UNIVERSITY OF BELGRADE
FACULTY OF SPORT AND PHYSICAL EDUCATION

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NEUROMUSCULAR QUICKNESS ASSESSMENT – TEST OPTIMIZATION AND SENSITIVITY EVALUATION

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Procena brzine neuromišićnog odgovora – optimizacija testa i ispitivanje njegove osetljivosti

Sažetak

Skalirajući faktor brzine razvoja sile (RFD-SF) se koristi za procjenu brzine neurmoišićnog odgovar. Međutim, standardni protokoli su obimni. Ovom studijom se procjenjivala validnost i pouzdanost skraćenog protokola za procjenu RFD-SF kao i njegova mogućnost za identifikaciju asimetrija donjih ekstremiteta. Trideset ispitanika je izvodilo standardni i skraćeni RFD-SF protokol tokom tri dana. Korelaciona analiza je korišćena za istraživanje povezanosti ishoda oba protokola, dok su Bland-Altmanovim graficima procenjivala validnost skraćenog protokola. Pouzdanost je procijenjena korišćenjem intra-klasnog korelacionog koeficijenta, koeficijenta varijacije, tipične greške mjerenja i t-testa za zavisne uzorke koji je dodatno korišćen za analizu osjetljivost i validnosti za otkrivanje analize asimetrija. Fpeak – RFDpeak korelacija je skoro savršena i za dominantnu (R^2 = 0,95/0,98) i za nedominantnu (R^2 = 0,94/0,98) nogu oba protokola. Korelacija između RFD-SF protokola je značajna ($p < 0,001$) i veoma velika za obje noge (dominantna: $r = 0,71$; nedominantna: $r = 0,80$). Bland-Altmanovi grafici su pokazali slaganje u prihvatljivim nivoima za RFD-SF vrijednosti. Nema značajnih razlika između protokola za dominantnu ($p = 0,480$, $d = 0,17$) i nedominantnu nogu ($p = 0,213$, $d = 0,31$). Pouzdanost je prihvatljiva za obje noge, bez razlike između dana za dominantnu ($p = 0,393$) i nedominantnu nogu ($p = 0,436$). Potvrđena je osjetljivost oba protokola ($p < 0,05$), bez značajne razlike u identifikaciji asimetrija između ekstremiteta ($p = 0,415$, $d = 0,19$). Rezultati sugerišu da je skraćeni protokol validna i pouzdana alternativa. Oba protokola su osjetljiva u otkrivanju razlika između sedentarnih i aktivnih ispitanika, kao i u identifikaciji asimetrija između udova.

Ključne reči: brzina razvoja sile; skalirajući faktor brzine razvoja sile; RFD-SF, protokol testiranja RFD-SF; asimetrije

Naučna oblast: Fizičko vaspitanje i sport

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Neuromuscular quickness assessment – test optimization and sensitivity evaluation

Abstract

The rate of force development scaling factor (RFD-SF) has been used to assess neuromuscular quickness. However, the standard protocols are lengthy. This study evaluated the validity and reliability of the reduced protocol to assess the RFD-SF and its validity in detecting inter-limb asymmetries. Thirty subjects performed the standard and reduced RFD-SF protocols across three days. Correlation analysis was used for the investigaton of association of both protocols outcomes while Bland–Altman plots assessed reduced protocol's validity. Reliability was evaluated using intraclass correlation coefficient, coefficient of variation, typical error of measurement, and paired-sample t-test which was additionally used for sensitivity and validity to detect asymmetries analysis. Fpeak – RFDpeak correlation was nearly perfect for both dominant ($R^2 = 0.95/0.98$) and non-dominant ($R^2 = 0.94/0.98$) legs of both protocols respectively. Correlation between RFD-SF protocols was significant ($p < 0.001$) and very large (dominant: $r = 0.71$; non-dominant: $r = 0.80$). Bland–Altman plots showed agreement in RFD-SF values. No significant differences occured between protocols for dominant ($p = 0.480$, $d = 0.17$) and non-dominant legs ($p = 0.213$, $d = 0.31$). Reliability was acceptable for both legs, with no between-day difference for dominant ($p = 0.393$) and non-dominant legs ($p = 0.436$). Sensitivity of both protocols is confirmed ($p < 0.05$), with no significant difference in detecting inter-limb asymmetries ($p = 0.415$, $d = 0.19$). Results suggest that the reduced protocol is a valid and reliable alternative. Both protocols detect differences between sedentary and active subjects and identify interlimb asymmetries.

Keywords: rate of force development; rate of force development scaling factor; RFD-SF; RFD-SF testing protocol; asymmetries

Scientific field: Physical Education and Sport
Scientific subfield: Science of Physical Education, Sport and Recreation
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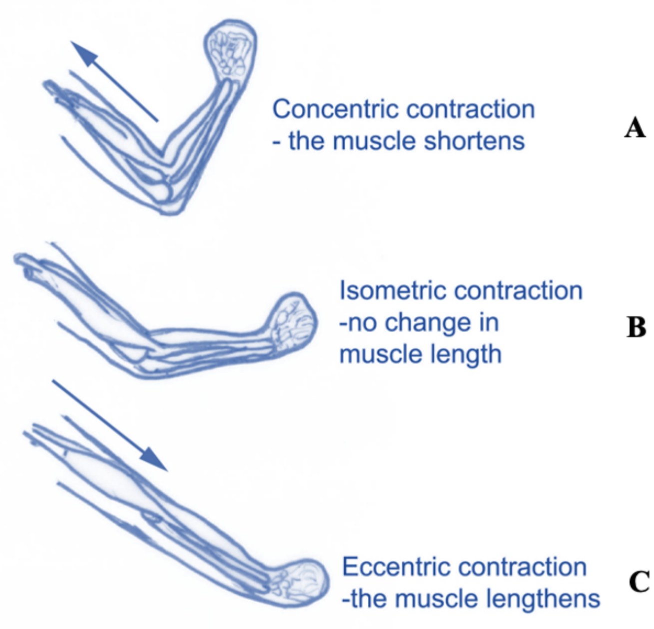
1. INTRODUCTION

Physical abilities are those human abilities that participate in solving motor movement tasks and condition successful movement, regardless of whether they were acquired through training (Logan et al., 2017). When analyzing physical abilities in sports activities, given that there is still not enough complex research on sports, a model composed of physical abilities skills of strength, speed, coordination, flexibility, balance, precision, and endurance is most often proposed and applied. Two of the most essential ones with regards to this dissertation will be presented in this general introduction.

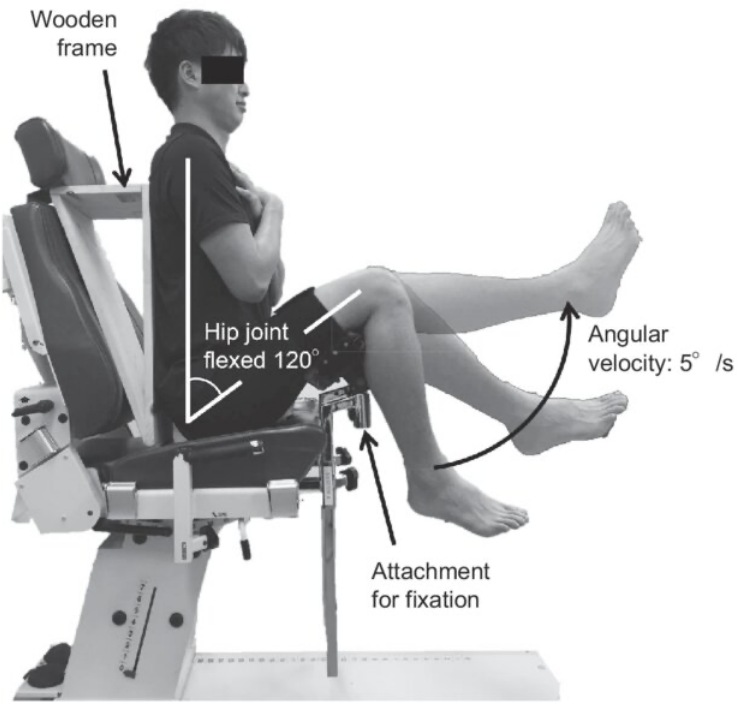
Strength refers to the ability to apply force (F) against an external resistance or object. As it is known in practice, it's developed and used in various exercise and training activities. However, before speaking about types of strength, it would be appropriate to shortly review the types of muscle contraction:

- isotonic contractions imply muscle movement during it's contraction. These are futher divided by:
  - concentric (Picture 1A): these occur when a muscle shortens as it contracts, like when you perform a biceps curl, bringing the weight closer to your shoulder. The force generated by the muscle is greater than the resistance, causing movement;
  - eccentric (Picture 1C): these occur when a muscle lengthens as it contracts against a resistive force that's greater than the force the muscle is generating. For instance, when slowly lowering a weight back down in a biceps curl, the bicep muscle is still contracting but in a controlled manner to resist the force of gravity;
- isometric contractions (Picture 1B): in this type, the muscle contracts, but its length remains the same, meaning there's no visible movement at the joint. Think of holding a weight in a fixed position without moving it. The muscle is active and generating force, but there's no change in the muscle length or joint movement. This type is essential for maintaining posture and stability;



Picture 1. Concentric contraction (A); isometric contraction (B); eccentric contraction (C). From, https://amactraining.co.uk/resources/free-learning-material/level-3-exercise-and-fitness-knowledge-index/level-3-55-exercise-and-fitness-knowledge-the-different-types-of-muscular-contraction/.

- isokinetic contractions (Picture 2) (Nishida et al., 2021): these refer to muscle contractions in which the muscle shortens or lengthens at a constant rate of speed. Unlike isotonic contractions, where the tension in the muscle remains constant while the length of the muscle changes, isokinetic contractions involve the muscle working at a constant speed throughout the entire range of motion. They are typically performed using specialized equipment such as isokinetic dynamometers. These devices control the speed of movement, allowing the muscle to generate maximum force at all points in the range of motion. The resistance automatically adjusts to the force applied by the individual, ensuring that the muscle works against a consistent load throughout the entire movement.



Picture 2. Isokinetic contraction. From "Association between passive stiffness of hamstring and eccentric knee flexion angle-torque relationship," by S. Nishida, 2021, *The Journal of Physical Fitness and Sports Medicine*, *10*(4), 205–211.

Accordingly, there are also different types (or forms) of the manifestation of strength, which are formed based on the criteria of their effect:

- explosive strength, which is most often defined as the ability to invest maximum energy in one movement in the shortest possible time, and is manifested in all activities in which the whole body, its parts, or the load extend their motion due to the obtained impulse, i.e., the initial acceleration. Its birth-rate coefficient, which represents how much of the abilitiy is approximately geneticaly predisposed, is about .80, so it's necessary to start developing this ability very early, i.e., between 5-7 years of age (Tomlinson et al., 2016);
- repetitive strength, which is most often defined as the ability to perform repetitions of individual and some simple movements of parts of the body or the whole body, and can be developed the most, given that the birth-rate coefficient is extremely low and amounts to .50 (Tomlinson et al., 2016);
- static strength, which is most often defined as the ability to maintain one maximum isometric muscle contraction, manifests when an athlete tries to overcome a resistance that exceeds his capabilities or exerts effort to maintain a specific position. These are conditions when the muscles are strained but without movement. The birth rate coefficient of this ability is about .50, which means that the development is prolonged (Tomlinson et al., 2016).

Speed is defined as the ability of a person to perform a high frequency of movements in the shortest time or to perform a single movement as quickly as possible under given conditions. It's considered to be one of the most essential physical abilities. Unlike strength, speed is much less researched. For now, it is known that some factors in different relations achieve the speed of movement. In addition, some factors, which were believed to have a decisive role, such as reaction speed, have been shown to slightly influence the formation of the speed of a particular movement.

Some research indicates the possibility of transfer of speed properties when it comes to the structure of movements, which have a joint coordination basis (jumping speed, throwing speed, starting speed), as well as that there is no connection between activities such as skipping and sprinting. However, running speed correlates highly with explosive and repetitive strength (Lesinski et al., 2014). From this, human abilities in terms of speed are specific and complex.

In addition to genetically determined general speed, the existence of the following abilities at a lower level was established in sports:

- motor reaction speed;
- single movement speed;
- change of direction speed;
- sprinting speed.

Since speed and explosive strength have a high correlation, it is necessary to develop them both at an earlier age (Lesinski et al., 2014).

2. MUSCLE BIOMECHANICAL RELATIONSHIPS AND MECHANICAL CHARACTERISTICS

Muscles are responsible for generating movement, and using them effectively can lead to superior athletic performance. While, there has been substantial research into the physiological responses of muscles to exercise and training (Figueiredo et al., 2018), there has been limited investigation into understanding how muscles function during sports and movement, as well as exploring potential adjustments in the mechanical characteristics of muscles due to exercise and training. The critical mechanical properties of interest in optimizing movement include the force-length relationship and the force-power-velocity attributes of skeletal muscles. Additionally, the neuromuscular aspects of movement control, crucial for enhancing movement performance, have received relatively little attention in sports research.

Skeletal muscles have demonstrated adaptability, shrinking during periods of disuse, such as bed rest or exposure to microgravity, and growing in response to intense resistance training (Falk & Eliakim, 2003). Additionally, muscle wasting is linked to aging and neuromuscular disorders (Distefano & Goodpaster, 2018). Understanding muscle adaptations is crucial for determining the type and intensity of exercises needed to slow down muscle deterioration associated with aging and neuromuscular diseases or to increase muscle strength and explosiveness. Additionally, improvements in neuromuscular coordination, often driven by enhanced motor unit recruitment and firing frequency, contribute to faster force development (Maffiuletti et al., 2016). Increased muscle stiffness and better synchronization of muscle activation further enhance the efficiency of force transmission (Del Vecchio, 2023). These adaptations collectively enable the muscles to respond quickly to neural signals, resulting in a higher explosiveness of contractions .

Understanding these adaptations is crucial in the context of muscle biomechanical relationships, as they play a pivotal role in shaping the functional attributes of the musculoskeletal system. Comprehensive analysis of how specific characteristics that can be modeled through muscle biomechanical relationships which are influenced by aforementioned adaptations, contribute to the intricate dynamics of muscle biomechanics, will be shown within this chapter. This exploration will not only shed light on the nuanced interplay between physiological changes and biomechanical responses but also provide valuable insights to optimize testing protocols of muscle characteristics in the function of training protocols, rehabilitative strategies, and overall musculoskeletal health interventions.

Biomechanical muscle relationships can be described by the following relationships: force-length (F-l), force-velocity (F-v) and force-power (F-P).

2.1.Force-length relationship

The maximum force a muscle can generate when it's not changing in length, known as isometric force, is influenced by the muscle's length. This relationship between force and length was described over a century ago. Gordon et al. (1966) conducted experiments on frog striated muscle and found that the force-length relationship of the sarcomeres (the basic contractile units of muscle) was linear on the descending limb. This supported the cross-bridge theory of muscular contraction proposed a few years earlier. This relationship is directly linked to the lengths of the thick and thin myofilaments (myosin and actin) within the sarcomere.

However, it's essential to note that the identified force-length relationship does not represent the typical force-length properties of a muscle during dynamic contractions or real-life scenarios. Stretching a sarcomere on the descending limb doesn't produce the expected isometric force. Instead, it results in a much higher force than predicted by the cross-bridge theory.

In most cases, it's challenging to determine the force-length properties of individual human skeletal muscles in vivo. However, for certain multi-joint muscles, these properties can be estimated experimentally in humans. This becomes particularly crucial in athletic contexts as force-length properties might adapt to the specific demands of sports movements.

Here is the example of two studies (Bohm et al., 2021; Lee et al., 2021) conducted on two distinctive groups of athletes – cyclists and runners, where muscles' adaptations to specific training were investigated. These adaptations might have originated in neuromuscular innervation or muscle activation control. However, the number of sarcomeres in series within the rectus femoris muscle fibers may have adapted to the requirements of cycling and running. Cyclists' rectus femoris muscles can operate mainly on the descending limb of the force-length relationship if they have fewer sarcomeres in series and longer average sarcomere lengths than runners. Conversely, runners' rectus femoris muscles work mainly on the ascending limb if they have more sarcomeres in series and shorter average sarcomere lengths than cyclists. If this explanation holds, it suggests that using running as cross-training for cycling (or vice versa) is not advisable. Additionally, it implies that a triathlete who trains in both running and cycling may excel less than a specialized runner or cyclist, even with equal training and talent. Due to long-term training, these force-length adaptations should be considered when developing theoretical models of the musculoskeletal system.

The adaptations observed, potentially originating from neuromuscular innervation, muscle activation control, and sarcomere arrangement, imply distinct force-length relationships during muscle contraction for cyclists and runners. These biomechanical variations may influence the speed at which force is generated and possible mismatch in adaptations. Additionally, it implies that a triathlete engaging in both activities may face performance challenges compared to specialized runners or cyclists. Understanding of the relationship between muscle adaptations and characteristics has significant implications for refining training protocols and theoretical models of the musculoskeletal system, particularly in the context of diverse athletic disciplines.

2.2.Force-velocity relationship

The maximum force a muscle can generate at its ideal length depends on how fast it contracts. When a muscle shortens, its force decreases as it contracts faster, while during lengthening, the force increases as it contracts more rapidly (Herzog et al., 2015).

The force-velocity (F-V) relationship is fundamental in biomechanics and exercise physiology. It describes the inverse relationship between the force a muscle can generate and the velocity at which it contracts (Jaric, 2015). This relationship plays a pivotal role in understanding the capabilities of skeletal muscles during various activities, such as strength training, athletic performance, and daily movements. Investigating this relationship provides valuable insights into muscle function, helping researchers, coaches, and clinicians optimize training protocols and enhance human performance.

This idea was established based on Hill's pioneering research involving frog muscles in isolation back in 1938 (Hill, 1938), and Huxley further developed theories on muscle contraction mechanisms in 1957 (Huxley, 1957). Recent studies have delved into the F-V relationship within real-life scenarios, aiming to understand muscle performance in activities like vertical jumping, sprinting, and rowing (Haugen et al., 2019), and even daily tasks like walking or rising from a chair, especially among older adults (Alcazar et al., 2018). Additionally, there's growing interest in utilizing the F-V relationship as a guide for effective training strategies (Morin & Samozino, 2016).

As muscle contracts, the F-V relationship is described by the hyperbolic curve proposed by Hill (1938). This curve illustrates that maximal force is generated at zero velocity (isometric contraction), while maximal velocity is achieved with minimal force (maximal concentric contraction). As the contraction velocity increases, the force production progressively decreases due to limitations in the time available for cross-bridge formation and attachment.

Understanding the F-V relationship is crucial for optimizing muscle performance across various contexts. In strength training, it guides the selection of appropriate resistance and repetition ranges to target specific adaptations. For instance, heavy loads (high force, low velocity) stimulate muscle hypertrophy and maximal strength gains. In contrast, lighter loads (low force, high velocity) contribute to improvements in power and speed (García-Ramos et al., 2016).

Athletes and coaches utilize the F-V relationship to design training programs that align with the specific demands of their sport. For instance, sprinters focus on enhancing their ability to generate force rapidly during explosive movements, while endurance athletes aim to improve their force production efficiency over prolonged durations. By manipulating the F-V relationship through various training modalities, athletes can tailor their regimens to achieve optimal performance outcomes (Petrovic et al., 2021).

The F-V relationship also has practical implications for clinical populations and rehabilitation settings. Patients recovering from injuries or surgeries often undergo rehabilitation programs that target muscle strength and function. Understanding the F-V relationship helps clinicians design progressive resistance exercises that accommodate the individual's capabilities and pace of recovery. Additionally, it aids in developing interventions for special populations, such as older adults, who may experience age-related declines in muscle force and power (Alcazar et al., 2018).

Emerging technologies, such as isokinetic dynamometers and velocity-based training devices, enable precise measurement and manipulation of the F-V relationship (Janicijevic et al., 2020). Isokinetic dynamometers provide constant angular velocity during muscle contractions, allowing accurate force measurements across various velocities (Janicijevic et al., 2019). Velocity-based training devices enable real-time feedback on barbell or body movement velocity, assisting athletes and coaches in optimizing training loads and velocities for maximal gains (Weakley et al., 2021).

2.2.1. Standard method for F-V relationship modelling

Following Jaric's proposal (Jaric, 2015), the approach to modeling F-V relationships during complex joint movements has commonly involved collecting data from more than two experimental points. These points consist of pairs of force and velocity measurements, referred to as the multiple-point method. Researchers in several studies have employed this method (Cuk et al., 2016; García-Ramos et al., 2016; Petrovic et al., 2021).

While increasing the number of experimental points enhances the accuracy of determining F-V relationship parameters, concerns have been raised about this procedure's potential fatigue and time-consuming nature. The studies by Jaric (2016) and Perez-Castilla et al. (2018) indicated that a possible solution to address these issues is to utilize only the two most distant experimental points (Jaric, 2016; Pérez-Castilla et al., 2018). This approach could lead to improved time efficiency and mitigate the potential negative effects of fatigue.

The force-velocity relationship is a fundamental concept that underpins our understanding of muscle contraction and performance. It has far-reaching implications for strength training, athletic performance, rehabilitation, and clinical practice. Researchers, coaches, and clinicians can develop targeted interventions that enhance muscle function and optimize human performance by comprehending the physiological basis of this relationship and its applications. Continued advancements in technology and research will further elucidate the intricacies of the force-velocity relationship, enabling more effective strategies for improving muscle strength, power, and overall well-being.

2.2.2. Two-point method for F-V relationship modeling

Even though F-V relationship parameters are more accurate when the number of experimental points increases, some researchers claimed that this method could be fatiguing and time-consuming. In recent studies, authors showed that using just two furthest points could be usable for increased time efficiency and to diminish possible fatigue occurrence (García-Ramos et al., 2018; Garcia-Ramos & Jaric, 2018; Janicijevic et al., 2019, 2020; Jaric, 2016; Pérez-Castilla et al., 2018).

In their opinion, the two-point method might be able to differentiate between maximal muscle capacities in less time and without the influence of fatigue compared to the method regularly used for

F-V relationship modeling, known as the multiple-point method (i.e., two or more sets of force and velocity values are used for F-V relationship modeling). In an already mentioned study by Pérez-Castilla et al. (2018), it has been shown that the most distant pair of loads could provide the highest reliability and validity among all two-point methods assessed.

2.3.Force-power relationship

Power, the product of force and velocity, is crucial in understanding muscle function. In the context of muscles, power is calculated as the force's magnitude multiplied by the contraction velocity. The power-velocity relationship can be derived from the force-velocity relationship by multiplying the corresponding force and velocity values. Notably, power is zero during isometric contractions (no speed) and when muscles contract at their maximum shortening speed (no force). Measuring power in muscles is more complex as it requires direct measurements of both muscular force and contraction velocity.

The ability to generate force quickly and produce significant external mechanical power is crucial for sports performance (Boccia et al., 2018). Previous studies have shown that rate of force development (RFD) and power levels vary between athletes who start games and those who don't, as well as among athletes of different skill levels (Stien et al., 2021). Given the significance of RFD and external mechanical power for an athlete's performance, identifying and developing trainable factors to enhance these variables is paramount.

