

TESTS OF NEUROMUSCULAR FUNCTION

APPLICATION IN ATHLETIC TRAINING AND SPORTS MEDICINE

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HUMAN MOVEMENT AND MUSCLE ACTION

The assessment of the function of the neuromuscular system is of profound importance in sport and in a number of human movement-related areas. A large variety of routine procedures for assessment of neuromuscular function have been applied with purposes such as the identification of performance-limiting factors, exploration of the intrinsic risk factors of sport injury, monitoring the effects of training and rehabilitation programmes, comparisons among the individuals and groups and talent identification¹⁻³.

However, assessment of the abilities of the role of neuromuscular function is not straightforward. Movements performed in daily life or during sport activities differ

considerably in their kinematic and kinetic patterns and, as a consequence, require different patterns of neuromuscular activation. Maintaining postures while performing relatively slow but heavy lifting tasks usually requires exerting high muscle forces during relatively longer periods of time (e.g. 3 to 5 seconds) and depends greatly on maximal muscle strength capacities^{1,2}. However, numerous other functional movements are based on relatively fast and forceful muscle contraction with limited time for force production (e.g. sprinting, jumping, kicking, punching, postural corrections etc). The time allowed to exert force during these aforementioned movements is typically very limited and enters in the time span of the majority

ABBREVIATIONS

<i>SST</i>	<i>standard strength tests</i>
<i>F</i>	<i>maximum force</i>
<i>RFD</i>	<i>rate of force development</i>
<i>RFR</i>	<i>rate of force relaxation</i>
<i>BFP</i>	<i>brief forces pulse</i>
<i>CMC</i>	<i>consecutive maximum contractions</i>
<i>ACMC</i>	<i>alternating consecutive maximum contractions</i>



the ability of muscle to relax could be critical for functional tasks characterised by reversal or cyclic movements

of explosive actions that range between 50 to 250 ms⁴. Therefore, researchers and practitioners have also been interested in 'explosive' muscle strength qualities related to the ability of the neuromuscular system to rapidly exert force⁵. In addition to the ability to exert maximal muscle force within a limited period of time, the ability of muscle to relax could be critical for functional tasks characterised by reversal or cyclic movements (e.g. running, cycling, throwing, kicking) as well as for postural corrections⁶. As a result, neuromuscular abilities that include production of maximum force (F), rate of force development (maximum derivative from the recorded force-time curve [dF/dt] during contraction phase [RFD]) and rate of force relaxation (maximum dF/dt during relaxation phase [RFR]) could be of critical importance for the functional movement performance⁷.

ASSESSMENT OF NEUROMUSCULAR FUNCTION

Tests of neuromuscular function should be based on muscle activation patterns that closely correspond to a number of routine daily and, in particular, high performance movements.

Standard strength tests

Generally, the assessment of neuromuscular function has been conventionally performed through application of the standard strength tests (SST) (Figure 1)¹. SST have been based on the maximum voluntary isometric or concentric contraction exerted either against a single force transducer^{2,3} or against a submaximal

external load (often known as 'one repetition maximum' tests)¹.

However, being based on relatively long (3 to 5 seconds) and sustained contractions, SST may not capture the neural activation pattern typical for rapid exertion of force which could be critical for functional tasks providing limited time for exerting relatively high muscle force^{3,8}. This casts doubts regarding the validity of SST variables when used to assess the ability of performing rapid discrete and cyclic movements (e.g. running, jumping, cycling or correcting postures)⁷, training adaptations¹ etc. Since general recommendations for testing of each muscle group are five to six consecutive trials as well as a separate series of trials for recording F and RFD, fatigue appears to be an important issue³. The total number of trials needed to record SST variables may be even greater because longer familiarisation

