Despite its frequent use, both the validity and applicability of SST have often been questioned. The reasons for that are not only both the excessive forces exerted (Abernethy et al., 1995, Wilson and Murphy, 1996) and a large number of trials needed for a reliable assessment of both F and RFD (Sahaly et al., 2001, Wilson and Murphy, 1996), but also the associated pattern of neural activation that may not capture the neural activation pattern typical for rapid cyclic movements (Enoka and Fuglevand, 2001, Holtermann et al., 2007, Van Cutsem et al., 1998). To address those shortcomings, we recently proposed the test of *alternating consecutive maximum contractions* (ACMC) that allows for the assessment of two antagonist muscles within a single trial (Bozic et al., 2011, Suzovic et al., 2008). The outcome of ACMC typically provides a quasi-sinusoidal force-time pattern with a self-selected frequency approximately between 1 and 1.5 Hz that reveals F and RFD exerted in the direction of action of each of the tested antagonistic muscles (Bozic et al., 2011, Bozic et al., 2012). The same studies revealed a high concurrent validity if ACMC with respect to both SST and standard isokinetic tests. From the perspective of the present study, of importance here are the differences between the strength properties observed from the two tests. Namely, while F and RFD obtained from SST mainly originate from the action of the tested muscles, the same variables obtained from both ACMC and other functional tests based on alternating contractions of antagonistic muscles (e.g., the tests based on jumping, or running) should better reflect the action of two antagonistic muscles acting around the joint (Jaric et al., 1997, Jaric et al., 1995). For example, the rate of change of the net muscle force assessed by RFD obtained through ACMC should result from both an increased agonist contraction and decreased antagonist contraction. The mechanisms of neural activation could also be different in SST and ACMC (Enoka and Fuglevand, 2001, Van Cutsem and Duchateau, 2005). Therefore, although these two tests have revealed a similar external validity (Bozic et al., 2011, Bozic et al., 2012), it still remains unknown to what extent the ACMC and other muscle tests based on cyclic force exertion assess different strength properties from those assessed through SST.

To address the questions raised above we designed a study aimed to explore the relationships among the strength properties of different muscle groups obtained through different strength tests. In particular, we evaluated the muscle strength through both F and RFD of different muscle groups acting in two joints and, thereafter, subjected the comprehensive set of variables obtained through 2 different tests to the principle component analysis. The loading of the individual principal components or factors was expected to reveal the similarities among particular variables. Based on the implicit presumption of strength assessment based on testing either a single or very few muscle groups (see above for details), we hypothesized that the results would reveal the differences between the muscle strength variables (i.e., F vs. RFD) and tests (SST vs. ACMC), rather than between the different muscles and joints.

Methods

Subjects

Fifty-eight physically active non-athletes (29 males, 29 females; age 21–55 years) participated in the study. All of them claimed to be both physically active and right-handed, while their body-mass index was below 30. None of them reported any neurological problem, cardio-respiratory problem, chronic disease, or recent injuries to the musculoskeletal apparatus. Their daily physical activity (on the-job activity and leisure-time activity) was assessed by a standard questionnaire (Taylor-Piliae et al. 2006). Three subjects reported low, 26 reported light-intensity, and 29 reported moderate-intensity activity. All

participants received a verbal explanation regarding the purpose and procedures of the study, as well as the information regarding possible risks. They signed an institutionally approved informed consent document according to the Helsinki Declaration.

Muscle function tests

The muscle strength tests were conducted on the flexor and extensor muscles acting in both the knee and elbow joint using a standard Kin-Com isokinetic dynamometer (Chatex Corp., Chattanooga, TN) set to static condition. The subject was fixed to the dynamometer by wide and tight straps according to manufacturer recommendations. The axis of the dynamometer was aligned with the knee and elbow joint axes and both joints were set to 120° (180° being full extension).

Standard Strength Test (SST)—We selected the maximum isometric exertion of muscle force as the most often applied muscle function test (Abernethy et al., 1995, Jaric, 2002). The subjects were instructed “to rapidly exert the maximum force” against the band attached to the dominant lower leg and to retain it for 3–4 s (Wilson and Murphy, 1996). The extensor and flexor muscle acting around both the knee and elbow joint were tested separately. On-line feedback regarding the current force was shown at a computer monitor positioned in front of the subject and verbal encouragement was provided. Three trials per muscle group were performed within the session. The rest interval between the consecutive trials was 2 min. Note that SST has demonstrated high reliability (Abernethy et al., 1995, Bozic et al., 2011).

