Published in final edited form as:

J Strength Cond Res. 2013 June ; 27(6): 1568–1578. doi:10.1519/JSC.0b013e3182711e21.

Evaluation of novel tests of neuromuscular function based on brief muscle actions

Predrag R. Bozic^{1,2}, Ozgur Celik¹, Mehmet Uygur³, Christopher A Knight^{1,3}, and Slobodan Jaric^{1,3}

¹Department of Kinesiology and Applied Physiology, University of Delaware, 541 S. College Ave, Newark, DE 19716, USA

²Serbian Institute of Sport and Sport Medicine, Kneza Viseslava 72, Belgrade 11030, Serbia

³Biomechanics and Movement Science Graduate Program, University of Delaware, 541 S. College Ave, Newark, DE 19716, USA

Abstract

Although widely used, the standard strength test (SST) is known to provide moderate correlations with functional measures, while being based on sustained maximum forces and a relatively large number of trials. The aim of the present study was to compare the concurrent (with respect to SST) and external validity (with respect to the standard balance and maximum power output tests) of two alternate tests of neuromuscular function based on brief isometric actions. The first test provides a slope between the rates of torque development (RTD) and peak torques (T) measured from a number of consecutive rapid actions performed across a wide range of T levels (*brief force pulses*; BFP). The second test (*alternating consecutive maximum contractions*; ACMC) provides T and RTD from multiple cycles of rapid alternating maximum actions of two antagonistic muscle groups. The results obtained from 29 young and healthy subjects revealed moderate-to-high concurrent validity of ACMC (median $r=0.56$; $p<0.05$) and its similar, if not higher external validity than SST. Conversely, both the concurrent and external validity of BFP appeared to be relatively low ($r=0.23$; $p>0.05$). Since ACMC could also have advantage over SST by being based on somewhat lower and transitional muscle forces exerted and fewer trials are needed for testing two antagonistic muscles, we conclude that ACMC could be considered as either an alternative or complementary test to SST for testing the ability for rapid exertion of maximum forces. Conversely, BFP may offer a measure of the neuromuscular system ‘as a whole’ that is complementary to SST by providing outcomes that are relatively independent of muscle size and function.

Keywords

muscle torque; validity; rate of torque development; power; balance

INTRODUCTION

The assessment of the neuromuscular function is of essential importance for various purposes, such as identifying performance-limiting factors, exploring the intrinsic risk factors of sport injuries, monitoring the effects of training and rehabilitation programs, comparisons among the individuals and groups, and talent identification (2, 55). The

assessment has been usually based on evaluation of maximum torque (T) of a particular muscle group exerted under various mechanical conditions (2, 24, 55). However, since numerous functional tasks are based on brief and forceful muscle action (e.g. jumping, sprinting, responses to postural perturbations), researchers and practitioners have been interested in “explosive” muscle strength qualities related to the ability of the neuromuscular system to rapidly exert T (1, 3, 21, 40). The most frequently calculated variable for that purpose has been the rate of torque development (RTD), which is typically calculated as the maximum derivative from the recorded torque-time curves (i.e., the peak dF/dt ; 3, 40).

The most frequently applied test of neuromuscular function (or, simply, muscle function) has been the standard strength test (SST) based on the maximum voluntary isometric action of a selected muscle group (2, 24, 55). Both T and, occasionally, RTD have been typically recorded over 3–5 s of a sustained maximum action. Although widely used, SST is known to have several shortcomings. First, the patterns of neural activation for rapid (15, 53) and sustained maximum actions (18) could be considerably different. Therefore, SST may not capture the neural activation pattern typical for rapid exertion of muscle torque which could be critical for functional tasks that require limited time for exertion of maximum T (23, 40, 48). As a consequence, it appears that the instructions “to exert maximum force” and “to exert it rapidly” may have profoundly different effects on the recorded T profiles (9, 49). Thus, separate series of trials could be needed to record T and RTD within SST. Since 3–6 consecutive trials are often recommended (although not regularly applied) for testing T, while RTD could require even longer familiarization (49, 55), fatigue may be an important issue (3, 55). Finally, note that the exertion of a sustained maximum action typical for SST could be painful or inappropriate for some individuals (55).

To address the shortcomings of SST, we recently initiated evaluation of two novel neuromuscular tests that are based on short lasting isometric muscle actions. The *brief pulse force* (BFP) protocol consists of rapid isometric force pulses performed across a range of submaximal amplitudes (8). The positive linear relationship between the T peaks and the corresponding RTD and its high reliability have been well documented and explained (8,19). In the present study we will refer to the regression slope observed between T and RFD as SLOPE. This variable is known to increase with power training in young individuals (van Cutsem et al., 1998). SLOPE decreases with the severity of the symptoms in Parkinson’s disease (Wierzbicka et al., 1991) and also effectively quantifies the age-related differences in neuromuscular function across a full range of T levels (27). Finally, the BPF protocol could have a comparative advantage over SST by providing similar outcomes for muscles of very different size and function (8).

In addition to BFP, we also explored the *alternating consecutive maximum contractions* (ACMC) of knee flexors and extensors were tested over a wide range of frequencies that correspond to the most of our natural movement tasks, such as walking, running, and cycling (11, 50), as well as at the ‘self-selected’ frequency. (12). A typical outcome was a quasi-sinusoidal force profile that allows for the assessment of the maximum T and RTD in direction of both the knee flexion and knee extension. The torque profiles not only revealed relatively stable values of T and RTD within the evaluated frequency interval, but also proved to be highly reliable. They also revealed both a moderate external validity regarding the prediction of various functional performances and ability to detect the differences among the individuals with different levels of physical fitness (12).