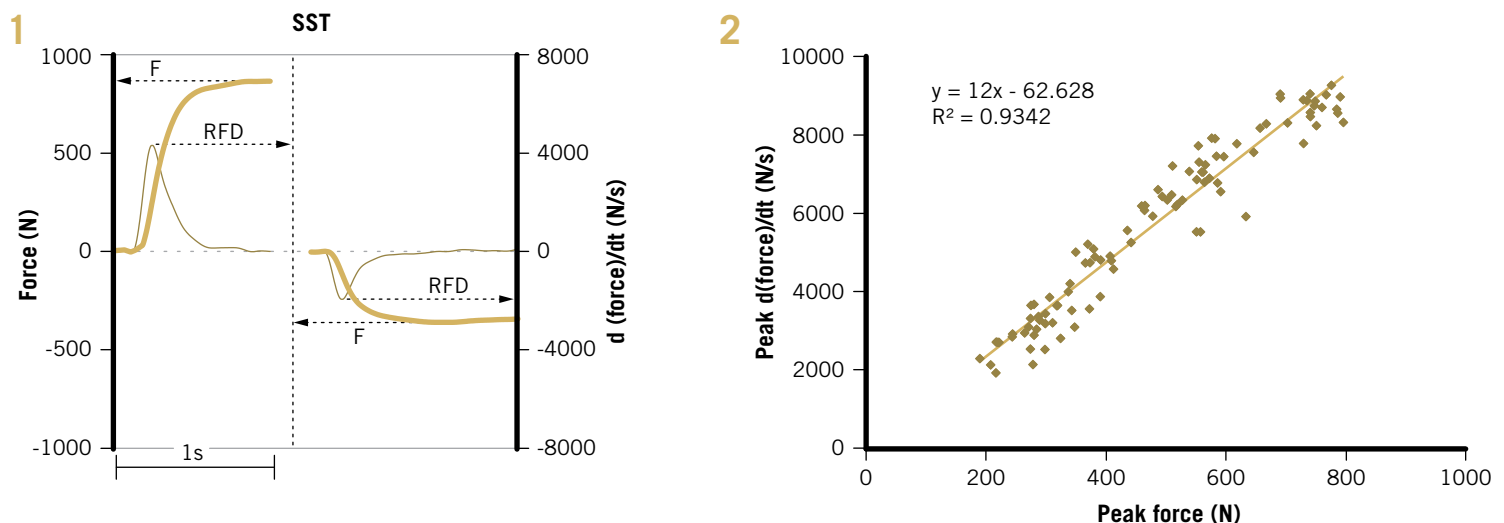


Figure 1: Force-time curves (thick line, left-hand axis) and their derivatives (thin line, right-hand axis) observed from a representative subject when performing the standard strength test (SST) for the knee extensors (the left panel) and flexors (the right panel). The data depicting the direction of flexion are shown as negative. RFD=rate of force development, F=maximum force.

Figure 2: Brief forces pulse slope of a regression line calculated from the peaks of each force pulse and corresponding rate of force development obtained from testing of the knee extensors. The data depicting the direction of flexion are shown as negative.

is required for rapid force production than for the sustained exertion of maximum muscle force⁹. Finally, the exertion of a sustained maximum contraction typical for SST could be painful or inappropriate for some individuals, such as the injured and recovering persons³.

Novel tests of neuromuscular function based on brief muscle actions

In light of the shortcomings of SST, several alternative or complementary tests for assessment of neuromuscular function have recently been evaluated^{7,10–13}. Novel tests address at least some of the shortcomings of SST such as by being based on brief and rapid force exertions (typical for rapid and cyclic movement), requiring exertion of moderate forces (relative to maximum force) within a fewer number of trials^{7,10–13}.

Brief forces pulse

One of the novel tests is the brief forces pulse (BFP) (Figure 2) protocol which consists of rapid isometric force pulses (as fast as possible) performed across a wide range of submaximal amplitudes¹⁰. The positive linear relationship between the F peaks and the corresponding RFD (termed as 'SLOPE') have been well-documented and explained¹⁰. SLOPE is a measure with high potential to inform trainers, physical therapist and scientists about the quality of quick force production across the full continuum of force

amplitudes that presumably cover plenty of functional movement tasks. In addition, SLOPE is an independent measure of strength and therefore size of the muscle group of interest. This feature facilitates comparisons between individuals and between muscle groups with respect to the underlying neuromuscular determinants of speed.