Alternating Consecutive Maximum Contractions (ACMC)—The selection of the test was based on its partial similarity to the muscle action regime typical for various rapid and cyclic movements (see Introduction for details). The subjects were instructed to consecutively exert the alternating maximum contractions of knee and elbow extensors and flexors “as strong and as quickly as possible” providing a quasi-sinusoidal force profile. Therefore, frequency of the alternating maximum contractions was self-selected (Bozic et al., 2011, Bozic et al., 2012). The feedback regarding the current force was shown on a computer monitor positioned in front of the subject. Each trial was initiated in the direction of the extension and its duration covered at least 5 full cycles. Three trials per session were performed with each joint. Note that ACMC variables have revealed moderate-to-high reliability (Bozic et al., 2012, Suzovic et al., 2008).

Experimental protocol

The testing procedure was performed within a single experimental session conducted within a university research laboratory. The same test leaders supervised all tests. The session was preceded by a standard 10-min stationary cycling and stretching procedure. Thereafter, the tests of knee and elbow muscles were performed in a random sequence, while ACMC always preceded SST conducted on the same muscles. The sequence of the SST applied on flexors and extensors was also randomized. The first trial was considered as practice, while out of the following two experimental trials the one with higher product of F and RFD was taken for further analysis (Bozic et al., 2011, Bozic et al., 2012). The ACMC trials showing inconsistent force profiles (i.e., the relative differences between consecutive peaks in either direction exceeding 10%) were repeated. The rest among the trials was 2 minutes, while about 5 minutes was needed for adjusting the device for another joint. When asked after completing either the SST and ACMC procedure, none of the subjects reported fatigue. Note that several recent studies have reported that a similar procedure could generally be fatigue-free (Bozic et al., 2011, Bozic et al., 2012, Suzovic et al., 2008).

Data acquisition and processing

A custom-made Lab View program (National Instruments Corporation, Austin, TX, USA) was used for data acquisition and processing, as well as for on-line visual inspection. The force–time curves recorded by the dynamometer were low-pass filtered (10 Hz) using a fourth-order (zero-phase lag) Butterworth filter. The force maxima (F) were assessed from each SST trial, as well as from each cycle of ACMC in both directions. Thereafter, derivatives of the force–time curves were calculated within a 20-ms moving average window providing the corresponding maximum rates of force development (RFD) for each force direction separately ((Bozic et al., 2012); see Fig.1 for illustration). The self-selected frequency of ACMC was calculated from the time intervals between the consecutive force peaks (Bozic et al., 2012). F and RFD variables observed from individual ACMC trials were calculated separately for each force direction as averaged values obtained from the last three cycles. Finally, note that both the theoretical models and experimental findings suggest that the results of F (Astrand, 1986, Jaric, 2002) and RFD (Mirkov et al., 2004) increase with body size, approximately proportionally to body mass on power $2/3$. Therefore, to account for the body size differences both within and between two gender groups, we divided all variables by the body mass on the power of $2/3$ (Astrand, 1986, Jaric et al., 2005).

Statistical analysis

Descriptive statistics were calculated using mean values and standard deviations. The Kolmogorov-Smirnov test was applied to assess the normality of distribution of all variables obtained from SST and ACMC. The relationships among the same variables were assessed by the Pearson's product–moments. The corresponding inter-correlation matrices of all variables were factorized using principal components factor analysis (PCA) (Nunnally and Bernstein, 1994). The data was analyzed using the FACTOR procedure in the SPSS (version 10.0) software package. The number of significant principal components or factors in the factor pattern matrix extracted by the PCA was determined by the Kaiser-Guttman criterion (Nunnally and Bernstein, 1994), which retains principle components with eigenvalues greater than 1. The original factor pattern matrix was rotated using a non-orthogonal Promax criterion with Kaiser normalization to improve the simple structure of the matrix. The final outcomes were the commonalities and factor loadings for each manifest variable, eigenvalues, and percentages of variance explained by each rotated principal component. Statistical significance was set at $P < 0.05$. Data were analyzed using SPSS 17.0 software (SPSS Inc, Chicago, IL, USA).

Results

Figure 1 shows typical force–time curves and their derivatives that served for the assessment of maximum forces (F) and their rates of development (RFD), respectively. In line with the data averaged across the subjects (see further text for details), the visual inspection suggests relatively stable values of ACMC variables across the three consecutive cycles. The same applies to F obtained from ACMC that appeared to be somewhat lower than F obtained from SST, while the opposite is true for RFD.