Taken together, the obtained results suggest the tests based on brief muscle actions (such as BFP and ACMC) could be considered as an alternative to SST. However, the basic properties of BFP and ACMC have not been compared yet. Since their high reliability has been already demonstrated, the aim of the present study was to compare BFP and ACMC

regarding (1) their concurrent validity regarding the most frequently used testing method (i.e., SST), and (2) their external validity regarding the outcome of various physical performance tests. To extend the scope of our recent studies that have included solely the tests of maximum power output, within the present study we also included a group of standard balance tests that are also based on quick muscle action. Specifically, we believed that the external validity of BFP and ACMC with respect to the ability for preserving of balance could be of particular importance for potential application of these two tests on various clinical populations and elderly. In general, the findings of the present study were expected to contribute to further development of BFP and ACMC as tests of neuromuscular function that could be either alternative or complementary to SST.

METHODS

Experimental Approach to the Problem

Since a number of functional tasks require alternating rapid and forceful muscle actions of antagonistic muscles, a valid procedure for the assessment of neuromuscular function should include tests based on brief muscle actions. Therefore, we designed an experimental cross-sectional study to test the knee extensor and flexor muscles through both the standard strength test (SST), and two novel protocols based on brief force pulses (BFP) and alternating consecutive maximum contractions (ACMC) of two antagonistic muscles that have been separately proposed in recent studies. Since both tests are still in a preliminary phase of their evaluation, we recruited a healthy and moderately active sample of participants that should allow for generalization of the observed findings more than any particular patient population. Several physical performance tests assessing either the balance or maximum power output were also conducted. To assess their concurrent validity, the outcome variables of BFP and ACMC were related with SST. Thereafter, the external validity of BFP and ACMC regarding the prediction of performance of various balance and power output tests was compared with the same validity of SST.

Subject

We conducted the sample size estimate based on the external and concurrent validity of ACMC observed in previous studies (11,12). According to standard guidelines (13) with power of 0.8 and an alpha level of 0.05, the sample sizes were 22 (11) and 14 (12) for external validity, and between 3 and 17 for the concurrent validity (12). Therefore, we conservatively tested sixteen female (age 23.5 ± 3.5 years; body mass 53.7 ± 7.0 kg; height 162.4 ± 5.5 cm; BMI 21.7 ± 2.3) and 13 male (24.8 ± 2.9 years; 79.2 ± 9.7 kg; 180.5 ± 5.8 cm; BMI 24.3 ± 1.9) college students. They were free from neurological diseases or recent injuries that could compromise the tested outcomes. The subjects were also screened for possible problems regarding their balance by Romberg's (26) and Tandem Gait tests (31), as well as the coordination by Finger-to-Nose test (51). To assess the fitness level, the lifestyle physical activity was assessed using a standard questionnaire (CV < 5 %; 52). Eleven subjects reported light, seven moderate, eight hard, and three very hard-intensity activity, although none of them was an active athlete. In line with the Helsinki Declaration, all subjects signed an informed consent document approved by the IRB of the University of Delaware.

Procedures

The study included two experimental sessions separated by 72 hours. During the first session, body mass and height were recorded. Thereafter, a series of physical performance tests was conducted. The second session included the tests of the knee extensor and flexor muscles through SST, BFP, and ACMC.

Each session began with a standardized 10-min warm-up protocol, including 5 minutes of cycling using a self-selected cadence, and 5 minutes of passive (10 s per muscle group) and active stretching exercises mainly focused upon the quads, hamstrings, hip adductors and calf muscles. The tests were performed in the same sequence and detailed explanations and demonstrations were provided prior to each one.

Neuromuscular function tests

For each of the three tests of neuromuscular function, the subject was seated on a padded chair designed for strength testing (Biodex Medical Systems, Shirley, NY, USA). The subject's thighs, pelvis, and trunk were tightly fixed to the chair using 5-cm wide non-elastic straps. A calibrated strain-gauge force transducer (Interface, Inc., SM-1000, Scottsdale, AZ, USA) was coupled to the subject's dominant leg by a non-elastic band positioned just above the lateral malleolus. The knee and hip joint were fixed at 120° (180° being full extension). The rigid interface between the transducer and the leg provided virtually isometric conditions for exerting the knee extensor and flexor forces. Real time feedback of the exerted forces was shown at a computer monitor positioned in front of the subject. The sequence and procedures of the tests are described in the following text.

Standard strength test (SST) was conducted on the knee extensors and flexors separately. The subjects were instructed "to exert force as strong and as fast as possible" against the force sensor for 3 – 4 s (55). Following a practice trial, three experimental trials were recorded. Strong verbal encouragement was provided.

Brief force pulses (BFP)—Subjects were instructed to produce discrete rapid isometric actions "as quickly as possible and then relax instantly". They were explicitly instructed not to target the approximate force levels requested because targeting has been shown to have a slowing effect on force production (20). In line with a recent study (8), subjects completed five trials consisting of at least five brief pulses to each of four approximate amplitudes (20, 40, 60, 80 % of maximum force obtained in the preceding SST) in a set, resulting in a total of at least 100 pulses. The purpose of the prescribed levels was only to spread the magnitudes of individual pulses over the large range and, therefore, the accuracy was not stressed (8). The timing of pulses was paced by beats of a metronome set to 0.5 Hz. Prior to the data recording, subjects practiced until they felt comfortable with the task and could perform discrete force pulses as instructed (typically two attempts at each force level). This apparently healthy sample did not demonstrate any difficulty in the performance of what could be described as discrete and smooth force pulses. The pulse amplitudes were presented in a balanced order across subjects.

Alternating consecutive maximum contractions (ACMC)—Subjects were instructed "to consecutively exert alternating maximum actions of knee extensors and flexors as strong and as quickly as possible". Therefore, the frequency of the alternating maximum contractions could be considered as self-selected (12). The trial duration covered at least eight full periods of ACMC force. The experimental trials were repeated if the muscle actions showed inconsistent force profiles (i.e., when the peak forces in individual cycles differed more than 5% from the trial average, which happened in less than 15% of trials). Following a practice trial, three experimental trials were recorded.

The rest intervals between the consecutive trials (in SST and ACMC) or series of trials (in BFP) were 1 minute. According to the subjects' reports, fatigue was never an issue.