Consecutive maximum contractions

In addition to BFP, consecutive maximum contractions (CMC) (Figure 3) exerted by selected muscle groups were evaluated⁷. In short, the test requires performing externally paced maximum isometric contractions (as fast and as hard as possible) where force is rapidly changing from zero to the maximum and back (i.e. a series of consecutive maximum force exertions and relaxations) over a wide range of frequencies that correspond with many of our natural movements (e.g. walking and running, 0.67 to 2.67 Hz). A typical outcome was a quasi-sinusoidal force profile that allows for the assessment of the peak F, RFD and RFR.

Alternate consecutive maximum contractions

Given the fact that the kinematic and kinetic patterns of a number of functional tasks require rapid changes in activation of antagonistic muscles (e.g. running, cycling, swimming etc.), evaluation of CMC were extended from unidirectional to alternating

consecutive maximum contractions (ACMC) (Figure 4)^{11–15}. Specifically, the tested task required exerting externally paced maximum contractions (as fast and as hard as possible) consecutively in two opposite directions (i.e. activating selected antagonistic muscles). The force profiles not only revealed relatively stable values of F and RFD within the frequency interval between 1 and 2 Hz, but also the values that closely corresponded to the same ones obtained under the 'self-selected' frequency. In addition to allowing for testing antagonistic muscles within a single trial, the consecutive maximum activation of antagonistic muscle groups in ACMC presumably involve neural networks and mechanisms (e.g. the central pattern generator or reciprocal inhibition)⁶ that could considerably contribute to the efficiency of muscle excitation in the most rapid cyclic and reversal movements.

It should be noted that F, RFD and RFR are dependent on body size and subsequently increase proportionally to body mass (with third square root)². Therefore, adequate means of normalisation of the results (e.g. dividing F, RFD and RFR with $BM^{0.67}$) could be critical when SST, CMC and ACMC are related to some functional performance or when people with different body sizes are compared². SLOPE obtained in BFP, as mentioned, is a measure independent of body size and therefore does not require normalisation.

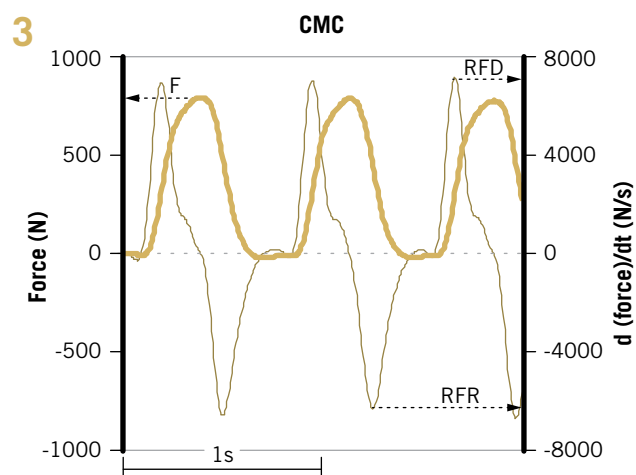


Figure 3: Force-time curves (thick line, left-hand axis) and their derivatives (thin line, right-hand axis) observed from a representative subject when performing consecutive maximal contractions performed in the direction of extension (CMC) of the knee extensors. RFD=rate of force development, F=maximum force, RFR=relaxation phase.

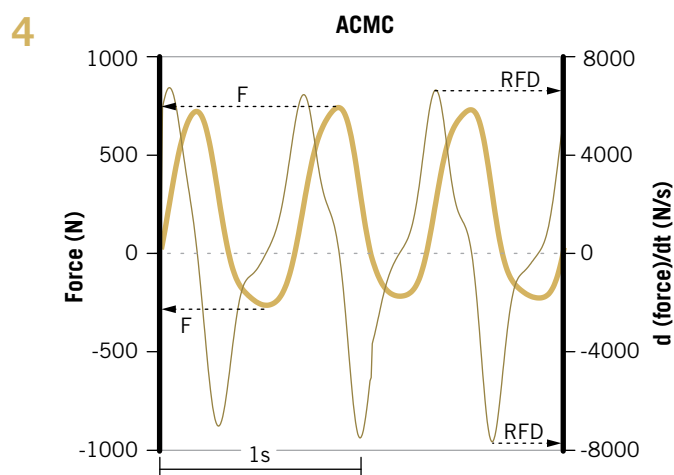


Figure 4: Force-time curves (thick line, left-hand axis) and their derivatives (thin line, right-hand axis) observed from a representative subject when performing the alternating consecutive maximum contractions (ACMC) of the knee extensors and flexors. The data depicting the direction of flexion are shown as negative. RFD=rate of force development, F=maximum force.