Descriptive statistics are presented in the upper part of Table 1. As expected, males revealed larger indices of body size than the females. The lower part of the table shows the variables normalized for body size of the standard strength tests (SST) and the alternative consecutive maximum contraction (ACMC) applied on the antagonistic muscle groups acting around the knee and elbow joint. Note that despite the applied normalization for body size, moderate differences between the genders remained. Nevertheless, the residuals of all variables of the muscle function tests appeared to be normally distributed not only regarding the individual genders, but also regarding the pulled data (Kolmogorov–Smirnov test, all $p > 0.17$). In line

with the data obtained from a representative subject (Fig. 1), corresponding F were higher in SST than ACMC, while the opposite was true for RFD, particularly regarding knee flexors. The self-selected ACMC frequency was similar across the different genders, as well as the joints. In particular, the frequency in both joints was 1.17 (0.19) Hz for males, while the females revealed 1.15 (0.14) and 1.14 (0.21) Hz in the knee and elbow joint, respectively. F obtained from three consecutive cycles of individual ACMC trials were fairly consistent revealing the averaged coefficients of variations for knee extensors and flexors were 3.5% and 1.6%, and 4.6% and 1.6%, for the elbow extensors and flexors, respectively.

Table 2 presents the Pearson's correlations observed among all 16 variables obtained from SST and ACMC. All correlation coefficients were positive and within the range from 0.37 to 0.95 (median $r = 0.56$; all $p < 0.01$).

Table 3 depicts the results of the PCA conducted on 16 variables obtained from different tests and muscles. Three principal components or factors were found accounting for 85.5% of the variance in all selected manifest variables. In general, the results revealed a consistent structure of individual factors. The highest correlations (i.e., 'loading') with the first factor were demonstrated by all variables obtained from the elbow flexor and extensor muscles independently of either the applied test or selected variable. The second and third factors were mainly loaded with the variables obtained from the knee extensors and knee flexors, respectively. The only exception was RFD of the knee flexors recorded by ACMC that loaded the second, but not the third factor.

Discussion

The main aim of the present study was to explore the relationships among the maximum forces (F) and the rates of force development (RFD) separately observed through the standard strength test (SST) and the test of alternating consecutive maximum contractions (ACMC) applied on different muscles. Instead of testing the relationships between particular pairs of variables [as it was done in recent studies; (Bozic et al., 2011, Bozic et al., 2012, Suzovic et al., 2008)], we subjected the entire comprehensive set of variables to principle component (i.e., factor) analysis. Although we hypothesized that the results of the analysis (i.e., the individual factors) would discern between the tests and variables, the results mainly discerned among the muscle groups.

Prior to discussing the observed findings from both the theoretical and practical aspects, several methodological issues need to be addressed. Although having closer to 5 subjects per variable could be of a methodological advantage, the number of the participants tested in the present study still exceeds both the minimum acceptable level (Nunnally and Bernstein, 1994) and the typical number tested in similar studies of the properties of muscle strength (see (Jaric, 2002, Wilson and Murphy, 1996) for review). The variables depicting the tested strength were not only highly reliable (Bozic et al., 2012, Suzovic et al., 2008), but were also moderately to strongly related, suggesting an appropriate selection of dependent variables (Nunnally and Bernstein, 1994). The exceptionally high cumulative variance explained by the extracted factors (i.e., 85.5%) also suggests that the selected non-orthogonal Promax rotation could have been a right choice. Finally, one could question pooling the data for two genders together, since marked differences in the strength properties still remained even after the normalization for body size. However, note that none of the variables revealed violation of normality, as well as that our pilot factor analyses performed separately on two genders (data not shown) revealed virtually identical factor structures to the present one. For example, when either the male and female populations were tested separately only 2 variables exchanged their positions within the factors 2 and 3, while the loading of the factor 1 remained unchanged. Therefore, we believe that the

involvement of both male and female subjects added to the external validity of our finding without diminishing their trustworthiness.

Regarding the main findings of the present study, we hypothesized that the analysis would discern both between the obtained variables and between the applied tests, rather than among the tested muscles. The hypothesis was based on partly different neuro-mechanical properties and processes involved in the exertion of a high force (i.e., F) and a rapid force exertion (RFD), as well as on the same differences associated with the force production in sustained (such as in SST) and brief alternating contractions (ACMC). Note that the routine procedures applied in the rehabilitation and athletic procedures also implicitly suggest that the outcomes obtained from either a single or very few muscles could be generalized across the muscular system (see Introduction for review). However, the first factor was loaded with *all* 8 strength variables observed from elbow muscles, while the second and third factor were loaded with the remaining 8 variables obtained from the knee muscles. With the exception of the ACMC variables obtained in the direction of flexion that were shared between the factors, the variables related to knee extensors loaded the second, and those related to knee flexors loaded the third factor. Therefore, contrary to our hypothesis, the applied PCA discerned among the tested muscles, rather than between the applied tests and their variables.