Physical performance tests

The testing of the physical performance consisted of 3 balance tests and 6 tests of maximum power output. The following description corresponds to the testing sequence.

Balance tests

Place alternate foot on stool (PAFS): Subjects were instructed to place each foot alternately on the 17.8 cm high stool as fast as they could while keeping at least one foot on the ground at all times. They were required to continue the task until each foot touched the top of the stool four times. High reliability and validity of *PAFS* have been reported (32).

Four Square Step Test (FSST): Four squares were marked on the floor by using four canes, 90 cm long, set in the shape of cross on the floor. Starting from the standard standing position in one of the four squares, the subject were instructed to step into each square moving their body as fast as possible forward, sideward right, backward and sideward left and back to the starting position while keeping at least one foot on the ground at all times. The score is recorded as the time taken to complete the sequence. The stopwatch started when the first foot left the floor and finished when the last foot came back to touch the floor in the starting square. High reliability, validity and sensitivity have been reported for this test (16).

Turning 360 degrees (T360°): Subjects were instructed to make complete turn around in a full circle and then turn a full circle in the opposite direction as fast as they can. Subjects were required to perform the task for three times. High reliability and validity have been reported for this test (32).

The time of each test was measured simultaneously by two experienced raters, and the averaged value was used for further analysis.

Maximum power output tests

Countermovement jump (CMJ): The vertical jump was initiated from the standard standing position. Subjects were instructed to perform the maximum vertical jump with a preparatory countermovement while holding their hands akimbo, as well as to land on extended legs approximately at the point of the take-off. The test was conducted on a force platform (AMTI, Inc., Newton, MA, USA) operating at 200 Hz which recorded the flight time needed to calculate the jump height. High reliability (ICC > 0.98) and factorial validity ($r = 0.87$) of CMJ have been reported (34).

Countermovement jump with dominant leg (CMJD): The vertical jump was initiated from the position standing on dominant leg with slightly flexed non-dominant leg. Subjects were instructed to perform the maximum vertical jump with a preparatory countermovement while holding their hands akimbo and to land on extended dominant leg approximately at the point of the take-off. High reliability (ICC > 0.86) of *CMJD* has been reported (38).

Standing long jump (LJ): The subjects were instructed to jump as far as possible from a standing position. They were allowed to move their arms freely. The distance from the starting point to the landing point at the heel contact was used for further analysis. The precision of the measurement was 1 cm. Markovic (2004) found a high intra-trial reliability (ICC = 0.93) and factorial validity of this test ($r = 0.80$).

Single hop test for distance (SH): The subjects were instructed to jump as far as possible from the position standing on dominant leg with slightly flexed nondominant leg. The distance from the starting point to the landing point at the dominant heel contact was used

for further analysis. The precision of the measurement was 1 cm. High reliability (ICC > 0.95) of *SH* has been reported (38).

Ball kick test (BK): The subjects were asked to place their nondominant foot on the side of the stationary balloon and to kick it as fast as possible with their dominant foot (44). A reflective marker was attached at the lateral side of foot and its speed was recorded by six CCD cameras (Motion Analysis, Santa Rosa, CA, USA). Although a high reliability of the ball velocity has been reported (33), we recorded the foot velocity as the variable of interest to avoid the possible effects of the differences in kicking techniques (46).

6 s maximal cycling sprint test (6-s MCST): The subjects were instructed to pedal as fast as possible during 6 s sprints on a standard friction-loaded cycle ergometer (Monark 894 E, Varberg, Sweden) The flywheel was loaded by 8% of body weight which could be the optimal for providing the maximum power output (7, 47). It has been demonstrated that even the individuals unfamiliar with either the cycling training or testing, could repeat a 6-s maximal MCST with a low within-subject variability (CV < 5 %; 39). In general, the test represents a short version of the standard Wingate anaerobic test recommended for providing a “more accurate determination of absolute power than the longer Wingate test, as this emphasizes alactic energy derivation only” (30).

Following a practice trial, each physical performance test was performed three times and the best result was taken for further analysis. The rests between the trials were 1 minute, and between the different tests about 2–4 minutes, depending on the time needed for the instructions and demonstrations. Regarding the selection of particular maximum power output tests, note that the maximum jump tests are often referred to as power tests (38) and could belong to same component of physical fitness (34). Jump height should also be a measure of the body size independent power output (36) that highly correlates with the outcome of various sprint running tests (28).

Data processing

A custom Lab View program was used for data acquisition and processing of the three neuromuscular function tests. The force-time curves were recorded at a rate of 200 Hz and filtered with a fourth-order, zero-lag, Butterworth low pass filter with a cutoff frequency of 10 Hz. Regarding SST and APMC, the recorded forces were multiplied by the corresponding lever arm (i.e., the distance from the knee joint center to the center of the transducer attachment to the lower leg) providing, therefore, the maximum torques and the maximum rates of torque development in each direction separately. The APMC variables were calculated as averaged values obtained from the last three periods of the individual trials. The self-selected frequency of APMC was calculated from the time intervals observed between the consecutive T peaks. Out of 3 consecutive experimental trials of both SST and APMC, the best one was selected for further analysis. Since the instruction was both to exert the maximum force and to exert it as quickly as possible, the criterion for the best trial in both tests was the highest value of the product of T and RTD.

The analysis of BFP was based on the application of bivariate linear regression to the RTD and T obtained from the series of isometric force pulses. The SLOPE, R^2 , and y-intercept were obtained for each subject and muscle group as the main dependent variables of interest (8). Note that both the theoretical models and experimental findings suggest that the results of the neuromuscular function assessed by T and RTD, and muscle power output tests increase with body size approximately proportionally to body mass (m) (25) and $m^{0.67}$ (m – body mass) (6, 43, 45), respectively, while the outcome of the tests of rapid movements should be body size independent (6, 35, 36, 44). Therefore, the outcomes of the

neuromuscular function (SST and APMC) and the muscle power output tests were divided by m and $m^{0.67}$, respectively, prior to being submitted to the statistical analysis.