RELIABILITY

According to the literature, isometric tests of neuromuscular function have been reported to have a high reliability^{7,11-14}. However, it should be noted that reliability may be affected by the particular variable being assessed. Generally, somewhat lower correlation coefficients and higher coefficients of variations (CV) have been reported for RFD compared to F^{3,7,11,13}.

Regarding SST, it was reported that individual practice and inconsistent instructions could affect the reliability³. Specifically, reliability of SST was enhanced when several practice trials were provided prior to data collection or when the values were averaged³. In addition, if time constraints do not limit the number of trials, the participant should be instructed to contract 'as hard as possible' and 'as fast as possible' in separate trials for obtaining F and RFD, respectively. Otherwise, it is recommended to ask participants to contract 'as hard and as fast as possible'. According to general recommendations from the literature, sufficient standardisation for SST protocols is required and several trials of familiarisation with three to five testing trials should be conducted³.

When brief practice is applied before testing and more than 75 pulses are used in BFP testing protocols (e.g. 4 sets of 25 trials), reliability and stability of the results over several days is found to be high³. In addition,

SLOPE is sensitive enough to detect changes less than 10% both within and between subject designs¹⁰.

Although one could assume that CMC and ACMC represent a more complex motor task than SST (e.g. rapid and transient force exertions and/or because of involvement of two muscle groups), the reliability of their variables appears to be comparable to SST variables^{11,13,14} or even higher than that obtained from SST variables in previous studies^{1,3}. As a result, CMC and ACMC could require very few familiarisation trials, whereas the observed within-subject variability (as assessed by CV) suggests that ACMC could detect changes in F and RFD below 10%^{11,13,14}.

VALIDITY

Evaluation of the validity of neuromuscular function tests requires the determination of various relationships. One of them is to examine the relationships between variables of neuromuscular function tests with the underlying morphology of the musculature. The literature suggests a significant relationship between F and muscle circumference or cross-sectional area, while RFD could be a more valid variable for assessment of percent of fast twitch fibres compared to F³ and tendon mechanical properties¹⁶.

Regarding the relationship with dynamic activities, SST usually shows low to moderate correlations¹⁻³. One of the important

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reasons for low correlations with dynamic activities was a different time span for force production in the most powerful activities (under 300 ms) compared to production of maximum F in SST (typically require several seconds)³. Therefore, in the last several years, the external validity for prediction of various maximum performance tasks were evaluated for several novel neuromuscular function tests (i.e. BFP, CMC and ACMC). Previous research^{7,11-13} suggests that moderate to high correlations of CMC and ACMC with speed, maximum power and balance tests that are comparable to¹¹⁻¹³ or even higher than¹³ the ones reported for SST. However, although based on brief force production¹⁰ and the capacity to generate high initial motor unit discharge rates⁸, BFP did not show meaningful ability to predict functional tasks¹².

Of high importance for evaluation factorial validity is the assessment of relationships among various tests and variables of neuromuscular function. Although F and RFD or RFR are presumed to depend on different neural factors, a positive relationship was also shown^{7,11,13}. These relationships could be mediated by a number of common factors such as body size, muscle cross-sectional area, level of physical fitness etc³. In addition, although relatively lower, F obtained in CMC and ACMC demonstrated an exceptionally strong relationship with F obtained in SST¹¹⁻¹³. It suggests that CMC and ACMC provide two variables depicting muscle abilities relevant for two distinct groups of movement tasks. Specifically, while RFD could describe the ability for rapid force production, F could describe the muscle ability for exerting sustained maximum forces even without exposing both the muscle and the connective tissues to them¹³. Finally, it is very important to know to what extent the strength measures recorded from a single or several muscles could depict the general function of the neuromuscular system as a whole of the tested individual. Recent findings suggest that a larger number of muscles should be tested in order to obtain a more comprehensive assessment of the neuromuscular system⁵. Therefore, an important advantage of ACMC could be brief testing procedures for testing two antagonistic muscles.