The amount of generated external mechanical power plays a significant role in distinguishing the performance levels of athletes in various sports. External mechanical power refers to the combined power exerted by the joints and can reflect the coordinated effort of the lower body (Moir et al., 2012). Instead of considering individual joint power, researchers often measure and analyze the overall external mechanical power of the system. This measure has been linked to various performance characteristics in sports, including sprinting, jumping, change of direction, and throwing velocity (van der Kruk et al., 2018). Consequently, many experts argue that external mechanical power is crucial in determining athletic performance (Cormie et al., 2012). Previous research has identified differences in external mechanical power between athletes of different playing levels and between starters and non-starters (van der Kruk et al., 2018). Therefore, it is unsurprising that coaches and trainers frequently focus on developing and enhancing external mechanical power to improve overall athletic performance.

Exploring the complex dynamics of the force-power muscle relationship lays the foundation for understanding the significant interactions within the strength training. Building upon the force-power relationship, the integration of phase potentiation introduces a systematic approach to training, emphasizing specific phases to unlock the full potential of muscular adaptations.

A periodization model called phase potentiation has been developed based on the concepts of Minetti (2002). The main idea behind this model is that each training phase builds upon the previous one, enhancing specific physiological characteristics. For instance, completing a strength-endurance phase focused on increasing muscle size and work capacity would improve the ability to develop muscular strength in a subsequent phase. Similarly, a maximal strength phase would enhance the ability to generate muscular power in a strength-power or explosive speed phase. Considering these principles, it is reasonable to assume that greater muscular strength would ultimately contribute to the ability to generate higher levels of net joint power.

Research has shown that participating in strength training programs can lead to an improvement in the amount of power generated by the body, either in absolute terms or relative to external mechanical power (van der Kruk et al., 2018). The effectiveness of these programs can be explained by Newton's second law of motion, which states that the forces acting on an object are equal to the object's mass multiplied by its acceleration. According to this law, when greater forces are exerted on an object over a specific period, it experiences a greater acceleration, resulting in increased velocity. Therefore, power output can be enhanced by increasing both force and velocity.

Since muscular strength is the ability to exert force against an external object or resistance, practitioners must focus on improving maximal strength to develop and enhance external mechanical power.

Research has demonstrated a strong connection between maximal strength and power generation (Dunn et al., 2022). Maximal strength sets the upper limit for how much power an individual can produce. Consequently, athletes with greater strength tend to have an advantage in generating power. Increasing maximum strength in weaker athletes has been proven to improve RFD and power more than solely focusing on power training (Dunn et al., 2022). There is a close relationship between maximal strength and power, with RFD bridging these two factors. This is particularly important because most sports skills require the expression of high force, and maximal strength plays a crucial role in developing this essential training variable. At the same time, RFD serves as the means through which athletes can effectively express high forces during athletic competition.

2.4.Rate of force development

Explosive strength is typically quantified by assessing the RFD, which measures the increase in force over time (dF/dt). Mathematically speaking, RFD represents the first derivative of the force-time curve (Maffiuletti et al., 2016). Additionally, some researchers have defined RFD as the speed at which force is generated within a specific time frame (Mirkov et al., 2004). It has also been referred to as "explosive strength." Producing force quickly is crucial for success in various sports events (Taber et al., 2016). This is because many sports involve rapid movements, such as jumping and sprinting, with limited time to generate force (typically between 50 to 250 milliseconds) (Guizelini et al., 2018). Impulse, which is the product of force and the duration over which it is exerted, is also important. While the impulse may influence vertical jump and weightlifting performance, the significance of RFD should be considered, as it may take longer (over 300 milliseconds) to reach maximum muscular force (Laffaye & Wagner, 2013). Therefore, training efforts often focus on increasing RFD to allow for greater force production within a given period. This, in turn, leads to an increase in generated impulse or a decrease in the time required to achieve an equal impulse, resulting in faster acceleration of an individual or an object.

Numerous studies have indicated that resistance training for strength gains has a positive impact on an individual's RFD characteristics (Methenitis et al., 2019; Presland et al., 2020). Latter mentioned study even suggested that maximal muscular strength may account for up to 80% of the variability in voluntary RFD within the range of 150 to 250 milliseconds. Limited research has been conducted to compare the RFD values between individuals of varying strength levels. However, some studies have suggested stronger individuals exhibit higher RFD values than weaker individuals (Thomas et al., 2015). Conversely, another study found no significant difference in RFD between the strongest and weakest individuals tested (Stone et al., 2004). Nevertheless, considering the latter study using the magnitude of effect indicates a substantial practical difference in RFD (Cohen's d = 23.5). The lack of statistical differences observed between stronger and weaker groups in this study could be attributed to the small sample size in each group (n = 6) and the range of abilities within each group (such as elite cyclists and recreational cyclists).

As mentioned earlier, RFD holds significant importance in the domain of neuromuscular function, especially in sports activities where there is a limited window to generate force rapidly, such as maintaining balance, sprinting, jumping, and delivering punches (Yi et al., 2022). Several studies revealed that power athletes, proficient in quick sporting actions like sprinters and jumpers, were able to harness their explosive strength much more effectively during the initial phase of muscle contraction compared to untrained individuals (Lum et al., 2021). However, their maximum voluntary contraction (MVC) which refers to the highest amount of force or tension that a muscle or group of muscles can generate during a voluntary contraction was only 26% higher. This finding suggests that RFD plays a more crucial role than differences in maximal strength in sports that demand swift force production. The correlation between RFD and athletic performance is influenced by the specific athletic tasks and the method used for assessment. Numerous studies have produced conflicting results regarding the relationship between measured RFD and athletic tasks in sports (Henderson et al., 2022; R. Wang et al., 2016). It is becoming evident that the time allocated for the athletic task and the duration over which RF' is measured are critical factors in understanding this connection.

The factors determining how quickly muscles can generate force, known as contractile RFD, involve both physiological aspects of the nervous system and muscle function. These factors play distinct but sometimes overlapping roles in two phases: the early phase (less than 100 milliseconds) and the late phase (100 milliseconds or more) of increasing muscle force (Maffiuletti et al., 2016). In the early phase (less than 75 milliseconds), the recruitment of motor units (MUs – groups of muscle fibers controlled by a single motor neuron) and the rate at which motor neurons discharge signals significantly impact the RFD. Motor units (MUs) are functional units within the neuromuscular system that play a crucial role in muscle contraction (Wulf et al., 2010). A motor unit consists of a motor neuron and all the muscle fibers it innervates. Additionally, intrinsic muscle properties, such as the distribution of type II muscle fibers, can explain differences in RFD among individuals and muscles during this phase (Del Vecchio, 2023). In contrast, the late phase RFD (100 milliseconds or more) is influenced not only by maximal muscle strength but also by the extent of neural input and muscle architectural properties, like the angle at which muscle fibers attach to the tendon (Del Vecchio, 2023).

Researchers examined RFD at various time intervals from the onset of force production (50, 100, 150, 200, and 250 milliseconds) during rapid isometric squats (Dos'santos et al., 2017). They correlated force production at each time point with both countermovement jump and sprint performance. The results demonstrated that RFD during the early phase of the squat (≤ 100 ms) was closely linked to acceleration capabilities during sprint running (5-20 meters). In contrast, the ability for late-phase squat RFD (>100 ms) was more associated with vertical jump height. This discrepancy is attributed to the varying time frames available for force production in each task, with sprint running requiring rapid force generation within 80-120 ms compared to jumping, which allows 250 ms for force production.

It's essential to note how the way RFD is analyzed can affect interpretation. When RFD is assessed from the onset of muscle contraction (e.g., 0 to 100 milliseconds), it reflects the combined effects of neural and muscular factors during that interval. However, when RFD is sequentially evaluated in a muscle that's already activated (e.g., at 100-150 milliseconds), neural activation may already be high or maximal, suggesting a greater reliance on peripheral physiological factors for late phase RFD (Figure 1) (Djordjevic & Uygur, 2018). This indicates that in healthy individuals, sequential RFD analysis can help assess the relative contributions of neural and intrinsic muscle factors during the early and late phases of muscle force development (Rodríguez-Rosell et al., 2018). However, it's important to consider that these findings were based on studies of healthy individuals, and it's uncertain whether similar relationships exist in injured populations, where neural activation may be slower at the beginning of muscle contraction but still relevant for late-phase RFD.

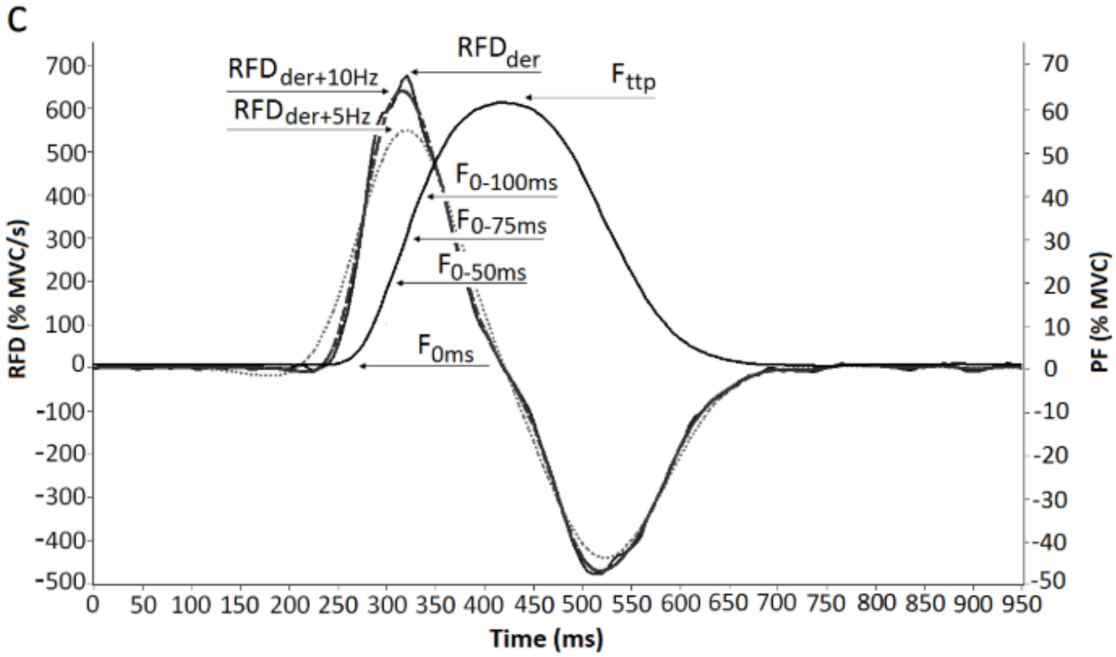


Figure 1. Different methods of RFD calculation. From "Methodological considerations in the calculation of the rate of force development scaling factor," by D. Djordjevic and M. Uygur, 2018, *Physiological Measurement*, *39*(1).

The stability of joints is influenced by the interplay between the active joint stabilizers (muscles) and the passive joint structures (like ligaments). For instance, in the case of an injury such as an anterior cruciate ligament rupture, which can happen within a mere 50 milliseconds after ground contact, the ability to generate force rapidly (within approximately 25-50 milliseconds) may be more crucial than one's maximum force-producing capacity when it comes to preventing injuries (Minshull et al., 2021). Consequently, the early phase of RFD might have greater significance as a risk factor for injuries, although it has yet to receive direct scientific attention.

A growing body of evidence suggests that RFD could play a pivotal role in injury occurrence. RFD has been shown to significantly impact the effectiveness of maintaining balance during walking and responding to disturbances that could lead to a fall or injury (E. Wang et al., 2017). In addition, training to improve balance has been associated with enhanced RFD and a reduced risk of joint injuries, particularly in previously injured individuals (Avelar et al., 2016). Furthermore, fatigue has been linked to a higher risk of injury and has been found to have a more pronounced effect on RFD than MVC (Boccia et al., 2017).

Recent research has highlighted that six month after anterior cruciate ligament reconstruction average MVC had mostly returned to pre-injury levels, while RFD at various levels of MVC remained significantly lower (Minshull et al., 2021). It took 12 months and a focused rehabilitation program emphasizing muscle power to reach pre-injury RFD values. This suggests that, in anterior cruciate ligament reconstruction cases, RFD criteria might be a valuable additional measure to determine when athletes can safely return to sports. Similarly, individuals with a previous hamstring strain demonstrated 40% lower early-phase eccentric RFD in the previously injured limb than in the unaffected limb (Bourne et al., 2020). Considering that many patients don't achieve satisfactory outcomes after anterior cruciate ligament reconstruction and that hamstring re-injury rates are high, the deficit in RFD upon returning to sports could have significant clinical implications for re-injury prevention. An improved ability to generate rapid force should enhance one's resistance to injury.

2.5.Neurophysiological factors influencing muscle strength and it's components

Muscular strength development is influenced by various factors related to the physical structure of muscles and the neural pathways that control them. These mechanisms responsible for improving muscular strength are complex and multifactorial, and they can also be affected by other elements such as the individual's initial strength level, their training status, and their genetic traits (Ahmetov et al., 2016). To better understand how muscular strength is impacted, it's essential to consider both morphological factors (pertaining to the structure and composition of muscles) and neural factors (concerning the nervous system's involvement in muscle activation). These factors interact uniquely for each individual, leading to diverse responses in how their muscular strength improves. It's worth mentioning that an athlete's history of muscle use, including factors like fatigue, post-activation effects, and temperature, can also play a role in influencing their expression of muscular strength (De Almeida Barros et al., 2020). Overall, comprehending these underlying factors is crucial in shaping training strategies that can effectively elicit improvements in muscular strength for athletes and individuals seeking to enhance their physical performance.

2.5.1. Muscle hypertrophy and structural design

The evidence suggests that previous training phases' effects influence future training phases. Two factors play significant roles in increasing muscle size (hypertrophy) to enhance strength: potentiation and residual training effects (McGlory & Phillips, 2015). There is an optimal training sequence to achieve the best results from resistance training. The recommended sequence involves first increasing the muscle's cross-sectional area (CSA) through hypertrophy and improving its work capacity (force production capacity). This initial phase is followed by a subsequent progression (Suchomel & Stone, 2017). By following this sequence, superior gains in strength and power can be achieved. The importance of larger muscle CSAs in generating greater absolute force production is evident in sports with weight classes like powerlifting and weightlifting. Muscle fiber CSA, particularly type II fibers, can influence the force-velocity characteristics of the muscle. Studies have shown a strong relationship between muscle CSA and greater force production (M. S. Miller et al., 2015).

Physiologically, increased muscle CSA improves force production by allowing cross-bridge interactions between actin and myosin within the muscle's sarcomeres. Additionally, hypertrophied muscles tend to have greater muscle fiber pennation angles, which can further enhance force production (M. S. Miller et al., 2015). However, it's essential to note that the relationship between muscle hypertrophy and strength changes can vary between individuals. Factors such as the time course of adaptation, methodological issues in measuring hypertrophy, or other physiological and neural factors beyond CSA can contribute to this variability (McGlory & Phillips, 2015).

In summary, increasing muscle CSA lays the foundation for improvements in strength, which changes in muscle architecture, fiber type, and neural factors like motor unit recruitment and muscle activation patterns can further enhance.

2.5.2. Muscle-tendon stiffness

The production of force and its expression as a measure of strength is closely tied to tissues exhibiting spring-like behavior, affecting muscle performance (Ramírez-delaCruz et al., 2022). When tissues become stiffer (meaning they resist more when stretched by a given force), they can enhance force transmission. This increased stiffness can result from adaptations in tendon stiffness and various structures within the muscle, including actin, myosin, titin, and connective tissue. These adaptations, in turn, influence muscular strength, rate of force development (RFD), and power (Brumitt & Cuddeford, 2015).

A large protein or viscoelastic spring called titin is one essential but often overlooked component in generating skeletal muscle force and strength. Titin likely causes passive tension within the sarcomere (the basic contractile unit of muscle), making it increasingly recognized for its significance in muscle function. Recent evidence suggests that titin's role may be more critical. It's worth noting that sarcoplasmic calcium levels can actively increase titin's stiffness, thereby contributing to the overall stiffness of the sarcomere (Herzog, 2018). Consequently, changes in tissue stiffness both within and around the muscle may partially influence alterations in muscular strength and force transmission.

2.5.3. *Activation of motor units*

The motor neuron is a nerve cell that transmits signals from the brain or spinal cord to the muscle fibers, leading to muscle contraction. MUs are activated in a specific order based on their size, with smaller MUs being recruited first and larger ones later (Farina et al., 2016). The recruitment of MUs is determined by the amount of force and rate of force development (RFD) required for a particular task. For instance, tasks involving smaller force magnitudes and RFD will engage smaller MUs, which consist of slow-twitch type I muscle fibers. On the other hand, tasks demanding higher forces and RFD will activate larger MUs, which contain fast-twitch type IIa/Iix muscle fibers (Mota et al., 2019). This recruitment order generally occurs in various actions, including slow, graded, isometric, and ballistic movements (J. D. Miller et al., 2020).

The specific type of activity and its purpose directly influence the recruitment of MUs and their adaptations. For example, distance runners primarily rely on low-threshold, slow-fatiguing MUs with type I fibers due to the moderate forces repeatedly required during races (J. D. Miller et al., 2020). Only when these type I MUs fatigue, they recruit high-threshold MUs with type II fibers to sustain the activity. Consequently, the maximal strength achieved by distance runners, who predominantly use type I MUs, may be limited because they infrequently engage MUs with type II fibers during training.

In contrast, weightlifters frequently perform ballistic tasks demanding high force and RFD, leading them to target MUs with type II fibers. Weightlifters likely recruit a combination of type I and type II MUs, following the recruitment order, but with lower recruitment thresholds (Sivokhin et al., 2020). This allows both types of MUs to be effectively trained. Previous research has shown that ballistic-type training results in the recruitment of MUs at lower force thresholds while still maintaining the orderly recruitment pattern (Gil et al., 2019).

For strength development, it seems advantageous to involve high-threshold MUs during training. Ballistic training methods can promote the activation of larger MUs containing type II fibers at lower force thresholds, leading to positive adaptations in strength and power.

2.5.4. *Firing frequency (rate of coding)*

Once specific MUs are recruited, the rate at which α-motoneurons send action potentials to the muscle fibers of those MUs can influence the properties of force production. Studies have shown that the magnitude of force produced may increase significantly, ranging from 300% to 1500%, when the firing frequency of the recruited MUs goes from its minimum to its maximum (Kline & De Luca, 2015).

Moreover, additional research has revealed that the firing frequency of MUs can also affect the RFD. Higher initial firing frequencies have been linked to increased doublet discharges, which means two consecutive MU discharges occurring within a 5-millisecond interval (Del Vecchio et al., 2022). This suggests that increased firing frequency of MUs could lead to greater force production and improved RFD, potentially contributing to strength and power development.

It was found that 12 weeks of ballistic training could enhance MU firing frequency (Elgueta-Cancino et al., 2022). Therefore, it is reasonable to speculate that other ballistic training methods, such as weightlifting movements and sprinting, might also positively impact MU firing frequency, ultimately benefiting strength and power characteristics.

2.5.5. *Synchronization of motor units*

Some studies suggest that MUs synchronization might be more closely related to RFD than the actual magnitude of force produced (Vecchio et al., 2019). The simultaneous activation of specific muscle units, specifically C 2 MUs, can enhance peak force production by enabling greater RFD during short periods.

Previous research has shown that six-week resistance training increased MUs synchronization (Soria-Gila et al., 2015). Additionally, one study found that MUs synchronization was stronger in weightlifters' dominant and non-dominant hands than musicians and untrained individuals (Herda et al., 2015). Furthermore, evidence supports the idea that heavy resistance training may increase MU synchronization and force production (Del Vecchio et al., 2019). However, the findings regarding MU synchronization changes are mixed when it comes to ballistic-type training. Some studies have suggested that MU synchronization remains unchanged following ballistic-type training (Haghighi et al., 2021), while others have indicated that it improves during ballistic tasks (Wallace & Janz, 2009).

Incorporating heavy resistance training and/or ballistic-type movements into training strategies may help improve MUs synchronization. Although there is limited research on changes in MU synchronization within resistance training literature associated with gross motor movements, it is essential to consider the connection between improved neuromuscular activation patterns and subsequent force production.

2.6. Influence of strength on general sport skills

Jumping, sprinting, and rapid change of direction tasks are frequently observed in various sports. The successful execution of these movements can greatly impact the results of sporting events. As mentioned earlier, muscular strength is crucial in determining critical force-time aspects essential for performance. It is believed that improvements in force-time characteristics should translate into better overall performance in sports skills. Hence, the impact of muscular strength on jumping, sprinting, and change of direction should not be disregarded.

2.6.1. Jumping

Jumping tasks, whether they involve leaping vertically or horizontally, are commonly performed and are often essential skills for success in sports competitions. In some instances, the ability to jump higher or farther than competitors determines the winner, as seen in events like the high jump, long jump, and triple jump. However, in other sports, repetitive jumping tasks do not directly determine the outcome of the competition. In team sports, jumping tasks are incorporated into rebounding in basketball, spiking/blocking in volleyball, and diving in baseball.

While an individual's impulse ultimately influences their jumping performance, the specific characteristics of force and time play a significant role in shaping and determining the magnitude of the impulse created. It has been observed that greater muscular strength can modify an individual's force-time characteristics. Resistance training, which increases muscular strength, can affect both the peak performance variables and the shape of the force-time curve (Suchomel & Sole, 2017).

Research has shown stronger individuals exhibit distinct force-time curve characteristics compared to weaker individuals. This includes differences in the duration of the unweighted phase, the relative shape of the different phases of the jump, and the net impulse forces generated (McMahon et al., 2018). Stronger subjects tend to have a shorter unweighted phase and produce greater forces in the region of the force-time curve corresponding to net impulse compared to weaker subjects.

Additionally, improvements in maximal strength resulting from ten weeks of strength training have produced positive adaptations in force during the late eccentric/early concentric phase of jump squats (Cormie et al., 2010).

2.6.2. Sprinting

The capacity to accelerate quickly and achieve high speeds during sprints is crucial in many sports and athletic events. While top sprinting speeds often determine the winners in certain track events like the 100 or 200-meter races, athletes participating in field sports such as soccer, rugby, and field hockey may only sometimes reach their maximum velocity. In these sports, the average sprint times are relatively short, around 2 seconds, covering distances of approximately 14 meters in soccer (Haugen et al., 2014) and 20 meters in rugby (Cross et al., 2015). Research has shown that rugby union players may only reach about 70% of their maximum sprinting speed after sprinting for 2 seconds as stated in the latter study mentioned in the previous sentence. This suggests that the ability to accelerate quickly over short distances is crucial for field athletes.

Previous studies have demonstrated that elite athletes achieve higher speeds over short distances than non-elite athletes, while faster runners exhibit specific characteristics such as greater force application, shorter ground contact times, and longer strides (Colyer et al., 2018). Further research has indicated that sprint performance may be limited by the ability to generate a high rate of force development (RFD) during the brief ground contacts rather than the sheer ability to apply force. Proficient sprinters can generate greater vertical forces during the initial phase of their stance (Clark & Weyand, 2014). As shown earlier, maximal strength is strongly associated with RFD, making it logical that sprinting performance is also linked to an individual's strength level. Previous research has shown that strength improvements co-occur as short sprint performance enhancements (Comfort et al., 2012).