Statistical analysis

Pearson correlation coefficient (r) was employed to assess the concurrent and external validity of BFP and APMC through the relationships among the SST, BFP and APMC variables, as well as between these variables and the outcomes of the physical performance tests, respectively. The magnitude of the relationship was considered either small ($r = 0.1$), moderate ($r = 0.3$), or large ($r = 0.5$) in line with standard Cohen's suggestions (Cohen 1988). For the purpose of comparisons among the tests, the absolute values of the correlation coefficients were Z-transformed. Since the Kolmogorov-Smirnov test did not reveal any violation of normality of the distribution of the Z scores, parametric statistics was applied. For the assessment of concurrent validity, a 2×2 factorial analysis of variance (ANOVA) with the main factors of sex (male and female) and 2 neuromuscular test (BFP and APMC) was applied. To compare the external validity among the three neuromuscular tests, a $2 \times 3 \times 2$ factorial analysis of variance (ANOVA) with the main factors of sex (male and female), 3 neuromuscular test (SST, BFP and APMC) and 2 groups of physical performance tests (three balance and six maximum power output tests) was applied. Since the lower scores of the balance tests reveal better performance, the sign of their correlation coefficients was inverted prior to the analysis. When significant effects were detected, a Tukey *post hoc* test was performed. The effect size was also used to estimate the magnitude of differences of main effects, their interactions, and the post-hoc differences ("p η^2 " for ANOVA and "d" for post hoc calculations; 13). The differences were considered as either a small ($\eta^2 = 0.01$; $d = 0.2$), moderate ($\eta^2 = 0.06$; $d = 0.5$), or large ($\eta^2 = 0.15$; $d = 0.8$). The level of statistical significance was set to $\alpha = 0.05$. Data were analyzed using SPSS 17.0 software (SPSS Inc, Chicago, IL, USA).

RESULTS

Force profiles

The first three panels of Figure 1 show typical force-time curves obtained from a representative subject performing the standard strength tests (SST), brief force pulses (BFP), and the alternating consecutive maximum contractions (APMC). While the thick lines show the recorded forces, the thin lines depict the corresponding force derivatives for the calculation of rate of force development. A visual inspection suggests stable values of APMC variables obtained across the three consecutive cycles and a relatively proportional increase in the peak force and their rates of development observed in BFP. Note that the depicted forces obtained from SST and APMC were later on converted into torques (i.e, T and RTD). The bottom panel illustrates calculation of the slopes and intercepts observed from a series of individual BFP.

Concurrent validity

Table 1 shows variables obtained from BFP and APMC (first column), as well as from SST (first rows; data shown separately for males and females). Note that the maximum T was lower in APMC than in SST, while the opposite is true for RTD. To assess the concurrent validity of BFP and APMC with respect to the previously validated SST, we calculated the correlation coefficients between the individual variables (see the main part of Table 1). Virtually all individual correlation coefficients calculated for APMC were both significant and within the range between moderate and high, yet BFP revealed relatively weak relationship with SST. The residuals of Z-scores calculated from the correlation coefficients obtained among the neuromuscular tests were normally distributed (KS = 0.63; $p = 0.82$). A 2×2 factorial ANOVA applied on the Z-scores revealed significantly higher values of

ACMC than BFP ($F_{[1,60]} = 65.8$; $p < 0.01$; $\eta^2 = 0.52$), while no differences were obtained between males and females ($F_{[1,60]} = 2.3$; $p > 0.01$; $\eta^2 = 0.04$) and no interaction ($F_{[1,60]} = 0.8$; $p > 0.01$; $\eta^2 = 0.01$).

External validity

The first rows of Table 2 show the descriptive statistics of the individual physical performance tests separately for males and females (note that the same data for 3 neuromuscular tests are shown in Table 1. The remaining part of Table 2 depicts the external validity of SST, BFP, and ACMC through their predictive power regarding the tests of physical performance. The absolute values of the medians of the observed correlation coefficients of the three neuromuscular tests with the physical performance tests are presented in Table 3. The residuals of dependent variables observed from the individual neuromuscular function tests and the physical performance tests appeared to be normally distributed ($KS = 0.47 - 0.81$; $p = 0.57 - 0.98$). The same was true of the residuals of Z-scores calculated from the correlation coefficients obtained between the neuromuscular tests and the physical performance tests ($KS = 0.48$; $p = 0.98$). A $2 \times 3 \times 2$ factorial ANOVA applied on the Z-scores revealed the main effect of neuromuscular test ($F_{[2,204]} = 27.6$; $p < 0.01$; $\eta^2 = 0.21$). ACMC showed on average the higher correlations with the physical performance tests than both SST ($p = 0.01$, $d = 0.48$) and BFP ($p = 0.00$, $d = 1.47$). In addition, the post hoc analysis also suggested that the correlation coefficients obtained from SST were higher than those obtained from BFP ($p = 0.00$, $d = 0.76$). Regarding the main effect of sex, a higher correlations were obtained in the females than in the males ($F_{[2,204]} = 8.2$; $p < 0.01$; $\eta^2 = 0.04$). The main effect of groups of physical performance tests was non-significant ($F_{[2,204]} = 0.24$; $p = 0.63$; $\eta^2 = 0.01$). Finally, only one significant interaction were obtained between sex and groups of physical performance tests ($F_{[2,204]} = 8.22$; $p = 0.00$; $\eta^2 = 0.04$).

DISCUSSION

We evaluated and compared two novel tests for the assessment of neuromuscular function based on brief actions on 2 groups of moderately physically active young male and female subjects. First main finding revealed that the alternating consecutive maximum contractions (ACMC) could have a moderate-to-high concurrent validity with respect to the standard strength test (SST), while the same validity of the brief force pulses (BFP) could be relatively low. Second, the external validity of ACMC with respect to the battery of the balance and maximum power output tests appears to be higher than the external validity of SST, while the opposite could be true regarding BFP.