Since the extracted factors are expected to reveal relatively independent strength properties of the neuromuscular system, these data generally suggest that both the tests (i.e., SST and ACMC) and their variables (F and RFD) could assess the same strength property of a tested muscle. Regarding the similarity of the observed outcomes, note that although both tests recorded the strength of the same muscles, they could still differ regarding both the level of co-contraction (Bozic et al., 2012) and the neuro-mechanical conditions at the initiation of muscle activation (Enoka and Fuglevand, 2001, Komi and Bosco, 1978, Van Cutsem and Duchateau, 2005). However, the differences in their co-contraction levels have not yet been properly explored, while the differences in neuro-mechanical conditions could be relatively ineffective due to the static nature of both tests. Therefore, a future EMG analysis of both static and dynamic muscle actions could shed a light on the causes of both the similarities, as well as differences in the strength properties assessed through SST and ACMC. Regarding the similarity in the outcome of F and RFD obtained from the same muscles, note that the pattern of neural activation could differ between the maximum sustained and explosive contractions (Enoka and Fuglevand, 2001, Holtermann et al., 2007, Van Cutsem et al., 1998). There is also evidence that F and RFD could be selectively affected by strength training and rehabilitation procedures (Gruber and Gollhofer, 2004, Holtermann et al., 2007). However, it has been also suggested that F and RFD could be closely related, particularly through the muscle size (Bellumori et al., 2011). Therefore, several authors have considered presenting RFD per unit of F (Aagaard et al., 2002, Sahaly et al., 2001), which is apparently in line with our findings.

Implication of our findings could be of considerable importance for revisiting standard methods of strength testing. First, the results suggest that F and RFD obtained through various strength tests could be highly related. Therefore, only F should be recorded due to both a simpler procedure as well as higher reliability, as compared with RFD (Abernethy et al., 1995, Bozic et al., 2011, Wilson and Murphy, 1996). Second, SST and either ACMC or other tests based on alternating activity of antagonist muscles could record the same strength properties of the tested muscles. Therefore, the present findings suggest that ACMC could be an alternative, rather than a supplementary test to SST. Note that ACMC could have apparent advantages over SST, such as exposing the muscle and joint tissues to lower and transient forces, while allowing for the testing of 2 antagonistic muscles within a single trial (Bozic et al., 2011, Bozic et al., 2012). Third, our findings also suggest that the assessment

of the neuromuscular system as a whole through muscle strength could require testing more than a single or two antagonistic muscles acting around a single joint. More comprehensive studies based on a similar methodology as applied in the present study could provide the data regarding the intra-individual differences in strength outcomes across different muscles, joints and, perhaps, limbs.

To conclude, we found strong positive relationships both between the standard strength properties such as assessed by F and RFD, as well as between the same strength properties obtained from SST and ACMC applied on the same muscle. Conversely, the relationships between the same variables and tests obtained from different muscles were weaker. The neuro-muscular factors and mechanisms playing a role in the obtained relationships apparently deserve further studies that should include both a larger number of tested muscles and EMG recording. Regarding the implications for routine testing, the findings suggest that obtaining both F and RFD from the same muscles could be redundant. Instead, a larger number of muscles should be tested in order to obtain a more comprehensive assessment of the neuromuscular system. Finally, the tests based on alternating contractions (such as ACMC) should be recommended as an alternative, rather than as a complementary to SST, since they are likely to provide highly related outcomes. Important advantage of ACMC over SST could be a brief procedure for testing two antagonistic muscles through exertions of relatively low and transient forces.

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Figure 1.

Force-time curves (thick line, right hand axis) and their derivatives (dashed line, left hand axis) observed from a representative subject when performing the standard strength test in the direction of flexion (SST_{flx}) and extension (SST_{ext}), as well as the alternating consecutive maximum contractions (ACMC).