2.6.3. Change of direction

Rate of force development (RFD) is crucial for tasks that require quick changes of direction (COD) in sports, similar to the importance of speed in sprinting. The plant phase, which is when the actual change of direction happens, can vary in duration (0.23 – 0.77s) depending on the entry velocity and severity of the COD angle required. Ground contact times during a COD are longer than the ground contact times during the acceleration (0.17 – 0.2) and maximal velocity phases of sprinting (0.09 – 0.11) (Spiteri et al., 2013). Therefore, there is expected to be a strong relationship between maximal strength and COD performance, as there is more time available to utilize one's maximal strength. However, COD performance is not solely dependent on strength but also requires coordinated body movements within the constraints of the activity.

According to mathematical principles, individuals who can apply greater force over a given time (greater impulse) should be able to accelerate or change momentum with the highest velocity. However, the difference in the expected relationship between strength and COD performance may be attributed to the tests used to measure "COD ability" and "strength" rather than a lack of association between the two. Some research questions the validity of using "total time" as an assessment of COD ability and suggests that smaller time intervals (Chaabene et al., 2018) or direct measures of the center of mass velocity (Spiteri & Nimphius, 2013) provide more accurate assessments. These alternative measures can help us better understand the relationship between strength and COD ability.

Regarding measuring strength, recent research shows that eccentric, concentric, dynamic, and isometric strength all contribute to COD performance (Pardos-Mainer et al., 2021). However, most studies focus on measuring only one type of strength. When evaluating COD performance using demanding COD tasks, such as the 505 and T-test with angles greater than 75°, eccentric strength plays the most significant role (Pardos-Mainer et al., 2021). Therefore, our understanding of the association between strength and COD ability continues to evolve as we explore more specific and valid measures of each underlying physical quality.

2.7.Influence of strength on specific sport skills and performance

While it is generally considered beneficial for strength to translate into improved force-time characteristics, the crucial aspect is whether that strength transfers to an athlete's performance in their specific sport. If an athlete's strength doesn't contribute to their performance in sports or events, coaches might be less inclined to include resistance training in their athletes' preparation. However, existing literature supports the idea that muscular strength is a fundamental factor in strength-power performance and is also linked to enhanced endurance performance (Murlasits et al., 2017).

Studies indicate that stronger athletes tend to outperform their weaker counterparts in both strength-power-based and endurance-based sports or events. Supporting these findings, several studies have compared sports performance between stronger and weaker individuals. These studies revealed that stronger cyclists achieved faster 25-meter track cycling times compared to weaker cyclists (Mujika et al., 2016), stronger handball players exhibited greater standing and 3-step running throwing velocity compared to weaker handball players (Xaverova et al., 2015), and stronger sprinters achieved faster 100-meter times compared to weaker sprinters (Alt et al., 2021). These comparisons between stronger and weaker athletes provide substantial evidence that stronger athletes, within a relatively similar skill level, tend to perform better than their weaker counterparts.

2.8.Influence of strength on additional abilities

Muscular strength affects an athlete's force-time characteristics, general sports skills, and specific sports skills and impacts various training and performance aspects. It can influence an athlete's ability to enhance their performance through strength-power potentiation complexes, the extent of potentiation they can attain, and even their vulnerability to injuries.

2.8.1. Potentiation

Numerous studies have examined the immediate effects of strength-power potentiation complexes on an individual's explosive performance. Various factors can influence the extent of potentiation, and one of these factors that can be improved through regular strength training is an individual's strength. Studies have shown that individuals with greater strength experience earlier and more pronounced potentiation than those with weaker strength (Lockie et al., 2018). However, some studies have found no significant differences in potentiation between strong and weak individuals (Suchomel et al., 2016a). One possible explanation for these conflicting results could be the specific design of the strength-power potentiation complexes used in the studies.

In some cases, the protocols did not significantly improve vertical jump performance (Batista et al., 2011), making it difficult to compare the potentiation between stronger and weaker subjects. Additionally, the range of abilities within each group may have played a role. For example, one study combined males and females when comparing potentiation differences between stronger and weaker subjects (Prieske et al., 2020), while another study had significant variations in performance within the groups, potentially masking any statistical differences (Batista et al., 2011). Overall, the existing literature suggests that achieving greater strength allows individuals to experience potentiation effects earlier and to a greater extent. From a practical standpoint, some authors suggest that individuals who can back squat at least twice their body weight to a specific depth or achieve certain strength thresholds may have a greater potential for potentiation compared to weaker individuals (Seitz et al., 2014).

2.8.2. Injury rate

Previous studies have suggested that muscular strength is just as important as anaerobic power when it comes to soccer players' performance and injury prevention (Beato et al., 2021). Athletes, coaches, and practitioners are greatly concerned about the rate of injuries in sports and training, as it hinders athletes' ability to contribute to the team. Coaches may be hesitant to introduce new training methods due to the perception that specific exercises are prone to causing injuries. However, when strength training is appropriately prescribed and gradually increased using various methods, it can reduce the overall occurrence of injuries.

Research has shown that collegiate soccer players experienced a decrease in the injury rate per 1,000 exposure hours after implementing a strength training program (Zouita et al., 2016). Another study involving female volleyball players found that the highest isometric mid-thigh pull strength levels coincided with the lowest annual injury rate (Owens et al., 2011). These findings support the idea that increased strength can play a crucial role in reducing the likelihood of injuries. Some other studies and reviews also support this concept, with a meta-analysis revealing that strength training protocols can reduce sports injuries by more than two-thirds and nearly halve overuse injuries (Lauersen et al., 2018).

Resistance training can reduce injuries by strengthening ligaments, tendons, tendon-to-bone and ligament-to-bone connections, joint cartilage, and connective tissue sheaths within muscles (Forthomme et al., 2018). Additionally, it can lead to positive changes in bone mineral content, further aiding in reducing skeletal injuries (Maestroni et al., 2020). Therefore, it is evident from the existing literature that resistance training is an effective modality for decreasing injury rates, and athletes with greater strength are less prone to injuries. As a result, strength and conditioning practitioners should prioritize improving their athletes' overall strength to enhance performance and minimize the risk of injuries.

Several studies have demonstrated the significance of assessing F and RFD in various areas, including athletic performance, injury rehabilitation, monitoring muscle damage, exercise training adaptations, aging and neuromuscular diseases (Vesga-Castro et al., 2022). Adequate procedures for the assessment of muscle properties are needed since they can be of key importance for the prevention of injuries in athletes. Regular training and rehabilitation monitoring are part of the injury prevention protocols, so tests that include valid and reliable assessment of both F and RFD with the least amount of effort should be designed and applied as in practical, so in clinical settings.

2.9.Open and closed kinetic chain

Something which has to be considered when assessing muscle function is the open kinetic chain (OKC) vs. closed kinetic chain (CKC) movement characteristics, each offering different understanding of individual's strength, stability, and coordination. OKC movements involve single joint motion with the distal segment free to move, allowing for targeted muscle testing and rehabilitation exercises. In contrast, CKC movements involve motion across multiple joints thus have coordinated movement patterns with the distal segment fixed, mimicking functional activities and emphasizing multi-joint coordination and proprioception.

Steindler, among the first, introduced the concept OKC and CKC systems in joint movements (Steindler, 1955). In an OKC system, a series of joints allows the terminal segment to move freely, meaning the distal segment can move independently in space. Conversely, in a CKC system, the distal segment encounters external resistance that limits its free motion. The force applied to one segment results in predictable movement in all other kinetic chain segments.

It's now understood that muscle recruitment and joint movement patterns differ based on whether it's an OKC or CKC motion, and these differences are independent of the type of muscle contraction (e.g., isotonic, isometric, or isokinetic) (Schilling & Elazzazi, 2021). The concept of OKC and CKC joint motions applies directly to exercises and daily activities. Many therapeutic exercises combine OKC and CKC characteristics. An example of an OKC exercise is the seated knee extension leg curl, where the leg can move freely while the thigh and trunk are fixed. Typically, OKC exercises focus on a single joint, such as the knee. On the other hand, a CKC exercise, like the squat, keeps the feet fixed to the ground, and motion occurs across multiple lower extremity joints in a coordinated manner.

In many daily activities and sports, CKC sequences are common, where the movement starts from a stable base of support, and the force is transferred through the chain to more mobile distal segments. However, distinguishing between OKC and CKC activities can be challenging in some cases. For example, in swimming and cycling, traditionally considered OKC activities, there is a load on the distal segment, but it's not restricted from movement.

A classification based on the mobility of the terminal segment and whether it bears a load was suggested (Dillman et al., 1994):

- moveable with no load (resembling an open chain system);
- fixed with an external load (resembling a closed chain system);
- moveable with an external load (a combination of closed and open chain systems).

OKC exercises involve isolated movement at a specific joint and effectively strengthen particular muscle groups in isolation. Conversely, CKC exercises simultaneously contract the agonist and antagonist muscle groups around a joint. This biomechanical distinction makes CKC exercises valuable once isolated weaknesses have been addressed (Van Melick et al., 2016). CKC rehabilitation offers additional benefits, including the early establishment of stability in proximal areas like the shoulders, hips, and trunk, providing a solid foundation for distal functions and walking (Mendez-Rebolledo et al., 2021). Furthermore, it enhances proprioception and neuromuscular control and improves functional joint stability (Turgut et al., 2016).

In OKC exercises like knee extensions, the quadriceps mainly perform the movement, while the hamstrings engage to control it without contributing significantly to the work. In contrast, CKC exercises, such as squatting with the center of gravity directly over the knee, engage both the quadriceps and hamstrings simultaneously, resulting in knee stabilization through the coordinated action of opposing muscle groups. During OKC knee extension, as the leg moves into full extension, the quadriceps must generate increased force due to the growing moment arm, leading to higher shear forces across the knee. In CKC knee extension, simultaneous co-contraction of the hamstrings and quadriceps reduces shear stress and enhances knee joint stability (Nessler et al., 2017).

Two critical factors in CKC exercises can be highlighted: the placement of the center of gravity and the positioning of the terminal limb, particularly in the lower extremity (Perriman et al., 2018). The placement of the center of gravity relative to the knee determines which muscle groups are activated during knee flexion-extension movements. The knee extensors are primarily engaged if the center of gravity is directly over the knee. If it's behind the knee, greater stress is placed on the hip extensors; if it's in front of the knee, gastrocnemius is involved. Therefore, the center of gravity's position over the joint axis directly influences muscle recruitment.

The position of the terminal limb segment in the transverse or frontal plane is also crucial in CKC exercises. For instance, when the foot is in a pronated position, it may cause excessive internal rotation of the entire lower limb, increasing stress on the knee. This stress can lead to or exacerbate patellofemoral pain or potentially affect the healing of capsuloligamentous structures around the knee (Perriman et al., 2018).

2.10. Testing of strength characteristics

Assessing the strength and power of muscles in humans is crucial in scientific research, sports science, and clinical practice. A standard method to evaluate this is by measuring the maximum force or torque that individuals can generate voluntarily. However, many daily activities and sports-related tasks involve quick and explosive movements within a limited time frame. Therefore, the ability to rapidly produce force, known as explosive strength, is gaining importance in scientific research (Maffiuletti et al., 2016).

Frequently testing and monitoring an athlete's performance can benefit sports coaches, providing valuable information about the athlete's current training condition (Naqvi & Sherman, 2022). This data can then be used to customize and adjust training programs to ensure the best outcomes for the athletes. Sports scientists and practitioners utilize a variety of tests to evaluate an athlete's dynamic, isokinetic and isometric strength characteristics.

Regular monitoring also helps comprehend the connection between an athlete's maximum strength and their actual performance. Recognizing the motor learning strategies required to translate increased physical capacity into improved skilled performance is essential. The time gap between the increase in physical strength and its manifestation in improved performance is termed "lag time." This lag time concept is crucial when assessing the transfer of training effects from one physical attribute to specific athletic skills like sprinting and jumping (Suchomel et al., 2021). Thus, consistent testing and data assessment are vital to evaluate and determine the lag time in various activities.

2.10.1. Dynamic strength tests

While assessing strength through isometric testing has advantages, dynamic strength testing also offers valuable insights. Dynamic strength testing is one of the most common ways to measure an individual's strength. This involves conducting a repetition maximum (RM) test, where the person lifts the maximum weight they can handle for a specified number of repetitions. Most common examples are tests ranging from 1RM to 6RM, focusing on exercises like back squats, front squats, half squats, power cleans, hang cleans, leg presses, and bench presses. Additionally, researchers have explored concentric-only and eccentric-only movements (Schoenfeld et al., 2019) to assess maximal strength characteristics for each muscle action separately, contributing to overall dynamic strength evaluation.

Dynamic strength tests are relevant for athletes as they mirror movements commonly performed in various sports or activities. Prior studies have employed dynamic strength tests to investigate the impact of specific training regimens, the effects of competitive seasons on muscular strength, and factors influencing the change of direction performance (Spitz et al., 2020). Like isometric testing, dynamic strength assessment should be used judiciously due to its demanding nature. While some professionals use dynamic strength 1RM tests for determining training loads, others discourage constant maximal efforts. An alternative for those cautious about maximal attempts is estimating an individual's multiple RM.

Reactive strength refers to an athlete's capability to swiftly transition from stretching their muscles (eccentric contraction) to contracting them (concentric contraction) (Jarvis et al., 2022). Reactive strength is evaluated primarily using drop jumps or countermovement jumps, which yield variables like the reactive strength index (RSI) through drop jump height divided by ground contact time or the modified reactive strength index (RSImod) through countermovement jump height divided by time to takeoff. While these assessments differ from maximal isometric and dynamic strength tests, previous studies have shown significant correlations between maximal isometric strength and RSImod (Petridis et al., 2017).

Furthermore, reactive strength tests offer valuable insights to practitioners about how an individual attains a specific level of dynamic performance. For instance, research on RSI has established its reliability as a performance measure, ability to differentiate between athletes with varying acceleration capacities, potential for tracking neuromuscular fatigue, and indication of ongoing training conditions (Jarvis et al., 2022). Additional studies have validated RSImod as a dependable performance indicator, useful for acute assessment of explosive performance and tracking such performance across an entire competitive season (Kipp et al., 2016). Additionally, RSImod can distinguish disparities in performance among teams and within the same group (Markwick et al., 2015), and it offers insights into an athlete's skill in utilizing the stretch-shortening cycle for achieving specific jump heights (Byrne et al., 2017).

It's important to note that specialized scientific equipment is required for assessing RSI and RSImod. However, these assessments can yield more comprehensive information for practitioners, enhancing their comprehension of an individual's current performance capacity.

2.10.2. Isokinetic strength tests

Isokinetic testing is a method used to assess muscle strength and joint function, particularly in rehabilitation and sports medicine settings. It involves the measurement of muscle force while the muscle is contracting at a constant speed. Isokinetic testing is conducted using specialized equipment called isokinetic dynamometers. These machines allow controlled and adjustable resistance, ensuring that the speed of movement remains constant. They are designed to accommodate different joints and muscle groups. Individuals typically perform concentric and eccentric muscle contractions against a resistance that adapts to their force output. Common testing protocols include assessing muscles around the knee, shoulder, and ankle joints. Isokinetic testing devices control the speed of movement, ensuring a consistent velocity throughout the range of motion. This is crucial for obtaining accurate and reliable measurements of muscle strength. Unlike traditional resistance exercises where resistance changes with joint angle, isokinetic devices adjust the resistance to match the force exerted by the individual. This feature allows for maximal effort throughout the entire range of motion. Isokinetic testing provides precise and objective data on various aspects of muscle function, such as peak torque, total work, and power output. These measurements can be essential for evaluating muscle imbalances, monitoring progress during rehabilitation, and assessing readiness for return to sports activities. Isokinetic testing is commonly used in rehabilitation programs to evaluate muscle strength before and after injury or surgery (Vidmar et al., 2020). It helps in designing personalized rehabilitation protocols and tracking the progress of patients. Athletes can benefit from isokinetic testing to assess specific muscle groups used in their respective sports. This information can guide strength training programs and identify areas of weakness or imbalance that may increase the risk of injury (Xaverova et al., 2015). Isokinetic testing is employed in scientific research to study muscle function, joint biomechanics, and the effects of various interventions (Janicijevic et al., 2020). It also aids in diagnosing and monitoring conditions such as muscle weakness, joint instability, and neuromuscular disorders (Van Der Woude et al., 2022).

2.10.3. Isometric strength tests

Numerous studies evaluated subjects' maximum strength using isometric strength tests, like the isometric quad extension, isometric mid-thigh pull, isometric squat, or isometric half-squat (Bazyler et al., 2015; Comfort et al., 2019). Although these tests don't measure the maximum load lifted, previous research has demonstrated significant correlations between isometric strength tests and dynamic strength performance (Lum et al., 2020). Additionally, these tests have been utilized to explore different aspects of exercise, assess the impact of training programs on muscle strength, and compare force production among athletic teams.

Isometric strength tests offer versatility and time efficiency, especially when dealing with large groups of individuals. They can provide a more accurate measure of an individual's "maximum" strength than dynamic strength tests, where the final load attempted might be overestimated. However, it's essential to use isometric strength tests sparingly since they can be physically demanding and may require slight adjustments to the training on the day of testing.

Sports scientists and practitioners should consider the specific demands of the athlete's sport when employing isometric testing. The athlete should be tested in positions relevant to their sport's success. For example, testing during the second pull of weightlifting movements would be appropriate for weightlifting, as it aligns with the peak force and power production during that phase (Kyle Travis et al., 2018). Similarly, testing sprinters or bobsledders at hip and knee angles corresponding to different phases of speed development (acceleration, transition, velocity, competition speed) can provide insights into an athlete's overall sprinting performance (Onken, 2019). Based on the results, adjustments can be made to the athlete's training program to address weaknesses. However, ensuring that these tests maintain the athletes' planned training regimen is crucial.

When conducting isometric tests, measured muscle needs to be properly isolated to obtain the best possible results by strapping the subject as tight as possible. When measuring MVC during isometric testing, after positioning the subject, verbal instruction is given loudly to the participant. This instruction is most commonly "contract as hard and as fast as possible". By using this instruction, two most common variables peak force (Fpeak) and peak rate of force development (RFDpeak) are produced from measuring MVC. Testing can be separated by giving only first or the second instruction if the researcher wants to assess only one variable. Recently, F-V relationship has been popular method for the assessment of muscle properties (García-Ramos et al., 2018; Janicijevic et al., 2019, 2020).

2.10.4. Leg asymmetries

Leg asymmetries (i.e., the between-leg difference in size, strength, and/or neuro- muscular quickness) could significantly affect the outcomes of muscle capacity testing, especially in sports and rehabilitation settings, whereby a difference of 15% has been considered as an injury risk factor (Green et al., 2018). Studies have shown that asymmetries can increase the risk of injuries, alter movement patterns, and worsen sports performances (Palmieri-Smith & Lepley, 2015). Therefore, the accurate and reliable measurement of leg asymmetries is crucial in clinical and research settings. Testing methods usually include a single-leg hop test, isokinetic strength test, isometric mid-thigh pull test, and force plate analysis (Dos'Santos et al., 2018), with recent papers including the RFD-SF for assessing inter-limb asymmetries (Boccia et al., 2018; Smajla et al., 2020). By addressing asymmetries in muscle capacity, individuals can improve their movement patterns, reduce the risk of injury, and improve their athletic performance (Bishop et al., 2018).

2.10.5. Testing limitations

While extensively utilized in numerous research studies, standard force tests have several limitations. First, since subjects are instructed to produce force „as hard“ and „as fast“ as possible, the focus on both tasks can reduce the quickness of force rise (J. Gordon & Ghez, 1987). This is because, by Hick’s law, the more tasks the person has to focus on, the slower the performance will be (Longstreth et al., 1985), fundamentally affecting the outcomes of standard force tests when assessing F and RFD. This highlights the need for separate testing series to record F and RFD accurately or develop a different test type. In addition to RFD, the rate of force relaxation (RFR) is also important for rapid consecutive contractions of opposing muscle groups. Still, it is often overlooked in standard force tests (Mathern et al., 2019).

Typically, standard force tests involve multiple consecutive attempts for each muscle group, usually about five to six attempts. Fatigue is a common concern during these tests due to the extended duration of each attempt (Pethick et al., 2015). Even with rest periods between attempts, conducting 10-12 separate attempts to measure F and RFD can increase fatigue. This issue is exacerbated when individuals need extended familiarization for rapid contractions, which may require more attempts.

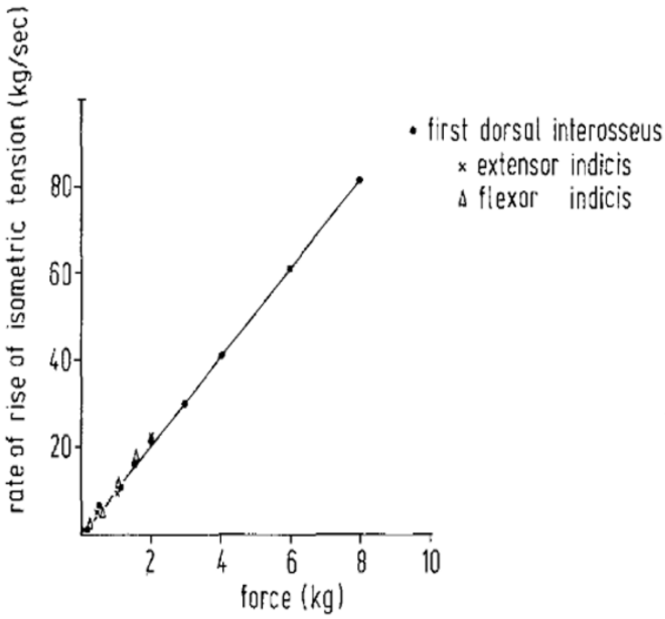
Prolonged maximal force efforts can be uncomfortable or unsuitable for specific individuals, like frail older people or those in recovery. Additionally, assessing F and RFD sometimes requires separate testing sessions, compounding the fatigue problem. People with neuromuscular diseases may not be able to sustain maximal effort, further complicating the testing process (Bellumori et al., 2013; Robichaud et al., 2005; Wierzbicka et al., 1991). Older individuals may experience more significant gains in maximum strength through strength training, but fewer functional improvements compared to training focused on short muscle actions. Therefore, there is a clear need for new tests to assess neuromuscular function effectively.

Fast and sustained muscle contractions involve different neural activation patterns. Since standard force tests focus on sustained contractions, they cannot accurately capture the neural activation pattern associated with rapid force production. This limitation can lead to imprecise results, especially for functional tasks that require high force output in short timeframes, like walking, running, or quick positional adjustments (Boraczyński et al., 2020). Traditional strength tests may not effectively assess an individual's ability to perform these activities. Some research has indicated only moderate correlations between standard strength tests and functional performance (Kollock et al., 2015).

When conducting F and RFD tests, it is essential to simulate conditions where subjects perform rapid consecutive contractions at maximum speed, matching the contraction frequency and producing short, rapid contractions at various percentages of peak force (Fpeak). These tests can address some of the mentioned limitations, such as being based on shorter strength expressions, involving moderate muscle strength (compared to Fpeak), reducing the number of testing attempts, and allowing for the evaluation of RFD in the muscle activation pattern.