Regarding the concurrent validity of ACMC with respect to SST, note that a similar relationship between ACMC and SST has been observed in our recent studies (11, 12, 50). This finding generally suggests that the brief (such as in ACMC) and sustained (in SST) exertion of T could share a number of neuromuscular factors and mechanisms responsible for both high and rapid force exertion. Among them could be the muscle cross-sectional area, muscle strength, muscle composition and stiffness (4, 10, 22, 42). However, the 'neural' factors, such as the presence of double discharges of action potentials (53) and silent periods (5, 14, 41) could explain why the discussed relationship between ACMC and SST variables may not be exceptionally high.

Regarding the concurrent validity of the main BFP outcome variable, note the neural correlate of SLOPE is the capacity to generate high initial motor unit discharge rates and the modulation thereof that may also depend on muscle fiber type (27, 53). SLOPE also decline with age (27) and Parkinson's disease (54). However, the observed SLOPE values did not show any meaningful covariation with either SST or ACMC variables. The reason could be

that the observed slope is a rate measure that is mathematically independent of the absolute values of T and RTD (such as recorded through SST and ACMC), but rather represent the covariance of their relative values.

Regarding the external validity, performance of the selected tests is predominantly based on brief T exertions that should have corresponded more with BFP and ACMC than with SST (8, 11, 12, 50). The average moderate-to-high relationship of ACMC with various physical performance tests was in line with the results obtained from our previous studies regarding a partly different set of performance tests (11, 12), or even higher than previously reported for SST (17, 28). Note that when compared with the findings of the above cited studies, the present study suggests not a similar, but higher external validity of ACMC when compared with the same validity of SST. However, one should acknowledge that similarly to SST, the predictive power of ACMC could be limited by some factors, such as being based on static testing conditions and, consequently, a lack of the stretch shortening cycle (2, 37, 55). Nevertheless, we found that the external validity of ACMC could be well above the same validity of BFP and similar, but higher than the external validity of SST. This finding supports ACMC as a candidate for routine neuromuscular testing. Regarding BFP, the observed low external validity could originate from the factors discussed within the previous paragraph. Furthermore, SLOPE represents the ability of the neuromuscular system to scale the RTD with the T amplitude at a high rate. As a result, the value of SLOPE does not reflect the ability of the tested muscles to exert high values of T or RTD relevant for the performance of the selected physical performance tests.

Although the present study revealed several similarities between SST and particularly ACMC, it is important to stress that the both of the novel tests could still retain some important methodological advantages. First, BFP and to a lesser extent ACMC expose the tested individuals not only to lower, but also transient forces which could be of considerable importance for testing of elderly or injured/recovering individuals. For the same reasons BFP and ACMC are less likely to cause fatigue. Second, conducting ACMC at the self-selected frequency provides the opportunity to test two antagonistic muscles within few, if not a single trial, which could considerably simplify the testing procedure. Regarding BFP, although the concurrent and external validity is low, it could deserve further studies due to being both relatively insensitive to muscle size and function (8) and sensitive enough to be applied on clinical populations (27, 54).

In general, both ACMC and BFP apparently need further evaluation regarding their external validity on a wide scale of the populations, as well as regarding a number of important functional tasks. Selection of variables to be obtained from the evaluated neuromuscular tests including SST particularly requires further attention. Namely, we found strong relationships among most of the variables observed both within and across individual tests (11, 12). Having also in mind the usually strong relationships between the tested forces and the rates of their development found in previous literature (40), as well as their relationship observed when testing two antagonistic muscle groups (23, 55), one could conclude that the different variables obtained from ACMC and SST could be partly assessing the similar properties of the neuromuscular system. Regarding BFP, while SLOPE could have apparent physiological and functional interpretation as ‘the scaling of quickness’ (8), the meaning and importance of the intercepts still remain unclear despite their relatively low values. Finally, note that the directly measured forces in all three neuromuscular tests are the direct results of the *net muscle T* and, therefore, inevitably represent the superposition of action of two antagonistic muscles. The coactivation is likely to be at a considerable level over the ACMC trial. Therefore, one could only nominally attribute T and RTD obtained from ACMC to a particular muscle group. That also explains why RTD appears to be considerably higher in ACMC than SST, since the net T change in the former test originates not only from the

agonist activation, but also from the antagonist relaxation. Although the role of muscle coactivation needs to be explored, note that the ACMC regime of the muscle neural activation should closely correspond to a number of important functional movements, including gait. These movements presumably involve neural networks and mechanisms that could considerably contribute to the efficiency of muscle excitation in cyclic movements (e.g., the central pattern generator, or reciprocal inhibition; 29).

PRACTICAL APPLICATIONS

Taking into account some shortcomings of the standard tests of muscle strength based on sustained maximal actions, a part of the observed findings suggest that the tests based on brief actions could be considered as either a complementary or alternative tests to SST. Due to the properties of a high concurrent validity, a moderate-to-high external validity and a brief procedure needed for testing two antagonist muscles, ACMC could be a particularly promising candidate for routine testing of the neuromuscular function. Conversely, it still remains to be explored whether BFP could offer unique information about the neuromuscular system 'as a whole' due to being relatively insensitive to muscle size and function.

Acknowledgments

The study was supported in part by NIH grant (AR06065) and grant from Serbian Research Council (#175037). We thank Dr. S. Radosavljevic Jaric for neurological screening of the subjects. The authors disclose professional relationships with companies or manufacturers who will benefit from the results of this study. The results of this study do not constitute endorsement of the product by the authors or the National Strength and Conditioning Association.