Table 1

Descriptive data

subjects		Male (N=29)		Female (N=29)		All (N=58)		
		mean (SD)	range	mean (SD)	range	mean (SD)	range	
	Age (year)	35.3 (9.3)	23–55	34.6 (9.8)	21–51	34.9 (9.5)	21–55	
	Body height (cm)	180.2 (4.9)	173–191	168.1 (5.5)	158–181	174 (8.0)	158–191	
	Body weight (kg)	82.9 (8.3)	68.5–109	62.0 (8.8)	51.0–84.5	72.4 (13.5)	51.0–109	
	BMI(kg/m ²)	25.5 (2.0)	21.8–29.9	21.9 (2.7)	18.3–27.5	23.7 (3.0)	18.3–29.9	
S S T	ext	<i>F</i>	42.6 (6.5)	28.3–58.1	33.0 (7.3)	15.7–49.3	37.8 (8.4)	15.7–58.1
		<i>RFD</i>	234 (31)	172–301	182 (31)	119–244	208 (41)	119–301
	KNEE	<i>F</i>	16.6 (3.2)	9.5–22.6	14.1 (2.8)	7.9–19.5	15.4 (3.2)	7.9–22.6
		<i>RFD</i>	99.6 (21.3)	53.6–143	75.0 (13.7)	49.5–104	87.3 (21.6)	49.5–143
	ext	<i>F</i>	18.9 (5.7)	10.2–29.4	12.3 (3.7)	6.3–19.8	15.6 (5.8)	6.3–29.4
		<i>RFD</i>	119 (36)	61–192	72 (26)	18–131	96 (39)	18–192
	ELBOW	<i>F</i>	19.9 (3.0)	14.0–26.0	12.3 (2.9)	6.3–17.8	16.1 (4.8)	6.3–26.0
		<i>RFD</i>	127 (25)	82–182	75 (24)	28–122	101 (36)	28–182
ACMC	ext	<i>F</i>	34.5 (5.4)	26.7–44.8	27.4 (5.6)	17.1–39.9	30.9 (6.5)	17.1–44.8
		<i>RFD</i>	266 (46)	166–367	205 (42)	117–291	235 (53)	117–367
	KNEE	<i>F</i>	12.9 (3.4)	6.7–19.6	9.9 (2.5)	6.2–15.8	11.4 (3.3)	6.2–19.6
		<i>RFD</i>	312 (55)	201–433	236 (60)	134–359	274 (69)	134–433
	ext	<i>F</i>	18.0 (3.6)	10.3–26.5	10.9 (2.8)	6.2–16.0	14.4 (4.8)	6.2–26.5
		<i>RFD</i>	203 (50)	118–298	118 (36)	56–209	161 (60)	56–298
	ELBOW	<i>F</i>	13.5 (3.6)	7.2–19.6	7.9 (2.2)	5.1–12.4	10.7 (4.1)	5.1–19.6
		<i>RFD</i>	203 (46)	125–289	114 (31)	54–185	158 (60)	54–289

SST- standard strength test; ACMC- alternating consecutive maximal contractions test; ext- extension; flx- flexion; F- maximum force (N); RFD- rate of force development (N/s)

Table 2

Correlations coefficients among the variables of two tests

		SST												ACMC											
		KNEE						ELBOW						KNEE						ELBOW					
		ext	flx	RFD	F	RFD	F	ext	flx	RFD	F	RFD	F	ext	flx	RFD	F	ext	flx	RFD	F	ext	flx	RFD	F
SST	KNEE	ext	flx	RFD	F	RFD	F	ext	flx	RFD	F	RFD	F	ext	flx	RFD	F	ext	flx	RFD	F	ext	flx	RFD	F
	ELBOW	ext	flx	RFD	F	RFD	F	ext	flx	RFD	F	RFD	F	ext	flx	RFD	F	ext	flx	RFD	F	ext	flx	RFD	F
	ACMC	ext	flx	RFD	F	RFD	F	ext	flx	RFD	F	RFD	F	ext	flx	RFD	F	ext	flx	RFD	F	ext	flx	RFD	F

N = 58, all p < 0.01 (see Table 2 for abbreviations)

Table 3

Results of PCA showing factor loadings for each manifest variable, eigenvalues, and percentage of variance explained by each rotated principal component.

		Factor loading		
		1	2	3
	<i>F</i>	.267	.874	.181
	<i>RFD</i>	.386	.683	.422
	<i>F</i>	.244	.268	.833
	<i>RFD</i>	.406	.280	.784
S S T	<i>F</i>	.880	.165	.181
	<i>RFD</i>	.848	.191	.280
	<i>F</i>	.878	.273	.210
	<i>RFD</i>	.835	.186	.314
ELBOW	<i>F</i>	.236	.884	.207
	<i>RFD</i>	.213	.714	.529
	<i>F</i>	.301	.330	.777
	<i>RFD</i>	.233	.904	.214
ACMC	<i>F</i>	.821	.251	.307
	<i>RFD</i>	.908	.231	.235
	<i>F</i>	.866	.278	.119
	<i>RFD</i>	.872	.302	.248
Variance		41.6%	25.3%	18.6%
Cumulative variance		41.6%	67.0%	85.5%
Eigenvalues		10.4	2.3	1.1