3. RATE OF FORCE DEVELOPMENT SCALING FACTOR

A measure of neuromuscular quickness, a variable independent of maximum force, has recently been introduced. To gain insights into neuromuscular quickness during submaximal contractions, researchers have proposed the rate of force development scaling factor (RFD-SF) as an alternative or complementary metric (Bellumori et al., 2011). When performing a series of most rapid submaximal contractions to different intensities, a strong linear relationship between peak force (Fpeak) and peak RFD (RFDpeak) occurs. The slope of this relationship has been named the rate of force development scaling factor (RFD-SF) (Bellumori et al., 2011). The linearity of this relationship (R^2) describes the scaling consistency of RFDpeak to Fpeak (consistency of contractions). This value is usually very large, > 0.9 (Bellumori et al., 2013). There are exceptions to this, which will be discussed later.



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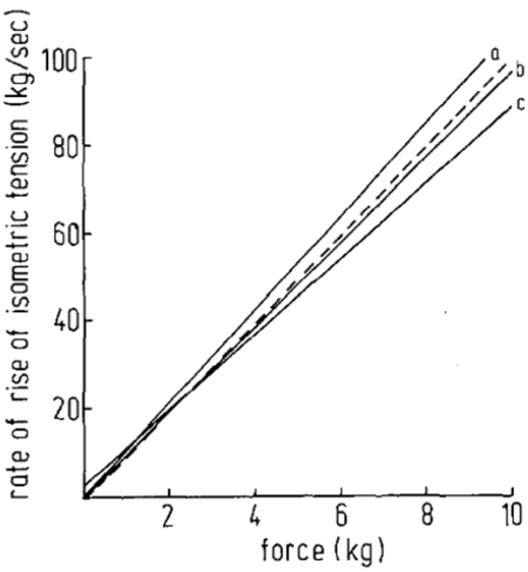

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Figures 2. & 3. Dependence of the rate of tension rise of the fastest possible voluntary target-directed isometric contractions on the peak force level. From "The relationship between speed and amplitude of the fastest voluntary contractions of human arm muscles," by H. Freund and J. Budingen, 1978, *Experimental Brain Research (1978) 31(1) 1-12.*

The introduction of RFD-SF began a few decades back (Freund & Büdingen, 1978), (Figures 2 & 3), but only recently has the protocol been systematized (Bellumori et al., 2011), with some adjustments being made until this day. The subject's task is to perform the fastest isometric contractions to different intensity levels. Since weak correlations between Fpeak and RFD-SF (r = 0.36) and small to moderate correlations between RFD and RFD-SF (r = 0.11 – 0.62) exist (Bellumori et al., 2011; Brustio et al., 2019; Corrêa et al., 2020), the underlying mechanism has to be looked for elsewhere. Several studies confirmed that time to force rise (peak) is invariant, no matter the contraction intensity which can be seen on Figure 4 (Freund & Büdingen, 1978; Büdingen & Freund, 1976; Wierzbicka et al., 1991). All of the studies also reported that the surface electromiography (EMG) signal is mostly constant (Figure 5), which means that motor unit firing rates remain mostly the same, and this is the most crucial mechanism essential to RFD-SF. During maximal voluntary contraction (MVC), the firing rate of motor units is one of the primary neural components of RFD (Maffiuletti et al., 2016). The question arises is if RFD-SF reflects neural component more than others already mentioned, like Fpeak, muscle fiber type, and cross-sectional area of it? Furthermore, an answer is needed if the lower value of RFD-SF reflects the poor capacity of RFD.

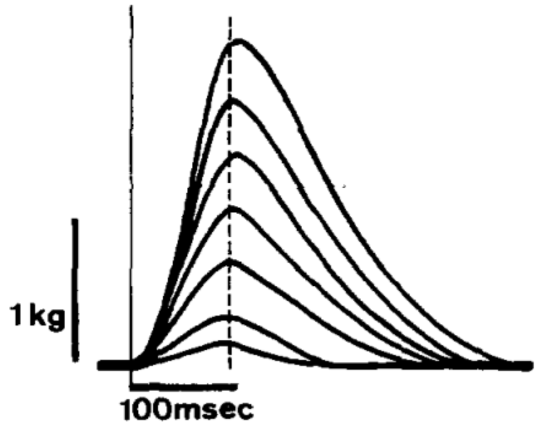

Figure 4. Fastest voluntary isometric contractions of one subject. From "The relationship between speed and amplitude of the fastest voluntary contractions of human arm muscles," by H. Freund and J. Budingen, 1978, *Experimental Brain Research (1978) 31(1) 1-12.*

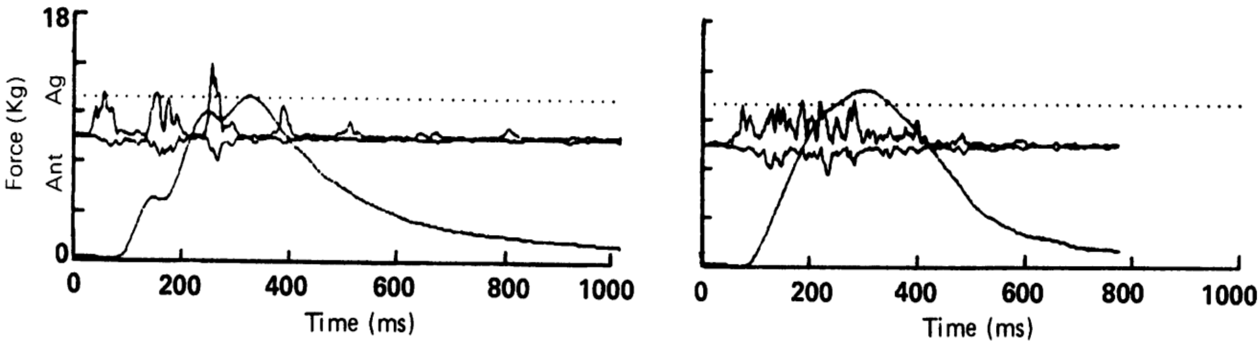

Figure 5. Single contraction with EMG superimposed. From "Abnormal most-rapid isometric contractions in patients with Parkinson's disease," by M. Wierzbicka et al., 1991, *Journal of Neurology Neurosurgery and Psychiatry (1991) 54(3) 210-216.*

3.1.RFD-SF assessment protocols

To determine intensity levels, usually, it is necessary to measure maximum voluntary contraction, from which the force (or torque) intensity level is calculated. Most often, intensities to which the subjects perform contractions are 20 – 80% (sometimes even 100%) of the measured MVC. The subject's main task is to perform contractions as fast as possible to a given level and relax as quickly as possible without trying to hit the level exactly. A two-second pause between contractions is sufficient for the subjects to reset. Subjects are encouraged to focus only on quickness and not accuracy (Casartelli et al., 2014; Djordjevic & Uygur, 2018; Uygur et al., 2020) since the focus on both tasks can reduce the quickness of force rise (J. Gordon & Ghez, 1987). This is because, by Hick's law, the more tasks the person must focus on, the slower the performance will be (Longstreth et al., 1985). Familiarization trials are given so the subjects become accustomed to the production of rapid pulses. Most researchers provided visual feedback of force reproduction with reference line for an intensity level (Bellumori et al., 2011, 2013; Brustio et al., 2019; Kozinc et al., 2020; Šarabon, Čeh, et al., 2020; Smajla, Knezevic, et al., 2020), while some of them provided zones of intensities (e.g., 20-40%, 40-60%, 60-80% of maximum force/torque) (Djordjevic & Uygur, 2018; Mathern et al., 2019; Uygur et al., 2020). Although not investigated, zones are assumed to be the preferred method for displaying force intensities since less attention to accuracy is present. Total number of contractions is mostly around 125 (Bellumori et al., 2011, 2017; Bozic et al., 2013; Casartelli et al., 2014; Mathern et al., 2019). A somewhat smaller number of contractions can be used to reduce fatigue, but lower reliability follows after (Bellumori et al., 2011; Boccia, Brustio, et al., 2018; Smajla, Spudić, et al., 2021). One of the most significant reliability issues is determining this number of contractions. As stated, ~75 contractions can be used to obtain results of acceptable reliability. Still, the greater the number of contractions used, the greater the reliability for knee and elbow extensors and finger abductors (Bellumori et al., 2011). Even fewer were reported for grip force measurements (45), but that number yielded unacceptable reliability (Haberland & Uygur, 2016). Contrary to that, a recent study showed that as little as 28 pulses across four levels of intensities are sufficient to produce acceptable reliability in knee extensors (Smajla, Žitnik, et al., 2021). This study included tighter fixations and a more rigid dynamometer setup, which could be the reason for their results. Be that as it may, the general agreement is to use ~100 contractions, and more studies are needed to prove that fewer contractions can be used. Slight fatigue during the protocol can happen, but it's mostly negligible since the pause between working blocks is 60s (Mathern et al., 2019; Uygur et al., 2020). Blocks are divided in such a way that each block contains every intensity level with five contractions for each of them. This diminishes the order effect (Bellumori et al., 2011).

3.2. RFD-SF accros muscle groups

RFD-SF has a measurement unit of s-1, which allows it to compare characteristics of individuals and muscle groups, independent of sex, size, and muscle group strength (Bellumori et al., 2011). To this day, RFD-SF has been assessed in several muscle groups: knee (Bellumori et al., 2011; Boccia et al., 2018; Boccia et al., 2018; Šarabon et al., 2020; Smajla et al., 2021), ankle (Klass et al., 2008; Smajla, Knezevic, et al., 2020; Van Cutsem et al., 1998), hip (Casartelli et al., 2014; Kozinc et al., 2020), elbow (Bellumori et al., 2011, 2013; Smajla et al., 2020), wrist (Smajla et al., 2020) and grip/finger muscles (Bellumori et al., 2011, 2013; Corrêa et al., 2020; Mathern et al., 2019; Uygur et al., 2020). For knee and elbow extensors and finger abductors, similar RFD-SF results were reported, as in healthy adults (8.3, 8.9, 8.2 respectively), so in a group of athletes (8.9 – knee extensors only) (Smajla et al., 2021). Similar values were obtained for hip muscles (8.8, 8.3, 8.3) for flexors, abductors, and adductors, respectively. Smaller values were reported for internal and external hip rotators (7.3, 7.1) (Casartelli et al., 2014). Basketball players had higher RFD-SF values for elbow extensors (8.5 – 8.9) than for wrist flexors (7.3 – 7.5) (Smajla et al., 2020). Higher values were obtained for knee and elbow extensors and handgrip muscles (9.6, 10.5, 9.3), respectively (Mathern et al., 2019). Two subsequent studies obtained nearly identical grip muscle values (Corrêa et al., 2020; Uygur et al., 2020). Young athletes exhibited higher mean knee extension (7.9) than ankle plantarflexion (5.9) RFD-SF values (Smajla et al., 2020). The general conclusion is that ankle and handgrip muscles' RFD-SF values are lower than those of other muscle groups (Van Cutsem et al., 1998; Van Cutsem & Duchateau, 2005). This could be because differences in the distribution of muscle fiber types exist. For RFR-SF, consistently lower results appear in the studies than for corresponding RFD-SF (Mathern et al., 2019; Smajla, Žitnik, et al., 2021; Uygur et al., 2020). Different muscle correlations were reported by a few studies (Bellumori et al., 2011; Mathern et al., 2019; Smajla et al., 2020), with no high correlations found except for RFD-SF values for elbow extensors and grip muscles (r=0.71) (Mathern et al., 2019). RFD-SF cannot be generalized across muscle groups due to the inconsistencies in reported values. In some measures, slight shared variance can be found in upper limb musculature, probably because they share the same central mechanisms.

3.3. Reliability of RFD-SF

Most studies showed good absolute and somewhat smaller but acceptable relative reliability. For knee extensors, the most tested muscle group, reliability was SEM ≤ 5.91 – 6.5% and ICC = 0.78 – 0.85 (Djordjevic & Uygur, 2018; Mathern et al., 2019). The same values regarding absolute reliability (SEM) were obtained for elbow extensors and grip muscles in the same studies. However, lower relative reliability (ICC = 0.64 – 0.68%) for those muscle groups was present. One study assessed hip muscles, which yielded results (SEM ≤ 8.9%, ICC ≥ 0.90) slightly better than in other studies (Casartelli et al., 2014). They used a higher sampling frequency of 2000Hz and a gold standard (isokinetic) dynamometer, which may be the explanation for better reliability. The drawback of this study was the fixation of internal and external rotation tasks. Subjects could not be adequately strapped, so compensatory moves were present, which resulted in an overestimation of Fpeak. Subsequently, the relationship between Fpeak and RFDpeak was not linear, and above 60%, subjects have not displayed an increase in RFD, leading to a more polynomial regression line (Figure 6).

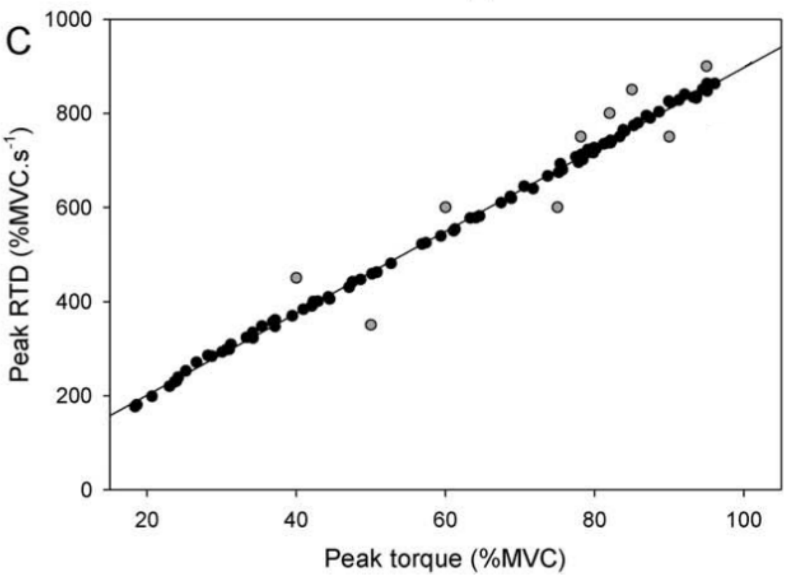

Figure 6. Regression line of pulse contractions from one subject. "From Assessment of the rate of force development scaling factor for the hip muscles," by N. Casartelli et al., 2014, *Muscle and Nerve (2014) 50(6) 932-938.*

3.4. Age-related differences in RFD-SF

Few studies compared young and old adults (Bellumori et al., 2013; Klass et al., 2008; Uygur et al., 2020; Wierzbicka et al., 1991). They all proved that older adults and patients with some form of neurological disorder had lower RFD-SF values, especially lower consistency of contractions (R^2), even though they had indistinguishable average agonist EMG signals. But despite that, they manifested lower motor unit firing rates and fewer motor units that discharge doublets. The potential to scale the firing rate of motor units and the number of discharge doublets is probably the most crucial factor elemental to RFD-SF. This was also manifested after 12 weeks of power training, which increased RFD-SF of ankle dorsiflexors (Van Cutsem et al., 1998).

3.5. Rate of force relaxation scaling factor

Measurement of RFD-SF can produce insight into a relaxation phase of the contractions, termed rate of force relaxation scaling factor (RFR-SF). Even though the first study assessed this part of the contraction, the authors didn't calculate the slope RFR-SF; they reported time to Fpeak for fast isometric contractions at three different intensities (Wierzbicka et al., 1991). The relaxation phase of a contraction has a proven clinical value in patients with Parkinson's disease (Robichaud et al., 2005; Wierzbicka et al., 1991), but only recently has the RFR-SF been properly established (Mathern et al., 2019). The measurement protocol is the same as in RFD-SF; the only difference is that RFR is used for the slope calculation instead of RFD. In the measurement of RFR-SF, the subjects are instructed to produce each pulse as fast as possible and relax immediately (Mathern et al., 2019). Naturally, the most rigid setup must be used since the relaxation phase is more prone to variations. Inter-rater relative reliability was good for knee extensor muscles (ICC = 0.76) but poor for grip and elbow extensors (ICC = 0.54 – 0.55). On the contrary, absolute reliability was poor for knee extensors (SEM = 13.1%) and acceptable for two other muscle groups (SEM = 6.7 – 8.7%). A more recent study used a better setup and tighter fixations, which yielded better reliability results (ICC = 0.96; SEM = 3.9%), with a total of 36 pulses (9 for each intensity level) (Smajla et al., 2021). Even though a study with more degrees of freedom had a flawed setup, a similar study by Uygur et al. showed high RFR-SF sensitivity of handgrip muscles to impairments in multiple sclerosis patients (Uygur et al., 2020). A study from the same year showed that both RFD-SF and RFR-SF for knee extensor muscles can be reliably acquired using contractions only up to 60% of MVC in knee osteoarthritis patients (Šarabon, Čeh, et al., 2020).

Since it has been shown that RFR-SF can be obtained with acceptable reliability with the removal of high-intensity pulses (Šarabon, Čeh, et al., 2020), this kind of testing can be an adequate substitution for traditional maximal force measurements. Measurement of RFD-SF and RFR-SF would be suitable for athletes in rehabilitation stages patients with neurological disorders or musculoskeletal diseases since it's not as strenuous as testing of F and RFD. Since only one study of RFD-SF and RFR-SF assessment in patients with musculoskeletal disease exists, future studies should investigate if these measures are sensitive enough to track rehabilitation progress.

3.6.Intra-muscular coordination

Only a few papers dealt with something interesting: agonist-antagonist activation. Producing quick submaximal muscle forces followed by quick relaxations is crucial for various sports tasks (Mathern et al., 2019). The force relaxation scaling factor (RFR-SF) rate and consistency of contractions (R^2) depend mainly on intramuscular coordination. Since antagonist muscles are responsible for decelerating the force in ballistic contractions (J. Gordon & Ghez, 1987), a phenomenon that needs to be introduced is tri-phasic activation. This consists of an agonist EMG signal burst in the initiation of the movement, followed by an antagonist and one more agonist burst (Irlbacher et al., 2006). The matching pattern of intramuscular coordination also appears in fast isometric contractions. This is important because the reciprocal activation of agonist and antagonist muscles determines an accelerating force. With the shortening of force brought out by the agonist, activating antagonist muscles at the time of RFD allows fast force rise without losing accuracy (J. Gordon & Ghez, 1987). Muscle tension before the start of an explosive contraction (pre-tension) changes the shape of the rising force–time curve by decreasing peak RFD, mainly due to a change in motor unit discharge pattern during the explosive contraction (Van Cutsem & Duchateau, 2005). Likewise, a countermovement (i.e., the production of a negative/antagonist force) immediately before the start of an explosive contraction also influences RFD as a function of the amplitude and duration of the countermovement (Maffiuletti et al., 2016). Accordingly, the pre-contraction set-up should be systematized across contractions, subjects, and sessions, to establish reliable measures of RFD, and contractions with pre-tension or countermovement should be rejected.

Despite that, adequate antagonist activation is needed for scaling in assessing RFD- SF. In addition to RFD-SF being able to evaluate neuromuscular capacity (maximal motor unit firing rate), as stated before, it can provide an insight into one's motor control (coordination of agonist and antagonist activation and scaling of motor unit firing rate). A topic that has not been researched is whether RFD-SF for both agonist and antagonist muscles can be used to assess their strength ratio.

3.7. Relationship with functional tests

Only one up-to-date study examined the relationship between RFD-SF and functional tests (Bozic et al., 2013). The authors found no correlations between RFD-SF for knee extensors and flexors and tests like jumps, sprints, etc. A moderate correlation was found for time to completion of the four-square step test and knee extensors (r = -0.51). For now, there is little to no evidence that RFD-SF has any practical value to athletic performance. This may be because protocol for the measurement of RFD-SF consists of isometric contractions, which is the opposite of what dynamic movements are. A recent study introduced dynamic RFD-SF through drop jumps that varied the drop's height, thus varying F and RFD intensities (Šarabon et al., 2020). Good consistency was achieved for concentric and eccentric phases (r2 = 0.87 – 0.80 ± 0.09 – 0.18). Since the correlation between the two phases was high (r = 0.83), drop jumps could be of value for describing dynamic neuro-muscular quickness. Electric muscle stimulation (EMS) training resulted in noticeable alterations in the neuromuscular performance of both the trained and untrained quadriceps muscles, suggesting that the employed training regimen could prompt CNS adaptations. While EMS led to an increased RFD, comparable to the increase in MVC, it concurrently led to a reduction in RFD-SF, which pertains to the quality of movement initiation and the swiftness of force generation. This discovery is significant in enhancing our comprehension of the neurophysiological mechanisms and adaptations associated with EMS training, especially in rehabilitation (Mirkov et al., 2019).

4. PROBLEM, SCOPE, AIMS AND HYPOTHESES OF THE RESEARCH

4.1.Problem of the research

Based on everything stated above, the problem of this research was the assessment of neuromuscular quickness by using the rate of force development scaling factor. Often used maximum voluntary contraction tests do not provide enough information regarding the neural component of muscle strength. Additionally, standard RFD-SF protocol can be time-consuming and, in some cases, fatigue-prone. With everything stated, there is a need to apply and further optimize the RFD-SF testing protocol to evaluate both contractile and neural components of muscle strength.

4.2.Scope of the research

This research's scope is optimizing the test for the assessment of neuromuscular quickness in isometric conditions. Also, the feasibility of optimized RFD-SF test protocol for investigating differences between different subject groups will be investigated.

4.3.Aims and hypotheses of the research

Based on the problem and scope of this research, the main aim is further evaluation of the RFD-SF testing protocol and the feasibility of protocol optimization.

Specific aims and corresponding hypotheses are as follows:

1) The first aim of this study is to confirm the linearity of the peak force – rate of force development relationship in the fastest contractions (Casartelli et al., 2014).

Hypothesis 1: The relationship between peak force – rate of force development in the fastest contractions is approximately linear.

2) The second aim is to evaluate the validity and between-day reliability of the two-point RFD-SF protocol (two intensity levels) with respect to the standard protocol based on the four force levels.

Hypothesis 2: The two-point protocol has acceptable validity and reliability compared to the standard protocol.

3) The third aim is to assess the sensitivity of standard and two-point protocols to distinguish between subjects with different physical activity levels, training background, or history of injury.

Hypothesis 3: RFD-SF protocols can differentiate betwen subjects of different physical activity levels.

5. METHODS

5.1.Experimental approach to the problem

This study was designed to examine the validity and between-day reliability of the reduced RFD-SF protocol for the assessment of neuromuscular quickness, as well as to estimate the sensitivity of the standard and reduced protocol to identify interlimb asymmetries in muscle function of knee extensors. The study employed a repeated measure design where subjects completed three testing sessions separated by 48 hours. In each session, they first performed MVC (Figure 7) followed by RFD-SF protocol, with the only difference being that in the first session, they performed standard RFD-SF protocol, while in the second and third sessions, they performed reduced RFD-SF protocol. The dominant leg (preferred kicking leg) was always tested first.