References

1. Aagaard P, Simonsen EB, Andersen JL, Magnusson P, Dyhre-Poulsen P. Increased rate of force development and neural drive of human skeletal muscle following resistance training. *J Appl Physiol.* 2002; 93:1318–1326. [PubMed: 12235031]
2. Abernethy P, Wilson G, Logan P. Strength and power assessment. Issues, controversies and challenges. *Sports Med.* 1995; 19:401–417. [PubMed: 7676101]
3. Andersen LL, Aagaard P. Influence of maximal muscle strength and intrinsic muscle contractile properties on contractile rate of force development. *Eur J Appl Physiol.* 2006; 96:46–52. [PubMed: 16249918]
4. Andersen LL, Andersen JL, Zebis MK, Aagaard P. Early and late rate of force development: differential adaptive responses to resistance training? *Scand J Med Sci Sports.* 2010; 20:e162–169. [PubMed: 19793220]
5. Aoki H, Tsukahara R, Yabe K. Effects of pre-motion electromyographic silent period on dynamic force exertion during a rapid ballistic movement in man. *Eur J Appl Physiol Occup Physiol.* 1989; 58:426–432. [PubMed: 2920720]
6. Astrand, PO.; Rodahl, K. Textbook of work physiology. New York: McGraw-Hill; 1986.
7. Baker J, Davies B. Influence of body mass on resistive force selection during high intensity cycle ergometry: interrelationships between laboratory and field measures of performance. *Journal of Exercise Physiology.* 2004; 7:44–51.
8. Bellumori M, Jaric S, Knight C. The rate of force development scaling factor (rfd-sf): protocol, reliability and muscle comparisons. *Experimental brain research.* in press.
9. Bemben MG, Clasey JL, Massey BH. The effect of the rate of muscle contraction on the force-time curve parameters of male and female subjects. *Res Q Exerc Sport.* 1990; 61:96–99. [PubMed: 2091174]
10. Bojsen-Moller J, Magnusson SP, Rasmussen LR, Kjaer M, Aagaard P. Muscle performance during maximal isometric and dynamic contractions is influenced by the stiffness of the tendinous structures. *J Appl Physiol.* 2005; 99:986–994. [PubMed: 15860680]

11. Bozic P, Suzovic D, Nedeljkovic A, Jaric S. Alternating consecutive maximum contractions as a test of muscle function. *J Strength Cond Res.* 2011; 25:1605–1615. [PubMed: 21602647]
12. Bozic PR, Pazin N, Berjan B, Jaric S. Evaluation of alternating consecutive maximum contractions as an alternative test of neuromuscular function. *Eur J Appl Physiol.* 2011
13. Cohen, J. *Statistical Power Analysis for the behavioral sciences.* Hillsdale, NJ: Lawrence Erlbaum Associates; 1988.
14. Conrad B, Benecke R, Goehmann M. Premovement silent period in fast movement initiation. *Exp Brain Res.* 1983; 51:310–313. [PubMed: 6617799]
15. Desmedt JE, Godaux E. Ballistic contractions in man: characteristic recruitment pattern of single motor units of the tibialis anterior muscle. *J Physiol.* 1977; 264:673–693. [PubMed: 845820]
16. Dite W, Temple VA. A clinical test of stepping and change of direction to identify multiple falling older adults. *Arch Phys Med Rehabil.* 2002; 83:1566–1571. [PubMed: 12422327]
17. Driss T, Vandewalle H, Monod H. Maximal power and force-velocity relationships during cycling and cranking exercises in volleyball players. Correlation with the vertical jump test. *J Sports Med Phys Fitness.* 1998; 38:286–293. [PubMed: 9973770]
18. Enoka RM, Fuglevand AJ. Motor unit physiology: some unresolved issues. *Muscle Nerve.* 2001; 24:4–17. [PubMed: 11150961]
19. Freund HJ, Budingen HJ. The relationship between speed and amplitude of the fastest voluntary contractions of human arm muscles. *Exp Brain Res.* 1978; 31:1–12. [PubMed: 639903]
20. Gordon J, Ghez C. Trajectory control in targeted force impulses. III. Compensatory adjustments for initial errors. *Exp Brain Res.* 1987; 67:253–269. [PubMed: 3622688]
21. Gruber M, Gollhofer A. Impact of sensorimotor training on the rate of force development and neural activation. *Eur J Appl Physiol.* 2004; 92:98–105. [PubMed: 15024669]
22. Harridge SD, Bottinelli R, Canepari M, Pellegrino MA, Reggiani C, Esbjornsson M, Saltin B. Whole-muscle and single-fibre contractile properties and myosin heavy chain isoforms in humans. *Pflugers Arch.* 1996; 432:913–920. [PubMed: 8772143]
23. Holtermann A, Roeleveld K, Vereijken B, Ettema G. The effect of rate of force development on maximal force production: acute and training-related aspects. *Eur J Appl Physiol.* 2007; 99:605–613. [PubMed: 17219170]
24. Jaric S. Muscle strength testing: use of normalisation for body size. *Sports Med.* 2002; 32:615–631. [PubMed: 12141882]
25. Jaric S, Radosavljevic-Jaric S, Johansson H. Muscle force and muscle torque in humans require different methods when adjusting for differences in body size. *Eur J Appl Physiol.* 2002; 87:304–307. [PubMed: 12111294]
26. Khasnis A, Gokula RM. Romberg's test. *J Postgrad Med.* 2003; 49:169–172. [PubMed: 12867698]
27. Klass M, Baudry S, Duchateau J. Age-related decline in rate of torque development is accompanied by lower maximal motor unit discharge frequency during fast contractions. *J Appl Physiol.* 2008; 104:739–746. [PubMed: 18174392]
28. Kukolj M, Ropret R, Ugarkovic D, Jaric S. Anthropometric, strength, and power predictors of sprinting performance. *J Sports Med Phys Fitness.* 1999; 39:120–122. [PubMed: 10399419]
29. Latash, ML. *Neurophysiological basis of movement.* Champaign, IL: Human Kinetics; 2008.
30. Logan, P.; Fornasiero, D.; Abernethy, P.; Lynch, K. Protocols for the assessment of isoinertial strength. In: Gore, CJ., editor. *Physiological tests for elite athletes.* Champaign, IL: Human Kinetics; 2000. p. 200–222.
31. Louis ED, Rios E, Rao AK. Tandem gait performance in essential tremor: clinical correlates and association with midline tremors. *Mov Disord.* 2010; 25:1633–1638. [PubMed: 20629168]
32. Mao HF, Hsueh IP, Tang PF, Sheu CF, Hsieh CL. Analysis and comparison of the psychometric properties of three balance measures for stroke patients. *Stroke.* 2002; 33:1022–1027. [PubMed: 11935055]
33. Markovic G, Dizdar D, Jaric S. Evaluation of tests of maximum kicking performance. *J Sports Med Phys Fitness.* 2006; 46:215–220. [PubMed: 16823350]
34. Markovic G, Dizdar D, Jukic I, Cardinale M. Reliability and factorial validity of squat and countermovement jump tests. *J Strength Cond Res.* 2004; 18:551–555. [PubMed: 15320660]