SENSITIVITY

One of the most important methodological characteristics of the neuromuscular function tests is the sensitivity to detect specific acute and chronic neuromuscular adaptations induced by training or detraining as well as discrimination among various populations. Although SSTs are widely used for assessment of various training and rehabilitation procedures, researchers' opinions are contradictory regarding its sensitivity for detection of specific adaptations. Some findings from the literature suggest that strength training and training aimed to improve speed, maximal power output or rapid reaction on perturbations have a different effect on F, RFD and RFR¹⁷⁻¹⁹. Specifically, strength training and detraining adaptations are followed by changes of F¹⁸, while adaptations from exercise that require high power output or rapid reactions on perturbation are more related to changes in RFD^{17,19}. However, some authors showed that training adaptations have not been accompanied by specific changes of SST^{3,20}. They explained that force production characteristics of SST may not be specific enough to evaluate adaptation induced by various functional training procedures.

Evaluation of acute and long-term training or rehabilitation effects as well as differentiation of athletes with various training history should be performed through the tests sensitive enough to assess specific functions and adaptations of the neuromuscular system

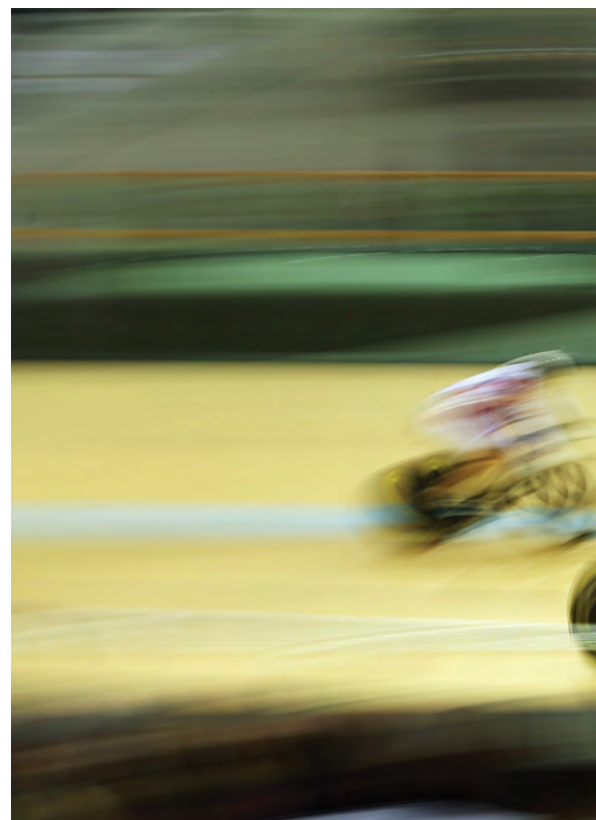
For the purpose of profiling athletes from various types of sports and distinguishing among various populations (e.g. according to training history, competition level, age, gender, injury etc), a number of tests of neuromuscular functions have been used. Generally, the literature suggests that SST is sensitive to differentiation among people who apply different training procedures over a long period of time (e.g. high resistance training vs speed training)²¹, however, in less heterogeneous situations where differences were presumed (e.g.

various competitions levels) their sensitivity has not been confirmed¹³.

Recently, findings from several studies suggest high sensitivity of BFP to assess adaptations induced with dynamic training⁸ and ageing²². Additionally, both F and RFD obtained in ACMC proved to be sensitive enough to detect the adaptation caused by various long-term trainings and, possibly, the effect of selection (e.g. when strength-trained, speed-trained, physically active and sedentary people were compared)¹³.

SUMMARY

Recent literature evidence suggests that the neuromuscular function tests based on brief actions could be considered as either complementary or alternative tests to SST. Because of the properties of a high reliability, sensitivity and concurrent validity, as well as a moderate-to-high external validity and a brief procedure for testing two antagonistic muscles, ACMC could be a particularly promising candidate for routine testing of the neuromuscular function. Nevertheless, novel tests based on brief muscle actions need further evaluation regarding a number of potentially important aspects. Future studies should apply EMG methods to evaluate neuromuscular difference among tests particularly in the levels of co-contraction between antagonistic muscles and characteristics of muscle activation at initiation of contraction.





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