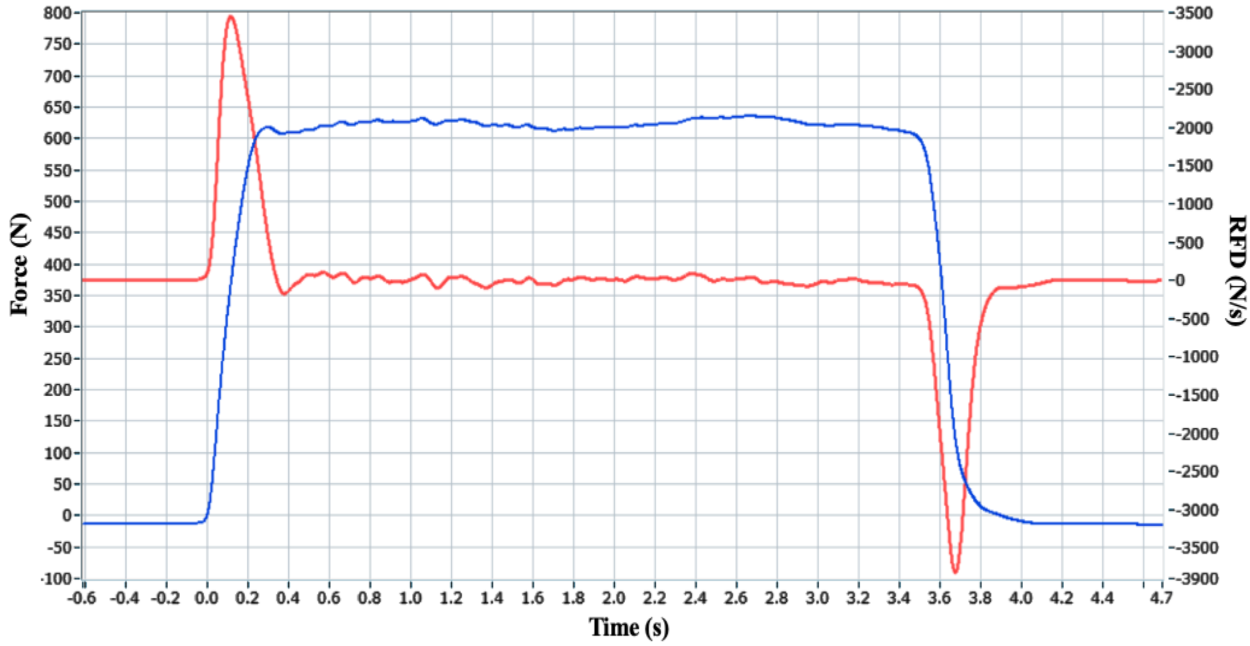

Figure 7. F/t (blue) and RFD/t (red) from MVC of one representable subject.

5.2. Subjects

Eighteen physically active subjects, 20.8 ± 0.6 years of age (6 females and 12 males), were included in the study for the assessment of the first and second aim. Their main characteristics were: body mass = 62.0 ± 5.8 kg and body height = 173 ± 6 cm for females, and body mass = 76.6 ± 10.7 kg and height = 181 ± 6 cm for males. All subjects had at least one year of lower-body resistance training experience and were actively involved in resistance training (3–5 sessions per week) at the time of the testing. Thirty subjects, 21.2 ± 0.7 years of age (11 females and 19 males), were included in the study for the assessment of the third aim. Their main characteristics were: body mass = 65.3 ± 4.6 kg and body height = 171 ± 5 cm for females, and body mass = 78.3 ± 10.2 kg and height = 183 ± 5 cm for males. Subjects were divided into two groups based on their activity levels: active and sedentary. Active subjects were involved in regular physical activity at least three times per week for the previous 12 months while sedentary subjects didn’t engage in any regular physical activity.

Inclusion criteria for all the subjects were as follows: no previous history of musculoskeletal injury or pain in the lower extremity at least six months before participation and no use of any medication that may affect neuromuscular function. The testing procedure and aims of the study were explained to the subjects in detail. All subjects signed the informed consent. The Institutional Review Board approved the study (02-1854/21-1). The study protocol was designed in accordance with the Declaration of Helsinki.

5.3.Testing setup and familiarization

A custom-made chair was used to assess the Fpeak and RFDpeak of the quadriceps muscles. Subjects were placed in a chair with their hips and knee angles set at 100° and 120°, respectively (full extension corresponding to 180°). The force transducer was connected to the lower leg via shanks that were wrapped around the leg, 2 cm above the lateral malleolus. Knees, hips, and chests were tightly fixed to the chair by rigid Velcro straps. A computer screen was placed in front of the subject for visual feedback (Picture 3).

Once positioned in the chair, each subject was familiarized with the protocol by performing three isometric contractions at four, gradually increasing self-selected submaximal efforts. After three minutes of rest, to assess their Fpeak, subjects performed three MVCs lasting 4-5 seconds with a one-minute between-trial rest interval. They were instructed to increase their force as strong and as fast as possible and maintain the maximal force for three seconds (Murphy et al., 1995), from which peak force was determined. After the Fpeak assessment, subjects rested for 10 minutes and then performed four bouts of five quick submaximal contractions (pulse contractions, Figure 8), each bout at a different intensity level. The instruction was to produce force and immediately relax as fast as possible.

Picture 3. Testing setup. Subject in a custom-made chair (1: force transducer; 2: shanks; 3: rigid straps; 4: acquisition and analog-to-digital conversion unit; 5: monitor with visual feedback).

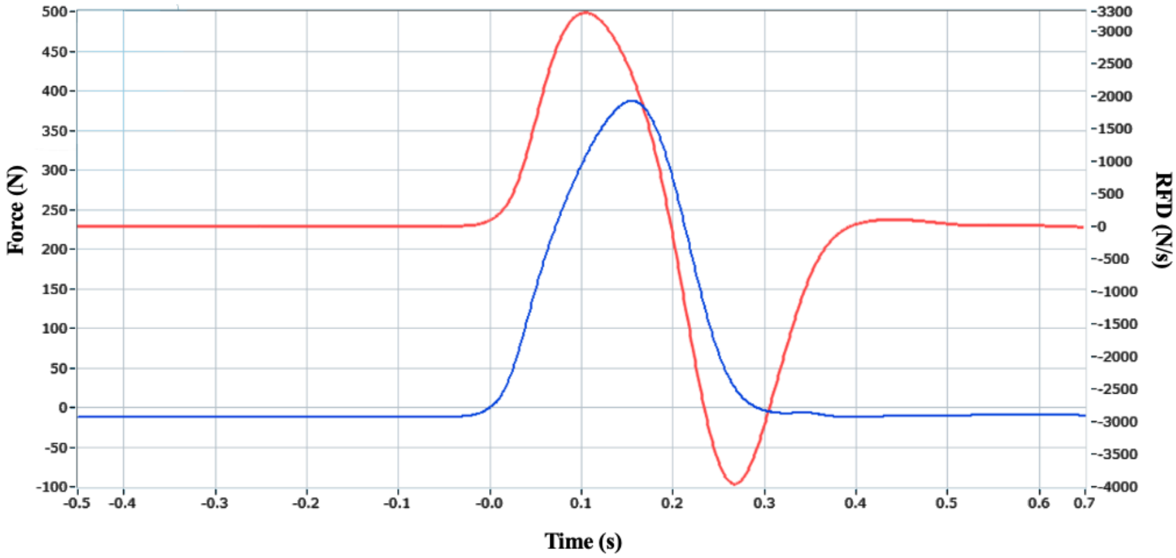

Figure 8. F/t (blue) and RFD/t (red) from pulse contraction of one representable subject

5.4.The standard and two-point RFD-SF protocol

To assess neuromuscular quickness, subjects performed a standard RFD-SF protocol (Figure 9A) in the first session with dominant and non-dominant legs, four sets with each leg (Bellumori et al., 2011). Each set consisted of five-contraction bouts performed at four intensity levels (20%, 40%, 60%, and 80% of Fpeak). Subjects were instructed to focus on the explosiveness of a contraction rather than trying to match a force level (J. Gordon & Ghez, 1987). The between-contraction rest was 3 sec. The contraction frequency was controlled via metronome so subjects could easily pace and control their contractions. The intensities were performed in a randomized order. The rest between the sets was 60 sec. The total number of contractions was ~100 as incorrectly performed contractions (e.g., slow contraction, pre-tension, poor relaxation) were repeated. The intensity levels were calculated based on the individual Fpeak of each subject.

In the second and third sessions, subjects performed a reduced "two-point" RFD-SF protocol (Figure 9B), which included two five-contraction bouts performed at only two intensity levels, 30% and 70% of Fpeak. Therefore, subjects performed twice the lower number of contractions, including those performed incorrectly. Visual feedback of a contraction was presented on a computer screen in front of subjects, with the force level shown as a horizontal line.

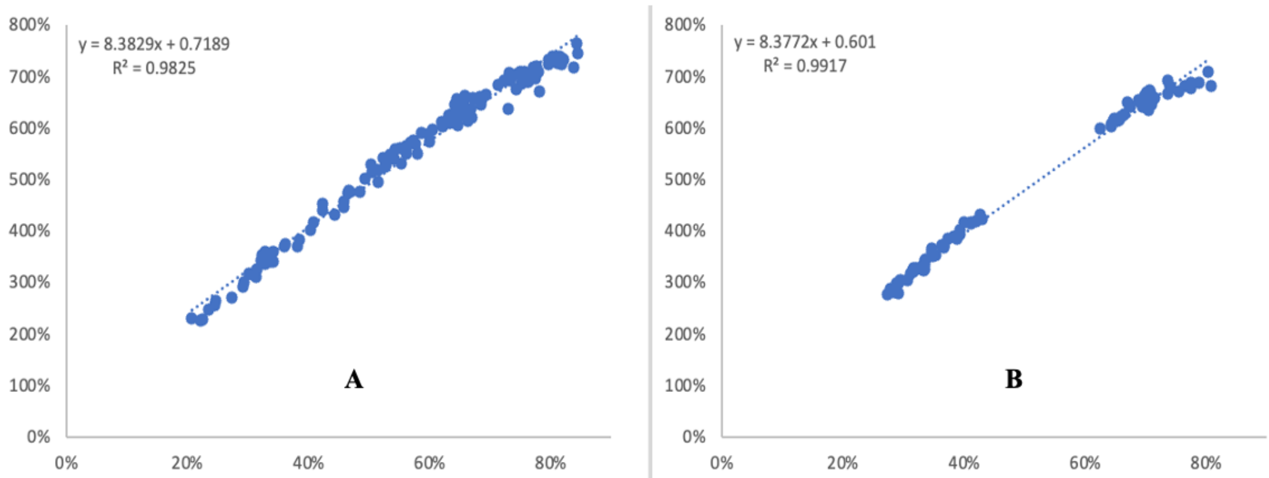

Figure 9. Standard (A) and reduced (B) RFD-SF protocol of one representative subject.

5.5.Data acquisition and analysis

Signals from a force transducer (Guangdong CZL302, China) were collected using the commercially available software Isometrics ("Sports Medical Solutions", Belgrade, Serbia), with a

1000Hz sampling rate. Signals were filtered with a low pass (5 Hz), second-order Butterworth filter. The software automatically calculated Fpeak (peak value on the force-time trace after reaching the plateau) and RFDpeak (peak of the first derivative of the force-time signal) (Mathern et al., 2019). The RFD-SF was computed as a slope (b) of linear regression (Y=a+bX) of Fmax and RFDmax (Bellumori et al., 2011). The coefficient of determination (R^2) in the regression analysis checked the strength of this regression (linearity of Fpeak and RFDpeak relationship). Interlimb asymmetry was calculated using the equation (RFD-SF of the dominant leg/RFD-SF of the non-dominant leg) − 1) × 100 (Smajla et al., 2020). An interlimb difference of >15% was used as a criterion to identify interlimb asymmetry (Green et al., 2018).

5.6.Statistical analysis

Statistical analysis was performed using SPSS (IBM SPSS v26.0 Chicago, IL, USA) and JASP (v0.16.13, University of Amsterdam, Amsterdam, Netherlands). Descriptive statistics of the dependent variables were presented as means, standard deviations, and standard error of the mean. The Shapiro-Wilk test tested the normality of data distribution, and all data were normally distributed. For all analyses, statistical significance was set at $p < 0.05$.

Pearson's correlation (r) was calculated to describe associations between RFD-SF values obtained using the standard and reduced protocols. The strength of correlation was defined as (0–0.19 trivial; 0.10–0.29 small; 0.30-0.49 moderate; 0.50–0.69 large; 0.70–0.89 very large; 0.90–0.99 nearly perfect; 1 perfect) (Hopkins et al., 2009). A paired samples t-test was used to assess the between-protocol difference in RFD-SF. Initially, G*Power (v3.1.9.4) was used to determine the minimum effect size required for the sample size employed in this study (Erdfelder et al., 2009). Accordingly, the effect size needed for the difference between the two protocols to be considered significant was set to 0.85, while the critical t was set to 2.09 for $p < 0.05$. Cohen's effect size (d) was used to quantify the differences as $d < 0.2$ (trivial or no effect), $d = 0.2–0.5$ (small), $d = 0.5–0.8$ (moderate), $d = 0.8–1.3$ (large), and $d > 1.3$ (very large) (Sullivan & Feinn, 2012). The Bland-Altman plot was used to evaluate the agreement between the two protocols.

Intra-class correlation coefficients ($ICC_{3,1}$) and coefficient of variation (CV%) were used for the evaluation of consecutive pairwise reliability, with benchmarks for "good" reliability set at ICC > 0.75 and CV < 15% (Staehli et al., 2010). Typical error of measurement was calculated according to Hopkins (Hopkins, 2012) to explain the extent to which results on repeated measures are close to each other. A paired samples t-test was used to assess the between-day difference in RFD-SF.

For sensitivity analysis, paired samples t-test was used to test differences between different groups of subjects (active and sedentary). Active students are considered those who engage in regular physical activity several times a week and sedentary are those who don't engage in any regular physical activity. The mean value of the dominant and non-dominant leg was used for the sensitivity analysis. Cohen's d was used to interpret the effect size, with $d = 0.2$ considered a small effect size, 0.5 representing a medium effect size, and 0.8 a large effect size (Lakens, 2013).

6. RESULTS

Descriptive statistics for Fpeak and RFDpeak of quadriceps extensors measured across all three days and trials for both legs are shown in Table 1. No statistically significant differences were found between trials for all Fpeak measurements ($p = 0.086$-0.948). Statistically significant between-trial differences were found for RFDpeak ($p=0.004$, $p=0.002$) for dominant leg on the second and third day, respectively. CV values, all under 15% represent small variability inside all measurements.

Table 1. Descriptive statistics of MVC test.

Day	Variable	Leg	Trial			mean ± SD	TEM	CV%
			1	2	3			
1	Fpeak (N)	D	607.5 ± 102.5	613.1 ± 91.8	606 ± 87.1	608.9 ± 94	19.34	3.90
		N	624.2 ± 107.4	623.8 ± 104.8	622.6 ± 110.3	623.5 ± 107.5	17.29	3.50
	RFDpeak (N/s)	D	3509.7 ± 626.2	3506.6 ± 555.9	3494.6 ± 610.5	3503.6 ± 598.3	175.9	5.80
		N	3479.7 ± 770.2	3497.4 ± 703.2	3403.7 ± 640.7	3460.2 ± 706.7	194.8	7.00
2	Fpeak (N)	D	632.8 ± 83.1	636.5 ± 88.7	634.8 ± 91.5	634.7 ± 87.8	18.36	3.60
		N	620.8 ± 95.9	627.5 ± 95.2	631.2 ± 93.5	626.5 ± 94.9	19.79	3.60
	RFDpeak (N/s)	D	3747.6 ± 601.3	3722.4 ± 537.5	3551.3 ± 480.4*	3673.7 ± 542	136.0	3.30
		N	3552.3 ± 614.3	3410.9 ± 600.3	3413.7 ± 531.7	3459 ± 583.2	200.8	7.00
3	Fpeak (N)	D	622.6 ± 99.7	626.4 ± 93.7	622.3 ± 93.1	623.8 ± 95.5	19.29	3.50
		N	624.1 ± 115.7	635.9 ± 112.3	622.7 ± 106.3	627.6 ± 111.5	22.20	3.50
	RFDpeak (N/s)	D	3731 ± 602.2	3653.8 ± 595.1	3497.8 ± 577.9*	3627.5 ± 591.8	142.1	4.20
		N	3607 ± 745.5	3581.8 ± 717.3	3496.7 ± 716	3561.8 ± 726.4	155.6	5.30

Notes: D – dominant leg, N – non-dominant leg, SD – Standard Deviation, TEM – Typical Error of Measurement, CV – Coefficient of Varriation.

The previously mentioned claim that time to peak force rise is invariant no matter the contraction intensity has also been confirmed with this study, which can be seen in Figure 10. Naturally, slight variability exists as the force rises, but this difference in a few dozen of milliseconds is neglectable compared to how much the force has increased. By inspecting straight dashed line cutting through the peak of lowest intensity contraction, this minimal variability can be observed in this representable subject.

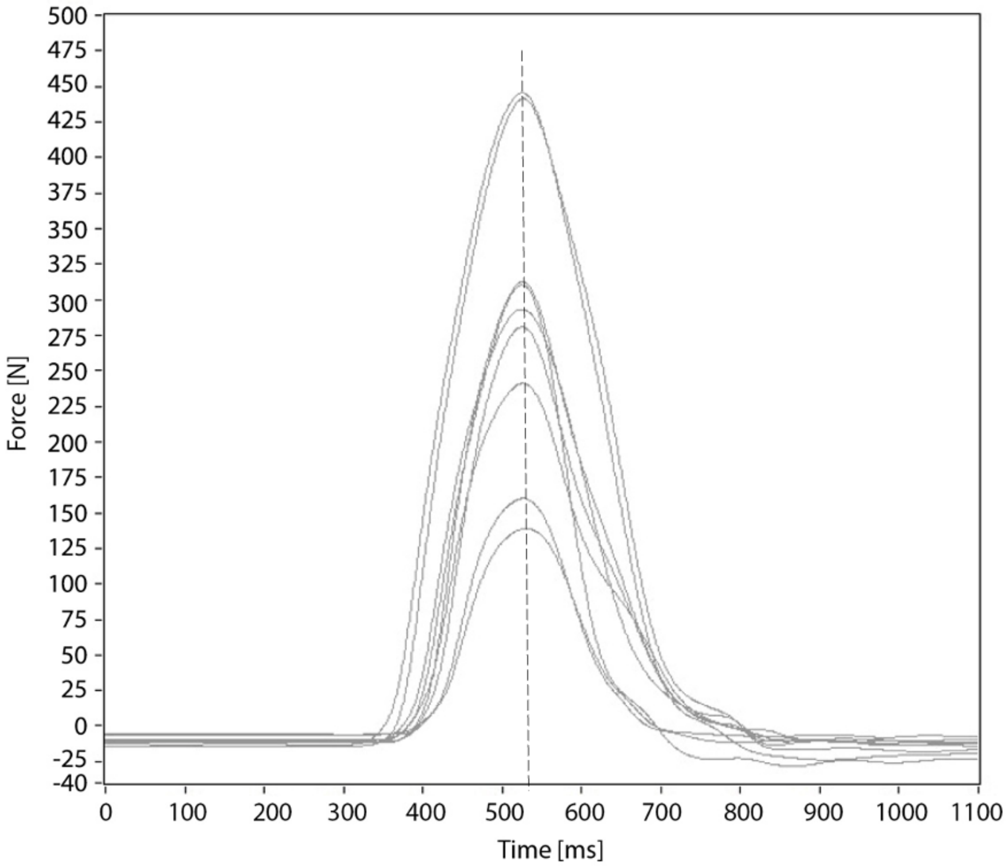

Figure 10. Force-time curves of several pulse contractions of the representative subject.

Linearity of the Fpeak-RFDpeak relationship

The coefficient of determination (R^2) showed a nearly perfect mean association between the Fpeak and RFDpeak for both legs. For dominant leg results were very high, $R^2 = 0.95$ and 0.98 for standard and reduced protocol, respectively. Similar results were obtained for non-dominant leg, $R^2 = 0.94$ and 0.98, for standard and reduced protocol, respectively. The minimum associations were very large in both legs (95% confidence interval range from 0.85 to 0.99). The distributions of associations are presented in Figure 11. The two-point protocol for both legs showed a narrower distribution of associations.

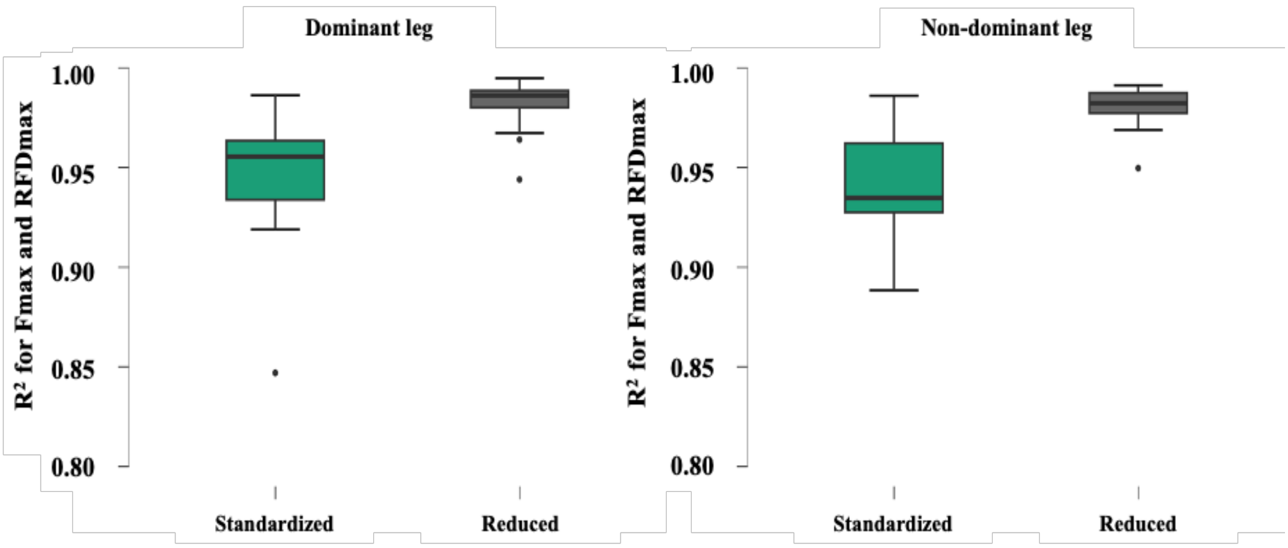

Figure 11. Distribution of R^2 for Fpeak-RFDpeak associations obtained in two protocols.

Validity of the modified RFD-SF protocol

The descriptive statistics for the RFD-SF slope and the correlation coefficient between the two protocols are presented in Table 2. The correlation between RFD-SF obtained in standard and reduced protocol was very large ($p < 0.001$) for both the dominant and non-dominant leg. The mean values obtained by the standard and reduced protocol were similar (Figure 12), with no significant difference between the protocols for the dominant ($t = -0.722$, $p = 0.480$) and non-dominant leg ($t = -1.295$, $p = 0.213$).