35. Markovic G, Jaric S. Movement performance and body size: the relationship for different groups of tests. *Eur J Appl Physiol.* 2004; 92:139–149. [PubMed: 15024662]
36. Markovic G, Jaric S. Is vertical jump height a body size-independent measure of muscle power? *J Sports Sci.* 2007; 25:1355–1363. [PubMed: 17786688]
37. Martin JC. Muscle power: the interaction of cycle frequency and shortening velocity. *Exerc Sport Sci Rev.* 2007; 35:74–81. [PubMed: 17417054]
38. Maulder P, Cronin J. Horizontal and vertical jump assessment: reliability, symmetry, discriminative and predictive ability. *Phys Ther Sport.* 2005; 6:74–82.
39. Mendez-Villanueva A, Bishop D, Hamer P. Reproducibility of a 6-s maximal cycling sprint test. *J Sci Med Sport.* 2007; 10:323–326. [PubMed: 16949868]
40. Mirkov DM, Nedeljkovic A, Milanovic S, Jaric S. Muscle strength testing: evaluation of tests of explosive force production. *Eur J Appl Physiol.* 2004; 91:147–154. [PubMed: 14523563]
41. Mortimer JA, Eisenberg P, Palmer SS. Premovement silence in agonist muscles preceding maximum efforts. *Exp Neurol.* 1987; 98:542–554. [PubMed: 3678431]
42. Narici MV, Hoppeler H, Kayser B, Landoni L, Claassen H, Gavardi C, Conti M, Cerretelli P. Human quadriceps cross-sectional area, torque and neural activation during 6 months strength training. *Acta Physiol Scand.* 1996; 157:175–186. [PubMed: 8800357]
43. Nedeljkovic A, Mirkov DM, Bozic P, Jaric S. Tests of muscle power output: the role of body size. *Int J Sports Med.* 2009; 30:100–106. [PubMed: 18788067]
44. Nedeljkovic A, Mirkov DM, Markovic S, Jaric S. Tests of muscle power output assess rapid movement performance when normalized for body size. *J Strength Cond Res.* 2009; 23:1593–1605. [PubMed: 19620902]
45. Nedeljkovic A, Mirkov DM, Pazin N, Jaric S. Evaluation of Margaria staircase test: the effect of body size. *Eur J Appl Physiol.* 2007; 100:115–120. [PubMed: 17273883]
46. Nunome H, Lake M, Georgakis A, Stergioulas LK. Impact phase kinematics of instep kicking in soccer. *J Sports Sci.* 2006; 24:11–22. [PubMed: 16368610]
47. Pazin N, Bozic P, Bobana B, Nedeljkovic A, Jaric S. Optimum loading for maximizing muscle power output: the effect of training history. *Eur J Appl Physiol.* 2011
48. Pijnappels M, Bobbert MF, van Dieen JH. Push-off reactions in recovery after tripping discriminate young subjects, older non-fallers and older fallers. *Gait Posture.* 2005; 21:388–394. [PubMed: 15886128]
49. Sahaly R, Vandewalle H, Driss T, Monod H. Maximal voluntary force and rate of force development in humans--importance of instruction. *Eur J Appl Physiol.* 2001; 85:345–350. [PubMed: 11560090]
50. Suzovic DAN, Pazin N, Planic N, Jaric S. Evaluation of consecutive maximum contractions as a test of neuromuscular function. *J Hum Kinetics.* 2008; 20:51–67.
51. Swaine BR, Desrosiers J, Bourbonnais D, Larochelle JL. Norms for 15- to 34-year-olds for different versions of the finger-to-nose test. *Arch Phys Med Rehabil.* 2005; 86:1665–1669. [PubMed: 16084824]
52. Taylor-Piliae RE, Norton LC, Haskell WL, Mahbouda MH, Fair JM, Iribarren C, Hlatky MA, Go AS, Fortmann SP. Validation of a new brief physical activity survey among men and women aged 60–69 years. *Am J Epidemiol.* 2006; 164:598–606. [PubMed: 16840522]
53. Van Cutsem M, Duchateau J, Hainaut K. Changes in single motor unit behaviour contribute to the increase in contraction speed after dynamic training in humans. *J Physiol.* 1998; 513:295–305. [PubMed: 9782179]
54. Wierzbicka MM, Wiegner AW, Logigian EL, Young RR. Abnormal most-rapid isometric contractions in patients with Parkinson's disease. *J Neurol Neurosurg Psychiatry.* 1991; 54:210–216. [PubMed: 2030347]
55. Wilson GJ, Murphy AJ. The use of isometric tests of muscular function in athletic assessment. *Sports Med.* 1996; 22:19–37. [PubMed: 8819238]

Figure 1.

Force-time curves (thick line, left hand axis) and their derivatives (thin line, right hand axis) observed from a representative subject when performing (A) the standard strength test (SST), (B) the brief force pulses in the direction of extension (BFP), (C) the alternating consecutive maximum contractions test (ACMC). The data depicting the direction of flexion are shown as negative. Panel (D) shows the slopes and intercepts of a regression line calculated from the peaks of each force pulse and corresponding rate of force development.