Table 2. Descriptive statistics for RFD-SF obtained from standard and reduced protocol and the association between them.

Leg	Mean ± SD		r
	Standard	Reduced	(95% CI)
Dominant	6.9 ± 0.9	7.0 ± 0.7	0.71 (0.37–0.89)
Non-dominant	6.5 ± 0.9	6.6 ± 0.9	0.80 (0.54–0.92)

Note. SD – Standard Deviation, r – Pearson Correlation Coefficient, CI – Confidence Interval.

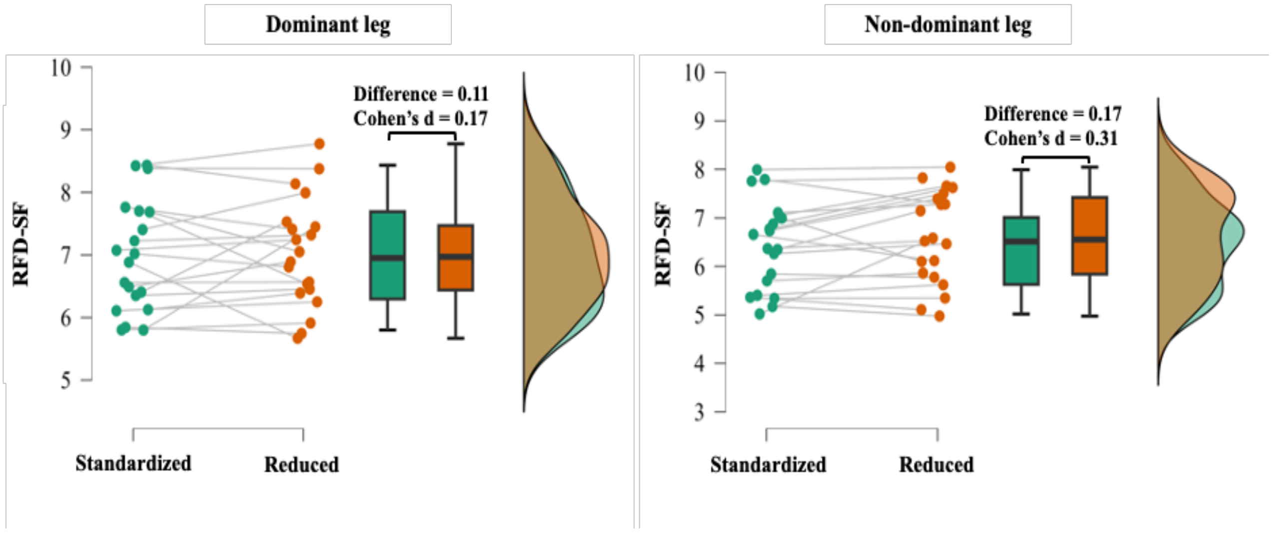

Figure 12. The distribution of subjects and the sample means for the standard and reduced RFD-SF protocols. Note: Difference = difference in RFD-SF obtained by standard and reduced protocols as obtained with paired samples T-test.

The Bland-Altman plot (Figure 13) revealed that most subjects provided the RFD-SF values within the limits of agreement. Two subjects were out of the limits of agreement with the dominant leg, and one with the non-dominant leg.

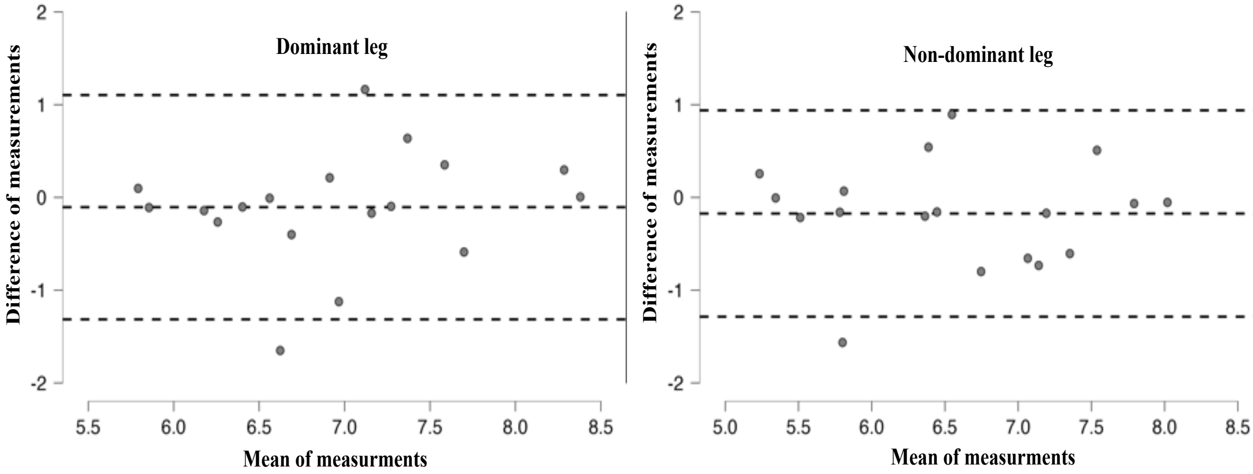

Figure 13. The Bland-Altman plot for the agreement between the two protocols

Reliability of the RFD-SF protocols

Measures of between-day reliability for the data obtained by the reduced protocol are presented in Table 3. Indices of absolute and relative reliability were acceptable for the dominant and non-dominant leg. The CV% was good, and the Typical error of measurement was low for both legs. Paired sample t-test revealed no between-day difference for the dominant (t = -0.875, p = 0.393) and non-dominant leg (t = -0.796, p = 0.436).

Table 3. Between-day reliability of the reduced RFD-SF protocol.

Leg	Day 1	Day 2	MD	TEM	CV%	ICC (95% CI)	d
	Mean ± SD						
Dominant	6.8 ± 0.7	6.9 ± 0.8	0.14	0.35	5.3%	0.80 (0.54–0.92)	0.13
Non-dominant	6.4 ± 0.8	6.5 ± 1.0	0.10	0.28	4.4%	0.92 (0.79–0.97)	0.11

Note. SD – Standard Deviation, MD – Mean Difference, TEM – Typical Error of Measurement, CV% – Coefficient of Variation, ICC – Intraclass Correlation Coefficient, CI – Confidence Interval, d = Cohen's effect size.

Sensitivity of standard and modified RFD-SF protocol

Sensitivity results for the data obtained by both protocols are presented in Table 4. The CV% was good, and TEM was low for both protocols. Statistically significant differences in both protocols between the groups of trained and non-trained subjects are present ($p < 0.05$). As previously mentioned, sensitivity results are presented as an average values of both legs.

Table 4. Sensitivity results for both protocols.

Protocol	Trained	Non-trained	p	t	d
	Mean ± SD				
Standard	7.7 ± 0.3	5.7 ± 0.3	0.00	50.77	6.67
Reduced	7.9 ± 0.4	5.6 ± 0.2	0.00	37.71	7.27

Note. SD – Standard Deviation, p = Statistical significance, t = t-test, d = Cohen's effect size.

Additionally, linear regressions derived from pulse contractions of two representable subjects (one trained and one sedentary), from both protocols, are presented on figures 14 and 15. Figure 14 represents physically active subject while figure 15 represents sedentary subject. By looking at these figures, sensitivity of both RFD-SF protocols can be visually inspected alongside statistical results. Absolute slope results show that there is substantial difference between physically active and sedentary subject.

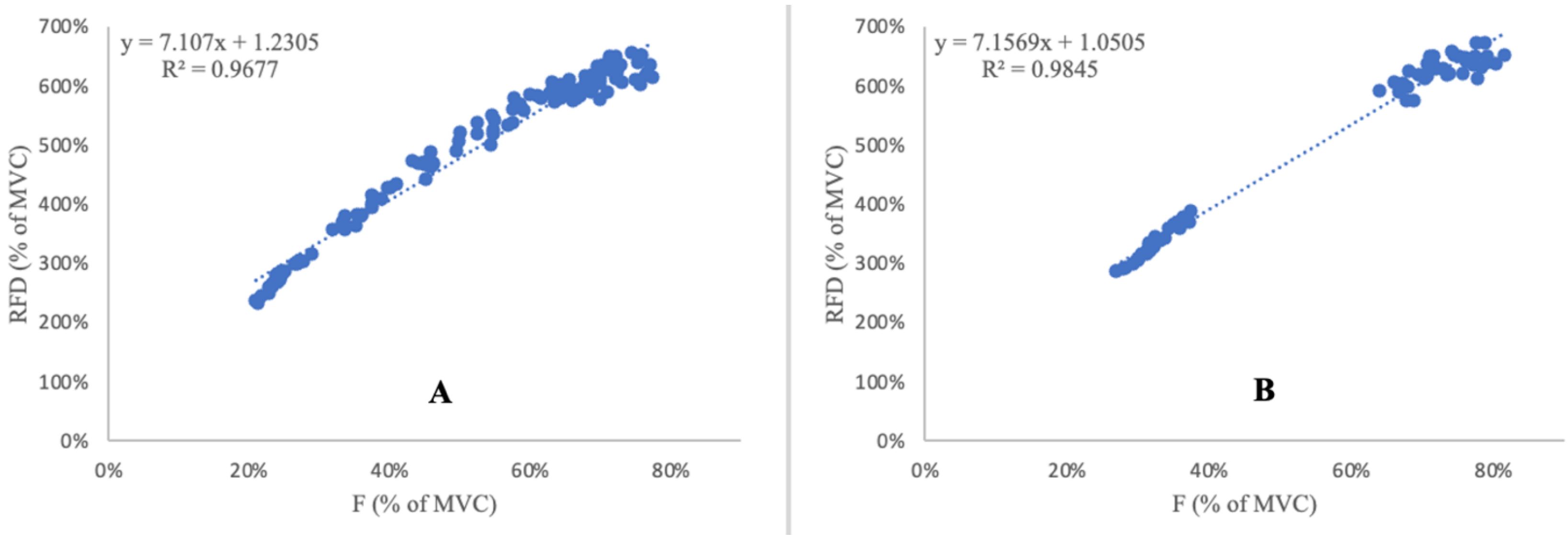

Figure 14. Pulse contractions with regression line of one representative physically active subject (A – standard protocol, B – reduced protocol).

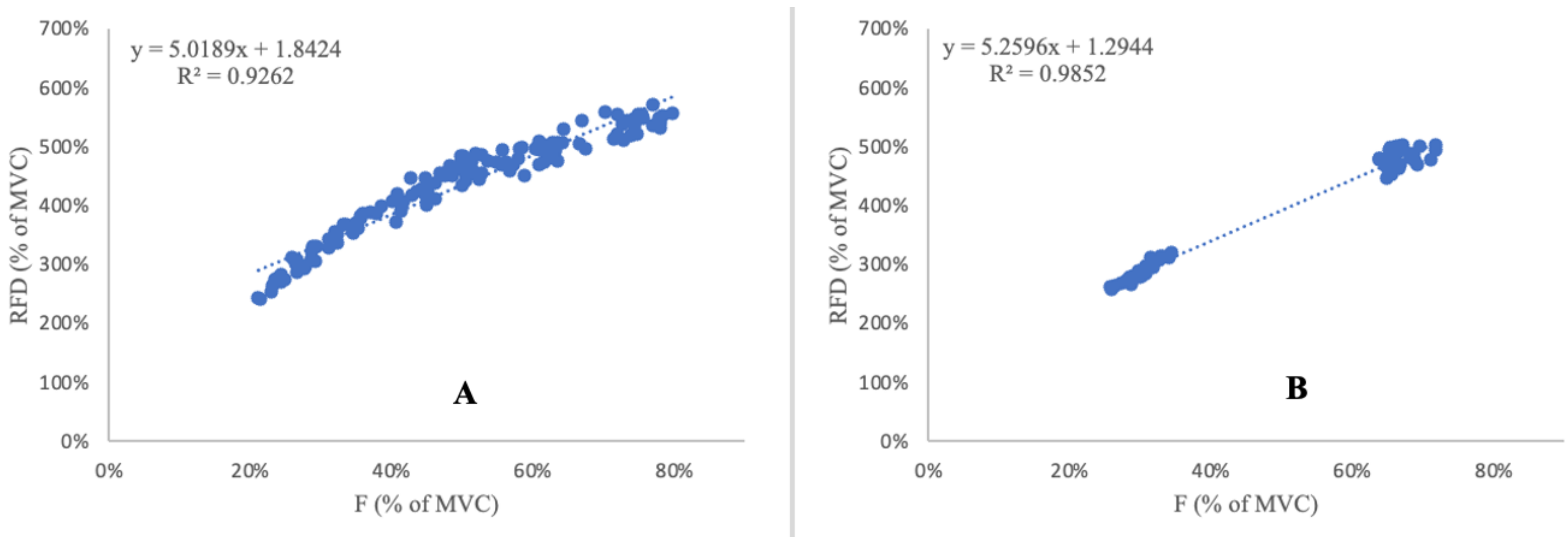

Figure 15. Pulse contractions with regression line of one representative sedentary subject (A – standard protocol, B – reduced protocol).

The interlimb asymmetries obtained in both protocols are shown in Figure 16. Three subjects showed an asymmetry larger than 15% when the standard protocol was used, and one showed an asymmetry of over 15% when the reduced protocol was used. Nevertheless, there was no significant difference between the two protocols (t = 0.835; p = 0.415; d = 0.19), with a mean difference of 0.97 and a 95% confidence interval of −1.49–3.43.

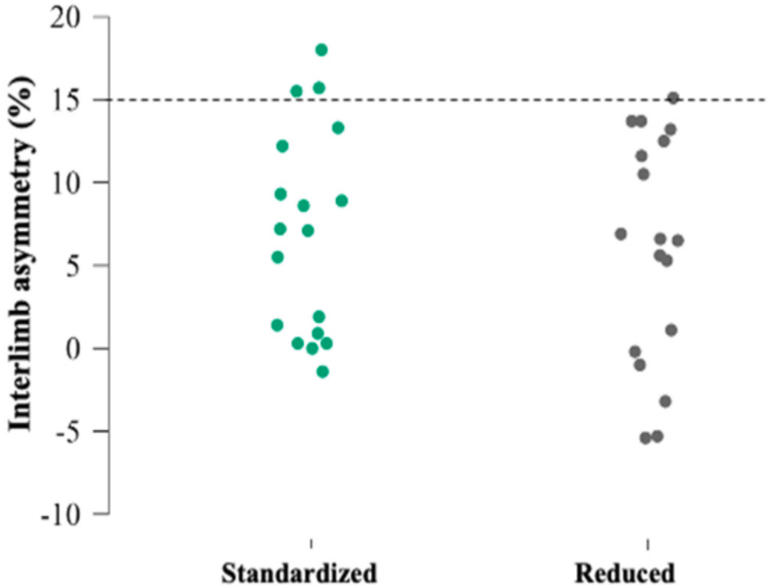

Figure 16. The asymmetries obtained using the standard and reduced RFD-SF protocol.

7. DISCUSSION

This research was designed with the following aims: 1. to confirm the linearity of the Fpeak – RFDpeak relationship in the fastest possible (pulse) contractions; 2. to explore validity and between-day reliability of the reduced protocol for assessing RFD-SF and, 3. to assess and compare the sensitivity of both standard and two-point protocols. Specifically, validity was investigated to check whether the two-point reduced protocol yields the same, or approximately similar results compared to the standard protocol, while between-day reliability analysis served to compare consistency of the reduced protocol in test – retest manner. Sensitivity was assessed to distinguish between subjects with different physical activity levels. The main findings related to our hypotheses were as follows: 1. the association between the Fpeak and RFDpeak values obtained using the standard and reduced protocols were very large for the dominant and non-dominant leg and without difference between them (hypothesis 1 confirmed); 2. validity and between-day reliability of the reduced protocol were acceptable for both legs (hypothesis 2 confirmed); 3. sensitivity of both protocols for the detection of differences between different groups of subjects has been confirmed (hypothesis 3 confirmed).

7.1.Linearity of Fpeak – RFDpeak relationship (R^2)

An apparent linearity, represented by R^2 value, can be observed regarding the relationship between Fpeak and RFDpeak. As the F value increases, so does the RFD value. Linearity of the Fpeak – RFDpeak relationship has been confirmed with this study, which is in line with the findings of others (Bellumori et al., 2011; Casartelli et al., 2014; Šarabon et al., 2020; Smajla et al., 2020). As previously mentioned, in two essential studies by Freund & Büdingen (1978); Büdingen & Freund (1976) and later Wierzbicka et al. (1991) researchers noticed that time to force rise (peak) is invariant, no matter the contraction intensity, thus indicating high linearity of Fpeak – RFDpeak. Later studies, including the current one confirmed this statement, and this relationship holds across various movements, indicating that it is a fundamental characteristic of muscular performance. In majority of previous studies on parameters of the RFD-SF testing protocol, knee- (Bellumori et al., 2011; Boccia et al., 2018; Boccia et al., 2018; Šarabon et al., 2020; Smajla et al., 2021), ankle- (Klass et al., 2008; Smajla, Knezevic, et al., 2020; Van Cutsem et al., 1998), hip- (Casartelli et al., 2014; Kozinc et al., 2020), elbow- (Bellumori et al., 2011, 2013; Smajla et al., 2020), wrist- (Smajla et al., 2020) and grip/finger muscles were assessed (Bellumori et al., 2011, 2013; Corrêa et al., 2020; Mathern et al., 2019; Uygur et al., 2020). Results on young, healthy subjects showed high linearity in all studies (R^2>0.9), supporting the abovementioned idea of this relationship being an essential performance characteristic.

However, it should be noted that the linearity of Fpeak – RFDpeak relationship may be influenced by the number of used force intensities. Interestingly, one study reported a non-linear logarithmic Fpeak – RFDpeak relationship for hip internal and external rotators (Casartelli et al., 2014). Authors stated that the relationship was linear until 60% of MVC, which stabilized with higher-intensity contractions. This is probably due to overemphasizing Fpeak as subjects were not strapped properly (i.e., insuficiently fixed). Tighter fixation with multiple rigid straps is needed to isolate the measured muscle (group) completely.

High linearity is necessary for an adequate assessment of RFD-SF since it has been shown that only in special conditions, this linearity is diminished. In the reduced protocol, since only two distant intensity levels are present, linearity will almost always be close to perfect. This could be potential limitation of the reduced protocol, but since the results of this study show that high linearity is present with the standard protocol and that the two protocols don't differ from each other, this limitiation is negligible. However, it is worth noting that the exact nature of this relationship can vary slightly depending on the specific muscle group being trained and other factors such as one's training history, overall fitness level, and measurement methodology. Only a few studies showed lower values of this relationship linearity (Robichaud et al., 2005; Wierzbicka et al., 1991), but all subjects had some form of neurological disorder. Both studies found that in Parkinson's disease, the motor program responsible for quick muscle contractions remains intact. However, its implementation shows issues with properly scaling the motor output. Patients showed an impaired ability to control and produce the most rapid contractions to a set amplitude, which means that the linearity of this relationship as a measure can quantify the severity of the illness (higher linearity means less severity).

The only question left, regarding the linearity of this relationship, is why the fifth intensity level (100% of MVC) was used in only a few studies (Bellumori et al., 2011, 2013; Casartelli et al., 2014) Those studies reported high linearity (R^2=0.96-0.98) of RFD-SF protocol for young, healthy subjects. These results contradict most previous studies since high linearity with five intensity levels has not been replicated (Casartelli et al., 2014). This could be explained by examining the pulse contractions graph from the mentioned research (Figure 18). Even though the fifth intensity level was given to the subjects, most of their pulse contractions were no greater than 85% of MVC, with only a few reaching close to 100%. These results laid the ground for future reduction of RFD-SF protocol.

7.2.Validity of two-point RFD-SF protocol

Before discussing the validity of the reduced RFD-SF protocol it is important to emphasize the validity of the RFD-SF as a measure of neuromuscular quickness. Different types of validity have been estimated since the protocol has been introduced by Büdingen & Freund (1976). In their research they compared contractile and electrical properties during muscle contraction. They revealed that the activation pattern of motoneuron units is structured to achieve a specific mechanical outcome. This outcome involves establishing a stable connection between the force generated by an individual motor unit upon its recruitment and the overall force output of the entire muscle. Despite variations in recruitment and firing rates linked to changes in RFD, the connection between the recruitment step of any motor unit and the tension output of other units remains largely unchanged within the muscle. This connection is primarily influenced by the excitability of the motor unit within the motoneuron pool.

It is essential to independently measure the electrical and mechanical recruitment of a muscle unit because the force exerted during muscle contractions varies at firing onset and during subsequent twitch contractions. The muscle tension at the peak of the first twitch contraction is determined by analyzing the twitch contraction time of individual motor units. EMG has been used to assess different neural properties when performing pulse contractions. The findings indicate that the skeleto-motor speed control system functions by modifying the speed of a contraction relative to its magnitude, maintaining a consistent contraction time which is in line with previously mentioned claim by Wierzbicka et al. (1991). This suggests that such speed control is crucial for achieving synchronization in synergistic muscle contractions.

The precise alignment between the changes in threshold force and total muscle force during motor unit contraction time results in the mechanical recruitment of motor units occurring at approximately the same force level, irrespective of the RFD, which has been mentioned and explained several times within this paper (for more details please see chapters 3. and 7.1.).

Only one study (Bozic et al., 2013) examined validity of RFD-SF protocol with respect to the groups od functional tests such as: balance tests (place alternate foot on stool, four square step test, turning 360°) and maximum power output tests (countermovement jump, countermovement jump with dominant leg, standing long jump, single hop test for distance, ball-kick test, six-second maximal cycling sprint test). Interestingly, no significant correlation between those task was found, neither for concurent, nor external validity (Bozic et al., 2013). Even though these specific types of validity were not confirmed in their study, the authors stated that RFD-SF protocol could serve as a comprehensive indicator of the overall neuromuscular system, complementing MVC test by delivering results that are relatively unaffected by variations in muscle size and function. Interestingly, only one study measured RFD-SF for drop jumps i.e., dynamic RFD-SF protocol (Šarabon et al., 2020). The idea behind this study was to implement RFD-SF into dynamic contractions thus ensuring more practial application of this test compared to performing it under isometric conditions. The results confirmed that the RFD-SF could be used in dynamic conditions and that further research should focus on developing it further.

Nonetheless, no previous studies investigated the option of using only two-distinct force intensities to estimate RFD-SF. Keep in mind that such rationale has already been utilized in modeling the F-V relationship. After extensive research on linearity of F-V relationship in closed kinetic chain movements such as jumps, bench-press throws, rowing etc., Jaric (2016) proposed using only two loads to model the F-V relationship. Later research by Garcia-Ramos & Jaric (2018) showed that the smallest and the highest possible external load should be utilized in the reduced, two-point protocol in order to obtain the most valid results.

The two-point modeling rationale was used when conceptualizing the reduced RFD-SF protocol. The validity of the reduced protocol with respect to the standard protocol for RFD-SF assessment has been confirmed with this study. As mentioned above, the first study that investigated RFD-SF protocol proposed using five intensity levels (Bellumori et al., 2011), which was later simplified by removing the highest level (Bellumori et al., 2011; Kozinc et al., 2020), with the latest studies confirming that neuromuscular quickness could be assessed using fewer intensity levels (Šarabon et al., 2020; Smajla et al., 2021). The idea behind the reduced protocol incorporated in this study was to reduce the levels to the bare minimum so the subjects' focus can shift on the explosiveness of the contractions rather than precision to mitigate potential fatigue effects. Since Fpeak – RFDpeak linearity has been shown to be high in most of the reduced protocols up until now, two distant points of 30% and 70% of MVC were chosen for this protocol. Since high linearity is prequisite for investigating RFD-SF, it is necessary to assess it whenever a new protocol is introduced. In rare cases, measurement methodology problems were present when measuring RFD-SF with 4-5 levels. The lowest level was problematic for some subjects since they either produced contractions too strongly or executed them too slowly while trying not to exceed the set level of 20%. On the other hand, some subjects could barely make it to 80%, let alone 100%. Chosen levels of 30% and 70% for this protocol were neither too low not to be explosive enough nor to high to reach linearly, thus these intensities present the optimal values for expresing neuromuscular quickness (i.e., muscle force and corresponding RFD in pulse contractions).

The findings from the current study are in line with those mentioned above, which proposed protocols with three different levels (20%, 40%, 60% of Fpeak) and fewer contractions (36 contractions), respectively. Bland-Altman plots revealed acceptable agreement between the results of newly introduced and already validated protocols since most of the results are within a 95% confidence interval. Additionally, a correlation between the two protocols was very high for both dominant and non-dominant legs which is, to the best of our knowledge, the only study that calculated Pearson's correlation coefficient for the validity assessment of the adapted RFD-SF protocol. Therefore, the results of this study suggest that RFD-SF could be assessed validly using only two intensity levels. Reducing the protocol to only two intensities provides a good step towards the broader and more frequent implementation of RFD-SF assessment beyond the research and university setting.

Even though the correlation coefficients were very high, they were not close to perfect. As previously mentioned, there were cases of a slightly logarithmic relationship occurring, with regression line slightly "breaking" at ~60% of MVC. This trend was observed in multiple subjects included in the study, and could potentially explain the correlation results. Despite employing rigid fixations and 1000Hz sampling rate, as recommended by Casartelli et al. (2014) which had a logarithmic relationship in their study, regression line "breaking" could be observed in some cases which means that the reasoning for this trend should be investigated in the future. In fact, such occurence was observed in total of seven subjects out of a total sample of 18. Interestingly, most of them had lower RFD values compared to the rest of the subjects sample which implies they were lacking explosive muscular capacities. Since subjects in this study were physical education students who had moderate to high intensity physical activites within their curriculum, it is plausable that they were not completely rested even though they were instructed to refrain from any physical activity 48 hours prior to the testing.

Potential explanation of “breaking” phenomenon observed in some subjects when instructed to generate forces that exceed 60% MVC may come from neurophysiology. Namely, when muscle contractions exceed 60% of MVC, various neuromuscular factors come into play, and the behavior of muscle spindles, Golgi tendon organs (GTOs), and other intra-articular receptors can be influential in the regression line “breaking” (De Luca & Kline, 2011). Individual subjects vary in their neuro-muscular control strategies and some of them may recrut motor units more efficiently, resulting in a steeper Fpeak – RFDpeak relationship, while others may not show a proportional increase in RFD with increasing force. Muscle spindles are sensory receptors within muscles that are sensitive to changes in muscle length. As muscle contractions become more forceful, muscle spindle activation increases. This heightened activation is due to both the increased muscle tension and the stretching of the muscle fibers. Higher force contractions may lead to more pronounced stretch reflexes mediated by muscle spindles. The stretch reflex is a protective mechanism that helps maintain muscle length and prevent damage during forceful contractions (Cronin et al., 2008). GTOs, located at the junction between muscles and tendons, are sensitive to changes in muscle tension. As muscle force increases, GTOs are activated, leading to an inhibitory effect on the muscle. This inhibition serves as a protective mechanism to prevent excessive force production and potential muscle damage. GTO activation may lead to autogenic inhibition, where the muscle reflexively inhibits its own contraction to prevent overload and injury (Herbert & Gandevia, 2019). This is particularly important during high-intensity contractions. Receptors within the joints can also be activated during high-force contractions. These receptors provide feedback on joint position and movement and may contribute to the overall proprioceptive input during intense muscle contractions (Gutiérrez-Monclus et al., 2023). The distribution of fast-twitch and slow-twitch muscle fibers can influence the rate of force development (Maffiuletti et al., 2016). Individuals with a higher proportion of fast-twitch fibers might exhibit a different Fpeak – RFDpeak relationship compared to those with a higher proportion of slow-twitch fibers. While muscle spindles, Golgi tendon organs and intra-articular receptors play crucial roles in modulating muscle function, the overall response is multifaceted and subject to individual differences.

Since the earlier described “breaking” phenomenom occurred at 60-70% of MVC in the standard protocol, the reduced protocol introduced in this study had to include force intensities that would involve the most distinct points that may provide close to perfectly linear Fpeak – RFDpeak relationship. Since F-V relationship is closely linked to neuro-muscular system, representing the interaction between the nervous system and muscle contractions it was only rational to incorporate this relationship into the reduced RFD-SF protocol in trying to optimize neuro-muscular activation patterns essential for high RFD. Specific training protocols such as plyometric or ballistic exercises are designed to exploit the principles of F-V relationship to improve the ability of rapid force production, and reduced RFD-SF testing protocol could be used for an adequate assessment of those training interventions. This test could also be beneficial for tailoring the sport-specific training program, as for athletes, so for coaches to better understand how athletes’ performance aligns with the demands of their sport. Additionally the ability to rapidly and linearly generate force across different force intensities can contribute to joint stability and protective reflexes, reducing the risk of injuries during dynamic movements. Potentially this testing protocol could be used in clinical settings since first studies showed some connection with neuro-muscular diseases.

Thus, 30% and 70% were chosen for the reduced protocol. This phenomenon of logarithmic relationship occurrence is not present with these two levels, but could be the reason why we have not produced near-perfect correlations. The idea behind choosing 70% as the higher level is to produce very high correlations alongside nearly perfect linear relationship. Severeal complex interplaying factors which possibly influence line “breaking” were listed, but further studies are needed to prove the exact factors which contribute to this phenomenon.

7.3.Reliability of two-point RFD-SF protocol

The second hypothesis of this research was related to evaluating the between-day reliability of the reduced RFD-SF protocol. The obtained indices of absolute and relative reliability indicate very good day-to-day reliability of the proposed protocol, suggesting the protocol's ability to be utilized in repeated measurements with the same subjects.

Regarding the reliability with standard protocol, research studies have reported generally good absolute reliability and somewhat lower but acceptable levels of relative reliability when examining knee extensors, which have been the most frequently studied muscle group. The reliability is typically measured with a standard error of measurement (SEM) ranging from 5.91% to 6.5% and intraclass correlation coefficient (ICC) values between 0.78 and 0.85, as indicated by Djordjevic & Uygur (2018), as well as Mathern et al. (2019). Comparable SEM values for absolute reliability were observed in studies of elbow extensors and grip muscles, yet they showed slightly lower relative reliability, with ICC values ranging from 0.64% to 0.68%. In contrast, a study focusing on hip muscles conducted by Casartelli et al. (2014) yielded somewhat better results in terms of reliability. They achieved SEM values of less than or equal to 8.9% and ICC values greater than or equal to 0.90. This improved reliability might be attributed to using a higher sampling frequency of 2000Hz and including a gold standard (isokinetic) dynamometer in their testing procedures alongside better fixation of the subjects.

Although this study is one of the first to explore the between-day reliability of RFD-SF protocol with reduced intensities, the obtained findings are somewhat better than in some of the previously published papers. Specifically, in most studies where 4 or 5 intensity levels and ~100 contractions were utilized, the reliability parameters were good to very large (ICC = 0.64–0.92), with an acceptable coefficient of variation (CV<15%) (Bellumori et al., 2011; Casartelli et al., 2014; Djordjevic & Uygur, 2018; Mathern et al., 2019). In the current study, reliability remained good for both legs despite the number of contractions and levels being reduced by half. Interestingly, findings from this study appear to have better relative reliability than Bellumori et al. (2011a) who used ~50 contractions (ICC > 0.7). Moreover, our protocol showed similar reliability to that (ICC > 0.77, CV < 10%) reported by Šarabon et al. (2020), who omitted higher intensity level, and somewhat lower than the reliability (ICC ≥ 0.95, CV < 5%) reported by Smajla et al. (2021) who applied nine contractions per each of the four levels.

Interestingly, this could be explained due to the fact that researchers in the mentioned study reduced contractions from ~100 to 36, checking the lowest number needed for very high reliability. In contrast, in this study, only a few outlier contractions were removed. Possibly even higher reliability could be present with further, manual reduction of contractions, but the idea was for subjects to perfrom ~50 contractions and to remove fewest possible outliers, instead of performing ~100 contractions, then removing many of them when conducting data analysis. Results of this study suggest that the RFD-SF protocol can provide reliable data even when using only two contraction intensities. This practically means that researchers can use the reduced protocol with confidence of getting statistically similar results every time the protocol is employed, which further supports the claim that the two-point reduced protocol can replace the standard one when assessing RFD-SF.

7.4.Sensitivity of two-point RFD-SF protocol

The third hypothesis of this research regarding the sensitivity of both standard and reduced RFD-SF protocol for the detection of differences between different groups of subjects has also been confirmed. As earlier mentioned, effective methods for evaluating muscle characteristics are crucial for creating injury prevention protocols for athletes. Monitoring training and rehabilitation regularly is also essential for minimizing injury risk. Therefore, it is important to develop and use tests that accurately and reliably assess both F and RFD with minimal effort, applicable in both practical and clinical contexts. In addition, tests should be able to discriminate between different groups of subjects with the purpose of accurate rehabilitation and training monitoring. If the test is relatively short to conduct, non-fatiguing and sensitive to detects differences between different groups of subjects, it could used in both field and clinical settings.

Both standard and reduced RFD-SF protocols are able to differentiate between physically active and sedentary students. Several studies dealt with the problem of RFD-SF sensitivity. Few studies compared young and old adults (Bellumori et al., 2013; Klass et al., 2008), as well as patients with neurological disorders (Uygur et al., 2020; Wierzbicka et al., 1991). They proved that older adults and patients with some form of neurological disorder had lower RFD-SF values, which is line with the results of our study. Less scaling of RFDpeak with Fpeak was present in this population which is the reason they had lower values of RFD-SF. This could be due to the fact that elderly people experience natural decrease in muscle mass called sarcopenia (Colón et al., 2018), as well as neurological input decrease which is represented by reduced discharge of motor neurons and diminished maximal firing rates (Zampieri et al., 2015). One study assessed RFD-SF sensitivity in knee osteoarthritis patients (Šarabon et al., 2020). Their results didn't show acceptable RFD-SF sensitivity for impairment detection, but they stated that RFR-SF could be more useful. Additionally, a study that assessed rapid sub-maximal contractions after long-distance running fatigue, found no acceptable sensitivity (Boccia et al., 2018).

On the contrary, by observing figures 14 and 15 we can conclude that differences in RFD-SF truly exist in subjects with different activity levels. There was a difference between protocols of ~29% in these two representable subjects. Greater values which active subject achieved could be explained because active population has better force and explosiveness control (Salonikidis et al., 2009). Since contradictory results are present in the several studies that dealt with this problem, more research is needed to truly assess the sensitivity of the RFD-SF protocol. Future studies should examine the sensitivity between professional athletes and recreational active population, injured and non-injured athletes alongside other groups of subjects.

7.5.Asymmetries

Leg asymmetries can lead to increased risk of injury, especially in sports and physical activities that require repetitive movements (Owens et al., 2011). Identifying these imbalances early can help athletes and individuals take corrective measures to reduce the risk of injuries such as strains, sprains, and overuse injuries. Balanced strength and coordination between the legs are essential for optimal performance in sports and daily activities. Addressing asymmetries can improve overall performance by enhancing biomechanical efficiency and movement patterns (Sharifmoradi et al., 2021). Athletes with balanced strength and coordination are likely to have better speed, agility, and power. Leg asymmetries can affect functional movements such as walking, running, and jumping. Testing and correcting these imbalances can improve the quality and efficiency of these movements, leading to better overall functional capacity and reducing the risk of compensatory patterns that may lead to pain or dysfunction over time. For individuals recovering from injuries, identifying and addressing leg asymmetries is essential for effective rehabilitation (Bishop et al., 2018). Imbalances can develop during the recovery process due to compensatory movements or muscle weakness. By testing for and correcting these imbalances, rehabilitation programs can be tailored to restore balanced strength and movement patterns, reducing the risk of re-injury. Chronic leg asymmetries can contribute to joint wear and tear over time, potentially leading to conditions such as osteoarthritis (Šarabon et al. 2020). By identifying and addressing imbalances early on, individuals can take proactive measures to preserve joint health and reduce the likelihood of developing degenerative joint conditions later in life.

No differences were found in interlimb asymmetries when the common and reduced RFD-SF protocols were compared. Our findings related to asymmetry are in line with previous research by Smajla et al. (2020) who reported that the RFD-SF protocol with 20–25 rapid contractions for each of the four intensity levels (20%, 40%, 60%, and 80% of previously measured maximal isometric torque) could be a valuable tool for the identification of interlimb asymmetries. Similar to the findings of Mirkov et al. (2016), Smajla et al. (2020) confirmed that measures other than the Fpeak and RFDpeak (i.e., interval RFD or RFD-SF) could be more sensitive in identifying individuals with asymmetries in capacities for rapid force rise. Considering this, our results suggest that the reduced protocol provides a valid assessment of inter-limb asymmetries. This is of great importance for clinical and sport settings, as asymmetries represent important information for practitioners in these fields, especially considering that the protocol does not require maximal effort.

7.6.Limitations of the study

It is important to acknowledge the limitations of this study. The study sample included a narrow age span; all subjects were healthy, without injuries, and with a similar training level. However, the obtained validity, reliability, and sensitivity of this homogenous sample suggest an excellent representation of neuromechanical characteristics of human muscle, whereby a more diverse sample may show even better metrics of our protocol. Larger and more diverse subjects sample could solve the problem of generalizability. As far as the testing procedure goes, this study hasn't used a gold standard device for the assessment of neuromuscular properties, electromyography (EMG), so future studies should include this measurement device. Somewhat lower ICC value of reduced RFD-SF protocol for the dominant leg, could be due to the fact that it was impossible to totally control the external factors contributing to the subjects' readinees for the testing. Even though it was emphasized that they should refrain from any physical activity 48h before the testing, some of them had practical classes that couldn't be avoided and probably didn't report a small amount of fatigue.

The main idea behind measuring RFD-SF is to exclude MVC testing. As of now, MVC testing must be incorporated to determine intensity levels. Since we proved that RFD-SF could be measured using only two levels, future studies should try the assessment using two self-selected levels, i.e., low and high. This would greatly ease the RFD-SF testing with the exclusion of MVC testing, if shown to be valid and reliable. Additionally, researches should assess the smallest number of contractions needed for acceptable validity and reliability when using only two levels. It could be that the protocol could be reduced even more by using fewer number of contractions. Additionally RFR-SF should be assessed since it has been shown that the relaxation phase of the pulse contractions demonstrates important properties. Finally, the order of the protocols has not been randomized in this study. Therefore, future studies should take that into account as well.

8. CONCLUSIONS

This study was designed to assess the linearity of Fpeak – RFDpeak relationship in a series of brief submaximal contractions, to explore validity and reliability of the reduced RFD-SF protocol, and to check both protocols' sensitivity.

The results of this study suggest that the reduced protocol could be used as a valid and reliable alternative to the standard protocol, allowing for a more efficient and cost-effective method to assess neuromuscular quickness. Nearly perfect mean associations were present for both legs and protocols (R^2 = 0.94-0.98) which proves that high linearity of Fpeak – RFDpeak relationship is present. Correlation between the two protocols was very high (r = 0.71; 0.80), and the reliability of the reduced protocol was acceptable (ICC = 0.80; 0.92 and CV = 5.3%; 4.4%) for both dominant and non-dominant legs, respectively. Regarding sensitivity, both protocols can differentiate between active and sedentary student groups ($p < 0.05$).

Even though the linearity of the Fpeak – RFDpeak relationship has been confirmed in several studies, R^2 results that describe this relationship were assessed in this study since new protocol was employed and high linearity is needed for an adequate assessment of RFD-SF. This is also important because the consistency of pulse contractions has been proven to be significantly reduced for patients with neurological diseases. Until recently, RFD-SF protocol has consisted of performing ~100 most rapid contractions to either several intensity levels or different ranges. This procedure was occasionally time-consuming and fatigue-prone for some subjects. It was necessary for the protocol to be reduced in some way, by either removing some intensity levels or reducing the number of contractions. This was achieved in this study by using only two levels which reduced the number of contractions by half (~50). Additionally, both protocols can differentiate between active and sedentary students, which means that this test could be used to assess one's physical activity level.

Moreover, it could be used to identify interlimb asymmetries. In practical applications, this could be beneficial in settings such as clinical and sports performance where time and resources are limited, while quick and accurate measurements are necessary. The reduced protocol is relatively short, non-fatiguing, and submaximal in intensity, which makes it safe and comfortable for a wide range of subjects. Future studies should further investigate sensitivity, including other populations, and cut-off values for normal, pre-clinical, and clinical cases should be established.

Summing up, the design of the study presented in this doctoral dissertation is the first that included the assessment of validity and reliability of measuring the RFD-SF with a protocol consisting of only two intensity levels. Also, this is one of the few studies that assessed sensitivity to discriminate between active and sedentary groups. Furthermore, this study checked the possibility of leg asymmetry identification by using RFD-SF. However, besides the great potential of the reduced protocol demonstrated within this research, future studies should try to reduce the protocol even further by reducing the contraction number and by removing the MVC testing by employing self-selected intensity levels. Additionally, EMG device should be used alongside dynamometer so true measure of neuro-muscular properties could be achieved. Finally the assessment of RFR-SF could prove to be very useful and insightful, so researchers should focus on exploring properties achieved by analyzing relaxation phase of the contraction.

REFERENCES

Ahmetov, I. I., Egorova, E. S., Gabdrakhmanova, L. J., & Fedotovskaya, O. N. (2016). Genes and Athletic Performance: An Update. *Medicine and Sport Science*, *61*, 41–54. https://doi.org/10.1159/000445240

Alcazar, J., Rodriguez-Lopez, C., Ara, I., Alfaro-Acha, A., Rodríguez-Gómez, I., Navarro-Cruz, R., Losa-Reyna, J., García-García, F. J., & Alegre, L. M. (2018). Force-velocity profiling in older adults: An adequate tool for the management of functional trajectories with aging. *Experimental Gerontology*, *108*, 1–6. https://doi.org/10.1016/J.EXGER.2018.03.015

Alt, T., Komnik, I., Severin, J., Nodler, Y. T., Benker, R., Knicker, A. J., Brüggemann, G. P., & Strüder, H. K. (2021). Swing Phase Mechanics of Maximal Velocity Sprints—Does Isokinetic Lower-Limb Muscle Strength Matter? *International Journal of Sports Physiology and Performance*, *16*(7), 974–984. https://doi.org/10.1123/IJSPP.2020-0423

Avelar, B. P., Costa, J. N. de A., Safons, M. P., Dutra, M. T., Bottaro, M., Gobbi, S., Tiedemann, A., de David, A. C., & Lima, R. M. (2016). Balance Exercises Circuit improves muscle strength, balance, and functional performance in older women. *AGE 2016 38:1*, *38*(1), 1–11. https://doi.org/10.1007/S11357-016-9872-7

Batista, M. A. B., Roschel, H., Barroso, R., Ugrinowitsch, C., & Tricoli, V. (2011). Influence of strength training background on postactivation potentiation response. *Journal of Strength and Conditioning Research*, *25*(9), 2496–2502. https://doi.org/10.1519/JSC.0B013E318200181B

Bazyler, C. D., Beckham, G. K., & Sato, K. (2015). The use of the isometric squat as a measure of strength and explosiveness. *Journal of Strength and Conditioning Research*, *29*(5), 1386–1392. https://doi.org/10.1519/JSC.0000000000000751

Beato, M., Maroto-Izquierdo, S., Turner, A. N., & Bishop, C. (2021). Implementing Strength Training Strategies for Injury Prevention in Soccer: Scientific Rationale and Methodological Recommendations. *International Journal of Sports Physiology and Performance*, *16*(3), 456–461. https://doi.org/10.1123/IJSPP.2020-0862

Bellumori, M., Jaric, S., & Knight, C. A. (2011). The rate of force development scaling factor (RFD-SF): Protocol, reliability, and muscle comparisons. *Experimental Brain Research*, *212*(3), 359–369. https://doi.org/10.1007/s00221-011-2735-7

Bellumori, M., Jaric, S., & Knight, C. A. (2013). Age-related decline in the rate of force development scaling factor. *Motor Control*, *17*(4), 370–381. https://doi.org/10.1123/mcj.17.4.370

Bellumori, M., Uygur, M., & Knight, C. A. (2017). High-Speed Cycling Intervention Improves Rate-Dependent Mobility in Older Adults. *Medicine and Science in Sports and Exercise*, *49*(1), 106–114. https://doi.org/10.1249/MSS.0000000000001069

Bishop, C., Turner, A., & Read, P. (2018). Effects of inter-limb asymmetries on physical and sports performance: a systematic review. In *Journal of Sports Sciences* (Vol. 36, Issue 10, pp. 1135–1144). Routledge. https://doi.org/10.1080/02640414.2017.1361894

Boccia, G., Brustio, P. R., Buttacchio, G., Calabrese, M., Bruzzone, M., Casale, R., & Rainoldi, A. (2018). Interlimb asymmetries identified using the rate of torque development in ballistic contraction targeting submaximal torques. *Frontiers in Physiology*, *9*. https://doi.org/10.3389/fphys.2018.01701

Boccia, G., Dardanello, D., Brustio, P. R., Tarperi, C., Festa, L., Zoppirolli, C., Pellegrini, B., Schena, F., & Rainoldi, A. (2018). Neuromuscular fatigue does not impair the rate of force development in ballistic contractions of submaximal amplitudes. *Frontiers in Physiology*, *9*(OCT). https://doi.org/10.3389/fphys.2018.01503

Boccia, G., Dardanello, D., Tarperi, C., Festa, L., La Torre, A., Pellegrini, B., Schena, F., & Rainoldi, A. (2017). Fatigue-induced dissociation between rate of force development and maximal force across repeated rapid contractions. *Human Movement Science*, *54*, 267–275. https://doi.org/10.1016/J.HUMOV.2017.05.016

Bohm, S., Mersmann, F., Santuz, A., Schroll, A., & Arampatzis, A. (2021). Muscle-specific economy of force generation and efficiency of work production during human running. *ELife*, *10*. https://doi.org/10.7554/ELIFE.67182

Boraczyński, M., Boraczyński, T., Podstawski, R., Wójcik, Z., & Gronek, P. (2020). Relationships Between Measures of Functional and Isometric Lower Body Strength, Aerobic Capacity, Anaerobic Power, Sprint and Countermovement Jump Performance in Professional Soccer Players. *Journal of Human Kinetics*, *75*(1), 161–175. https://doi.org/10.2478/HUKIN-2020-0045