Descriptive statistics of the neuromuscular function tests [data presented as mean (SD)]; the first column and row] and correlation coefficients between BFP and APMC with respect to SST for the males (upper part) and the females (lower part)

Table 1

		SST					
		EXT			FLE		
		T (Nm/kg)	RTD (Nm/s/kg)	T (Nm/kg)	RTD (Nm/s/kg)	T (Nm/kg)	RTD (Nm/s/kg)
		Mean (SD)	25.32 (5.9)	1.44 (.29)	9.9 (2.2)		
BFP	EXT	Slope	8.2 (21.8)	.30	.16	.21	
		Intercept (N/s)	1152 (807)	.31	.18	.25	
	FLE	Slope	5.7 (1.9)	.23	.02	.25	
		Intercept (N/s)	794 (358)	-.05	.26	.14	
Male (n=13)							
ACMC	EXT	T (Nm/kg)	2.88 (.60)	.86**	.71**	.34	.48
		RTD (Nm/s/kg)	29.7 (6.0)	.72**	.74**	.65*	.79**
	FLE	T (Nm/kg)	1.20 (.27)	.38	.50	.49	.63*
		RTD (Nm/s/kg)	36.6 (13.9)	.85**	.64*	.37	.34
		Mean (SD)	2.83 (.45)	20.7 (4.8)	1.35 (.32)	8.8 (2.5)	
BFP	EXT	Slope	7.0 (2.0)	.26	.32	0.34	
		Intercept (N/s)	867 (418)	.15	-.12	.25	-.07
	FLE	Slope	6.5 (1.6)	.07	.23	.03	.25
		Intercept (N/s)	446 (193)	.15	-.02	.25	.05
Female (n=16)							
ACMC	EXT	T (Nm/kg)	2.46 (.44)	.75**	.82**	.49	.61*
		RTD (Nm/s/kg)	23.4 (5.4)	.73**	.61*	.52*	.33
	FLE	T (Nm/kg)	1.04 (.35)	.36	.07	.55*	.08
		RTD (Nm/s/kg)	31.7 (9.0)	.52*	.37	.51*	.38

SST - Standard strength test; BFP - Brief force pulses; APMC - Alternating consecutive maximum contractions; EXT - Extension; FLE - Flexion; T - Torque; RTD - Rate of torque development;

* p < 0.05;

** p < 0.01

Descriptive statistics of the physical performance tests [data presented as mean (SD); the first row] and their correlation with the neuromuscular tests for the males (upper part) and females (lower part)

Table 2

		PAFS	FSST	T360°	LJ	SH	CMJ	CMJD	BK	6sMCST
	Mean (SD)	2.85 (.28)	2.96 (.32)	5.71 (.58)	2.24 (.22)	1.62 (.21)	35.1 (5.2)	16.0 (2.9)	16.3 (1.6)	56.5 (6.8)
Males (n=13)	EXT	T	-.36	-.15	-.60*	.40	.64*	.02	.59*	.33
		RTD	-.28	-.02	-.15	.80**	.74**	.53	.69*	.70**
	SST	T	-.06	-.27	.19	.15	.38	-.67*	.33	.25
		RTD	.08	-.14	-.15	.21	.45	-.24	.30	.11
	BFP	slope	.25	.11	-.07	.11	.06	.15	.02	.05
		intercept	-.30	-.13	-.19	.27	.09	-.06	.54	.30
	FLE	slope	.12	.17	-.24	.03	.07	-.08	-.13	-.39
		intercept	.04	-.02	.14	.01	-.10	-.02	.24	.47
	ACMC	T	-.35	-.22	-.44	.50	.72**	.24	.65*	.42
		RTD	-.13	-.17	-.22	.55	.80**	.20	.44	.21
Females (n=16)	EXT	T	-.03	-.04	-.16	.43	.68*	.31	.41	.49
		RTD	-.68*	-.34	-.39	.44	.64*	.11	.71**	.54
	SST	T	-.28	-.49	-.42	.47	.45	.26	.26	.64**
		RTD	-.03	-.32	-.31	.22	.14	.23	.13	.32
	FLE	T	-.26	-.49	-.55*	.25	.59*	.24	.32	.78**
		RTD	.04	-.38	-.57*	.08	.37	.34	-.02	.60*
	BFP	slope	-.37	-.51*	-.49	.14	.07	.20	.01	.35
		intercept	.03	.16	.26	-.07	.08	-.24	.21	-.03
	FLE	slope	.15	-.02	-.11	.20	.15	.46	.28	.34
		intercept	-.56*	-.30	-.28	.11	.22	-.04	.32	-.02

		PAFS	FSST	T360°	LJ	SH	CMJ	CMJD	BK	6sMCST
ACMC	T	-.06	-.48	-.49	.35	.34	.38	.33	.06	.57 *
	EXT									
	RTD	-.42	-.70 **	-.57 *	.50 *	.34	.22	.33	.27	.55 *
	T	-.63 **	-.41	-.35	.42	.57 *	.23	.41	.68 **	.43
FLE										
	RTD	-.35	-.72 **	-.67 **	.34	.36	.02	.15	.37	.46

PAFS – Place alternate foot on stool; FSST – Four Square Step Test; T360° – Turning 360 degrees; LJ – Standing long jump; SH – Single hop test for distance; CMJ – Countermovement jump; CMJD – Countermovement jump with dominant leg; BK – Ball kick test; 6-s MCST – 6 s maximal cycling sprint test; see Table 1 for other acronyms;

* - p < 0.05;
 ** - p < 0.01

Table 3

Medians (range) of the correlation coefficients obtained between the neuromuscular tests, and the balance and maximum power output tests

		Balance tests	Power tests
Male	SST	.16 (.19 – -.60)	.28 (–.67 – .80)
	BFP	.01 (.25 – -.30)	.07 (–.39 – .54)
	ACMC	.26 (–.03 – -.68)	.42 (.09 – .80)
Female	SST	.34 (.04 – -.57)	.29 (–.17 – .78)
	BFP	.17 (.26 – -.56)	.11 (–.24 – .46)
	ACMC	.49 (–.06 – -.72)	.36 (.02 – .68)

Signs are inverted for the balance tests. See Table 1 for acronyms