Bourne, M., Schuermans, J., Witvrouw, E., Aagaard, P., & Shield, A. (2020). Neuromuscular factors related to hamstring muscle function, performance and injury. *Prevention and Rehabilitation of Hamstring Injuries*, 117–143. https://doi.org/10.1007/978-3-030-31638-9_5/COVER

Bozic, P. R., Celik, O., Uygur, M., Knight, C. A., & Jaric, S. (2013). Evaluation of novel tests of neuromuscular function based on brief muscle actions. *Journal of Strength and Conditioning Research*, *27*(6), 1568–1578. https://doi.org/10.1519/JSC.0B013E3182711E21

Brumitt, J., & Cuddeford, T. (2015). CURRENT CONCEPTS OF MUSCLE AND TENDON ADAPTATION TO STRENGTH AND CONDITIONING. *International Journal of Sports Physical Therapy*, *10*(6), 748. /pmc/articles/PMC4637912/

Brustio, P. R., Casale, R., Buttacchio, G., Calabrese, M., Bruzzone, M., Rainoldi, A., & Boccia, G. (2019). Relevance of evaluating the rate of torque development in ballistic contractions of submaximal amplitude. *Physiological Measurement*, *40*(2). https://doi.org/10.1088/1361-6579/aaff24

Byrne, D. J., Browne, D. T., Byrne, P. J., & Richardson, N. (2017). Interday Reliability of the Reactive Strength Index and Optimal Drop Height. *Journal of Strength and Conditioning Research*, *31*(3), 721–726. https://doi.org/10.1519/JSC.0000000000001534

Casartelli, N. C., Lepers, R., & Maffiuletti, N. A. (2014). Assessment of the rate of force development scaling factor for the hip muscles. *Muscle and Nerve*, *50*(6), 932–938. https://doi.org/10.1002/mus.24229

Chaabene, H., Prieske, O., Negra, Y., & Granacher, U. (2018). Change of Direction Speed: Toward a Strength Training Approach with Accentuated Eccentric Muscle Actions. *Sports Medicine*, *48*(8), 1773–1779. https://doi.org/10.1007/S40279-018-0907-3/METRICS

Clark, K. P., & Weyand, P. G. (2014). Are running speeds maximized with simple-spring stance mechanics? *Journal of Applied Physiology (Bethesda, Md.: 1985)*, *117*(6), 604–615. https://doi.org/10.1152/JAPPLPHYSIOL.00174.2014

Colón, C. J. P., Molina-Vicenty, I. L., Frontera-Rodríguez, M., García-Ferré, A., Rivera, B. P., Cintrón-Vélez, G., & Frontera-Rodríguez, S. (2018). Muscle and Bone Mass Loss in the Elderly Population: Advances in diagnosis and treatment. *Journal of Biomedicine (Sydney, NSW)*, *3*, 40. https://doi.org/10.7150/JBM.23390

Colyer, S. L., Nagahara, R., & Salo, A. I. T. (2018). Kinetic demands of sprinting shift across the acceleration phase: Novel analysis of entire force waveforms. *Scandinavian Journal of Medicine & Science in Sports*, *28*(7), 1784–1792. https://doi.org/10.1111/SMS.13093

Comfort, P., Dos'Santos, T., Beckham, G. K., Stone, M. H., Guppy, S. N., & Haff, G. G. (2019). Standardization and methodological considerations for the isometric midthigh pull. *Strength and Conditioning Journal*, *41*(2), 57–79. https://doi.org/10.1519/SSC.0000000000000433

Comfort, P., Haigh, A., & Matthews, M. J. (2012). Are changes in maximal squat strength during preseason training reflected in changes in sprint performance in rugby league players? *Journal of Strength and Conditioning Research*, *26*(3), 772–776. https://doi.org/10.1519/JSC.0B013E31822A5CBF

Cormie, P., McGuigan, M. R., & Newton, R. U. (2010). Adaptations in athletic performance after ballistic power versus strength training. *Medicine and Science in Sports and Exercise*, *42*(8), 1582–1598. https://doi.org/10.1249/MSS.0B013E3181D2013A

Cormie, P., McGuigan, M. R., & Newton, R. U. (2012). Developing Maximal Neuromuscular Power. *Sports Medicine 2011 41:1*, *41*(1), 17–38. https://doi.org/10.2165/11537690-000000000-00000

Corrêa, T. G. C., Donato, S. V. S., Lima, K. C. A., Uygur, M., Pereira, R. V., & de Freitas, P. B. (2020). Age- and Sex-Related Differences in the Maximum Muscle Performance and Rate of Force Development Scaling Factor of Precision Grip Muscles. *Motor Control*, *24*(2), 274–290. https://doi.org/10.1123/MC.2019-0021

Cronin, N. J., Peltonen, J., Ishikawa, M., Komi, P. V., Avela, J., Sinkjaer, T., & Voigt, M. (2008). Effects of contraction intensity on muscle fascicle and stretch reflex behavior in the human triceps surae. *Journal of Applied Physiology*, *105*(1), 226–232. https://doi.org/10.1152/JAPPLPHYSIOL.90432.2008/ASSET/IMAGES/LARGE/ZDG007088 0410004.JPEG

Cross, M. R., Brughelli, M., Brown, S. R., Samozino, P., Gill, N. D., Cronin, J. B., & Morin, J. B. (2015). Mechanical Properties of Sprinting in Elite Rugby Union and Rugby League. *International Journal of Sports Physiology and Performance*, *10*(6), 695–702. https://doi.org/10.1123/IJSPP.2014-0151

Cuk, I., Mirkov, D., Nedeljkovic, A., Kukolj, M., Ugarkovic, D., & Jaric, S. (2016). Force-velocity property of leg muscles in individuals of different level of physical fitness. *Sports Biomechanics / International Society of Biomechanics in Sports*, *15*(2), 207. https://doi.org/10.1080/14763141.2016.1159724

De Almeida Barros, N., Aidar, F. J., Gama De Matos, D., Fabrício, R., Souza, D. E., Borba, E., ‡7, N., Guilherme, B., Araujo, D. E., Cabral, T., Carmargo, A., & Reis, V. M. (2020). Evaluation of Muscle Damage, Body Temperature, Peak Torque, and Fatigue Index in Three Different Methods of Strength Gain. *International Journal of Exercise Science*, *13*(3), 1352. /pmc/articles/PMC7523903/

De Luca, C. J., & Kline, J. C. (2011). Influence of proprioceptive feedback on the firing rate and recruitment of motoneurons. *Journal of Neural Engineering*, *9*(1), 016007. https://doi.org/10.1088/1741-2560/9/1/016007

Del Vecchio, A. (2023). Neuromechanics of the Rate of Force Development. *Exercise and Sport Sciences Reviews*, *51*(1), 34–42. https://doi.org/10.1249/JES.0000000000000306

Del Vecchio, A., Casolo, A., Dideriksen, J. L., Aagaard, P., Felici, F., Falla, D., & Farina, D. (2022). Lack of increased rate of force development after strength training is explained by specific neural, not muscular, motor unit adaptations. *Journal of Applied Physiology*, *132*(1), 84–94. https://doi.org/10.1152/JAPPLPHYSIOL.00218.2021/ASSET/IMAGES/LARGE/JAPPLPHY SIOL.00218.2021_F006.JPEG

Del Vecchio, A., Casolo, A., Negro, F., Scorcelletti, M., Bazzucchi, I., Enoka, R., Felici, F., & Farina, D. (2019). The increase in muscle force after 4 weeks of strength training is mediated by adaptations in motor unit recruitment and rate coding. *The Journal of Physiology*, *597*(7), 1873–1887. https://doi.org/10.1113/JP277250

Dillman, C. J., Murray, T. A., & Hintermeister, R. A. (1994). Biomechanical Differences of Open and Closed Chain Exercises with Respect to the Shoulder. *Journal of Sport Rehabilitation*, *3*(3), 228–238. https://doi.org/10.1123/JSR.3.3.228

Distefano, G., & Goodpaster, B. H. (2018). Effects of Exercise and Aging on Skeletal Muscle. *Cold Spring Harbor Perspectives in Medicine*, *8*(3). https://doi.org/10.1101/CSHPERSPECT.A029785

Djordjevic, D., & Uygur, M. (2018). Methodological considerations in the calculation of the rate of force development scaling factor. *Physiological Measurement*, *39*(1). https://doi.org/10.1088/1361-6579/aa9f51

Dos'santos, T., Thomas, C., Comfort, P., McMahon, J. J., & Jones, P. A. (2017). Relationships between Isometric Force-Time Characteristics and Dynamic Performance. *Sports*, *5*(3). https://doi.org/10.3390/SPORTS5030068

Dos'Santos, T., Thomas, C., Jones, P. A., & Comfort, P. (2018). Asymmetries in isometric force-time characteristics are not detrimental to change of direction speed. *Journal of Strength and Conditioning Research*, *32*(2), 520–527. https://doi.org/10.1519/jsc.0000000000002327

Dunn, E. C., Humberstone, C. E., Franchini, E., Iredale, K. F., & Blazevich, A. J. (2022). Relationships between Punch Impact Force and Upper-and Lower-Body Muscular Strength and Power in Highly Trained Amateur Boxers. *Journal of Strength and Conditioning Research*, *36*(4), 1019–1025. https://doi.org/10.1519/JSC.0000000000003585

Elgueta-Cancino, E., Evans, E., Martinez-Valdes, E., & Falla, D. (2022). The Effect of Resistance Training on Motor Unit Firing Properties: A Systematic Review and Meta-Analysis. *Frontiers in Physiology*, *13*, 817631. https://doi.org/10.3389/FPHYS.2022.817631/BIBTEX

Erdfelder, E., FAul, F., Buchner, A., & Lang, A. G. (2009). Statistical power analyses using G*Power 3.1: tests for correlation and regression analyses. *Behavior Research Methods*, *41*(4), 1149–1160. https://doi.org/10.3758/BRM.41.4.1149

Falk, B., & Eliakim, A. (2003). Resistance training, skeletal muscle and growth. *Pediatric Endocrinology Reviews : PER*, *1*(2), 120–127. https://europepmc.org/article/med/16437017

Farina, D., Negro, F., Muceli, S., & Enoka, R. M. (2016). Principles of motor unit physiology evolve with advances in technology. *Physiology*, *31*(2), 83–94. https://doi.org/10.1152/PHYSIOL.00040.2015/ASSET/IMAGES/LARGE/PHY0021603170003.JPEG

Figueiredo, V. C., de Salles, B. F., & Trajano, G. S. (2018). Volume for Muscle Hypertrophy and Health Outcomes: The Most Effective Variable in Resistance Training. *Sports Medicine*, *48*(3), 499–505. https://doi.org/10.1007/S40279-017-0793-0/METRICS

Forthomme, B., Croisier, J. L., Delvaux, F., Kaux, J. F., Crielaard, J. M., & Gleizes-Cervera, S. (2018). Preseason Strength Assessment of the Rotator Muscles and Shoulder Injury in Handball Players. *Journal of Athletic Training*, *53*(2), 174–180. https://doi.org/10.4085/1062-6050-216-16

Freund, H. J., & Büdingen, H. J. (1978). The relationship between speed and amplitude of the fastest voluntary contractions of human arm muscles. *Experimental Brain Research*, *31*(1), 1–12. https://doi.org/10.1007/BF00235800

Garcia-Ramos, A., & Jaric, S. (2018). Two-point method: A quick and fatigue-free procedure for assessment of muscle mechanical capacities and the 1 repetition maximum. *Strength and Conditioning Journal*, *40*(2), 54–66. https://doi.org/10.1519/SSC.0000000000000359

García-Ramos, A., Jaric, S., Padial, P., & Feriche, B. (2016). Force–Velocity Relationship of Upper Body Muscles: Traditional Versus Ballistic Bench Press. *Journal of Applied Biomechanics*, *32*(2), 178–185. https://doi.org/10.1123/JAB.2015-0162

García-Ramos, A., Pérez-Castilla, A., & Jaric, S. (2018). Optimisation of applied loads when using the two-point method for assessing the force-velocity relationship during vertical jumps. *Https://Doi.Org/10.1080/14763141.2018.1545044*, *20*(3), 274–289. https://doi.org/10.1080/14763141.2018.1545044

Gil, M. H., Neiva, H. P., Garrido, N. D., Aidar, F. J., Cirilo-Sousa, M. S., Marques, M. C., & Marinho, D. A. (2019). The Effect of Ballistic Exercise as Pre-Activation for 100 m Sprints. *International Journal of Environmental Research and Public Health 2019, Vol. 16, Page 1850*, *16*(10), 1850. https://doi.org/10.3390/IJERPH16101850

Gordon, A. M., Huxley, A. F., & Julian, F. J. (1966). The variation in isometric tension with sarcomere length in vertebrate muscle fibres. *The Journal of Physiology*, *184*(1), 170–192. https://doi.org/10.1113/JPHYSIOL.1966.SP007909

Gordon, J., & Ghez, C. (1987). Experimental Brain Research Trajectory control in targeted force impulses II. Pulse height control. In *Exp Brain Res* (Vol. 67).

Green, B., Bourne, M. N., & Pizzari, T. (2018). Isokinetic strength assessment offers limited predictive validity for detecting risk of future hamstring strain in sport: a systematic review and meta-analysis. *British Journal of Sports Medicine*, *52*(5), 329–336. https://doi.org/10.1136/BJSPORTS-2017-098101

Guizelini, P. C., de Aguiar, R. A., Denadai, B. S., Caputo, F., & Greco, C. C. (2018). Effect of resistance training on muscle strength and rate of force development in healthy older adults: A systematic review and meta-analysis. *Experimental Gerontology*, *102*, 51–58. https://doi.org/10.1016/J.EXGER.2017.11.020

Gutiérrez-Monclus, R., Gutiérrez-Espinoza, H., Araya-Quintanilla, F., Gutierrez-Novoa, C., Cordero-Barzallo, P., Rodríguez-Baeza, A., Ferreres-Claramunt, Á., & García-Elias, M. (2023). Intra-articular Pressure in the Distal Radioulnar Joint: A Biomechanical Study. *The Journal of Hand Surgery*. https://doi.org/10.1016/J.JHSA.2023.11.015

Haberland, K., & Uygur, M. (2016). Simultaneous assessment of hand function and neuromuscular quickness through a static object manipulation task in healthy adults. *Experimental Brain Research 2016 235:1*, *235*(1), 321–329. https://doi.org/10.1007/S00221-016-4797-Z

Haghighi, A. H., Zaferanieh, A., Hosseini-Kakhak, S. A., Maleki, A., Esposito, F., Cè, E., Castellar, C., Toro-Román, V., & Pradas, F. (2021). Effects of Power and Ballistic Training on Table Tennis Players' Electromyography Changes. *International Journal of Environmental Research and Public Health 2021, Vol. 18, Page 7735*, *18*(15), 7735. https://doi.org/10.3390/IJERPH18157735

Haugen, T. A., Breitschädel, F., & Seiler, S. (2019). Sprint mechanical variables in elite athletes: Are force-velocity profiles sport specific or individual? *PLOS ONE*, *14*(7), e0215551. https://doi.org/10.1371/JOURNAL.PONE.0215551

Haugen, T. A., Tønnessen, E., Hisdal, J., & Seiler, S. (2014). The Role and Development of Sprinting Speed in Soccer. *International Journal of Sports Physiology and Performance*, *9*(3), 432–441. https://doi.org/10.1123/IJSPP.2013-0121

Henderson, F. J., Sasakabe, W., Satoshi, K., Shima, N., & Shimokochi, Y. (2022). Quadriceps Function and Athletic Performance in Highly Trained Female Athletes. *Journal of Sport Rehabilitation*, *32*(1), 63–69. https://doi.org/10.1123/JSR.2021-0359

Herbert, R. D., & Gandevia, S. C. (2019). The passive mechanical properties of muscle. *Https://Doi.Org/10.1152/Japplphysiol.00966.2018*, *126*(5), 1442–1444. https://doi.org/10.1152/JAPPLPHYSIOL.00966.2018

Herda, T. J., Siedlik, J. A., Trevino, M. A., Cooper, M. A., & Weir, J. P. (2015). Motor unit control strategies of endurance- versus resistance-trained individuals. *Muscle & Nerve*, *52*(5), 832–843. https://doi.org/10.1002/MUS.24597

Herzog, W. (2018). The multiple roles of titin in muscle contraction and force production. *Biophysical Reviews*, *10*(4), 1187–1199. https://doi.org/10.1007/S12551-017-0395-Y/METRICS

Herzog, W., Powers, K., Johnston, K., & Duvall, M. (2015). A new paradigm for muscle contraction. *Frontiers in Physiology*, *6*(MAY). https://doi.org/10.3389/FPHYS.2015.00174

Hill, A. V. (1938). The Heat of Shortening and the Dynamic Constants of Muscle. *RSPSB*, *126*(843), 136–195. https://doi.org/10.1098/RSPB.1938.0050

Hopkins, W. G. (2012). Measures of Reliability in Sports Medicine and Science. *Sports Medicine 2000 30:1*, *30*(1), 1–15. https://doi.org/10.2165/00007256-200030010-00001

Hopkins, W. G., Marshall, S. W., Batterham, A. M., & Hanin, J. (2009). Progressive statistics for studies in sports medicine and exercise science. *Medicine and Science in Sports and Exercise*, *41*(1), 3–12. https://doi.org/10.1249/MSS.0B013E31818CB278

Huxley, A. F. (1957). Muscle structure and theories of contraction. *Progress in Biophysics and Biophysical Chemistry*, *7*, 255–318. https://doi.org/10.1016/S0096-4174(18)30128-8

Irlbacher, K., Voss, M., Meyer, B. U., & Rothwell, J. C. (2006). Influence of ipsilateral transcranial magnetic stimulation on the triphasic EMG pattern accompanying fast ballistic movements in humans. *The Journal of Physiology*, *574*(Pt 3), 917. https://doi.org/10.1113/JPHYSIOL.2006.108563

Janicijevic, D., García-Ramos, A., Knezevic, O. M., & Mirkov, D. M. (2019). Feasibility of the two-point method for assessing the force-velocity relationship during lower-body and upper-body isokinetic tests. *Https://Doi.Org/10.1080/02640414.2019.1636523*, *37*(20), 2396–2402. https://doi.org/10.1080/02640414.2019.1636523

Janicijevic, D., Knezevic, O. M., Garcia-Ramos, A., Cvetic, D., & Mirkov, D. M. (2020). Isokinetic Testing: Sensitivity of the Force-Velocity Relationship Assessed through the Two-Point Method to Discriminate between Muscle Groups and Participants' Physical Activity Levels. *International Journal of Environmental Research and Public Health 2020, Vol. 17, Page 8570*, *17*(22), 8570. https://doi.org/10.3390/IJERPH17228570

Jaric, S. (2015). Force-velocity Relationship of Muscles Performing Multi-joint Maximum Performance Tasks. *International Journal of Sports Medicine*, *36*(9), 699–704. https://doi.org/10.1055/S-0035-1547283/ID/R4551-0016/BIB

Jaric, S. (2016). Two-Load Method for Distinguishing Between Muscle Force, Velocity, and Power-Producing Capacities. *Sports Medicine (Auckland, N.Z.)*, *46*(11), 1585–1589. https://doi.org/10.1007/S40279-016-0531-Z

Jarvis, P., Turner, A., Read, P., & Bishop, C. (2022). Reactive Strength Index and its Associations with Measures of Physical and Sports Performance: A Systematic Review with Meta-Analysis. *Sports Medicine*, *52*(2), 301–330. https://doi.org/10.1007/S40279-021-01566-Y/METRICS

Joachim Büdingen, H., & Freund, H. J. (1976). The relationship between the rate of rise of isometric tension and motor unit recruitment in a human forearm muscle. *Pflügers Archiv European Journal of Physiology*, *362*(1), 61–67. https://doi.org/10.1007/BF00588682

Kipp, K., Kiely, M. T., & Geiser, C. F. (2016). Reactive strength index modified is a valid measure of explosiveness in collegiate female volleyball players. *Journal of Strength and Conditioning Research*, *30*(5), 1341–1347. https://doi.org/10.1519/JSC.0000000000001226

Klass, M., Baudry, S., & Duchateau, J. (2008). Age-related decline in rate of torque development is accompanied by lower maximal motor unit discharge frequency during fast contractions.

Journal of Applied Physiology, *104*(3), 739–746. https://doi.org/10.1152/japplphysiol.00550.2007

Kline, J. C., & De Luca, C. J. (2015). Synchronization of motor unit firings: An epiphenomenon of firing rate characteristics not common inputs. *Journal of Neurophysiology*, *115*(1), 178–192. https://doi.org/10.1152/JN.00452.2015/ASSET/IMAGES/LARGE/Z9K0011634130010.JPEG

Kollock, R., Van Lunen, B. L., Ringleb, S. I., & Onate, J. A. (2015). Measures of Functional Performance and Their Association With Hip and Thigh Strength. *Journal of Athletic Training*, *50*(1), 14. https://doi.org/10.4085/1062-6050-49.3.49

Kozinc, Ž., Smajla, D., & Šarabon, N. (2020). Relationship between hip abductor strength, rate of torque development scaling factor and medio-lateral stability in older adults. *Gait and Posture*. https://doi.org/10.1016/j.gaitpost.2020.11.010

Kyle Travis, S., Goodin, J. R., Beckham, G. K., & Bazyler, C. D. (2018). Identifying a Test to Monitor Weightlifting Performance in Competitive Male and Female Weightlifters. *Sports 2018, Vol. 6, Page 46*, *6*(2), 46. https://doi.org/10.3390/SPORTS6020046

Laffaye, G., & Wagner, P. (2013). Eccentric rate of force development determines jumping performance. *Https://Doi.Org/10.1080/10255842.2013.815839*, *16*(SUPPL 1), 82–83. https://doi.org/10.1080/10255842.2013.815839

Lakens, D. (2013). Calculating and reporting effect sizes to facilitate cumulative science: A practical primer for t-tests and ANOVAs. *Frontiers in Psychology*, *4*(NOV). https://doi.org/10.3389/FPSYG.2013.00863/ABSTRACT

Lauersen, J. B., Andersen, T. E., & Andersen, L. B. (2018). Strength training as superior, dose-dependent and safe prevention of acute and overuse sports injuries: a systematic review, qualitative analysis and meta-analysis. *British Journal of Sports Medicine*, *52*(24), 1557–1563. https://doi.org/10.1136/BJSPORTS-2018-099078

Lee, H. J., Lee, K. W., Takeshi, K., Lee, Y. W., & Kim, H. J. (2021). Correlation analysis between lower limb muscle architectures and cycling power via ultrasonography. *Scientific Reports 2021 11:1*, *11*(1), 1–12. https://doi.org/10.1038/s41598-021-84870-x

Lesinski, M., Muehlbauer, T., Büsch, D., & Granacher, U. (2014). [Effects of complex training on strength and speed performance in athletes: a systematic review. Effects of complex training on athletic performance]. *Sportverletzung Sportschaden : Organ Der Gesellschaft Fur Orthopadisch-Traumatologische Sportmedizin*, *28*(2), 85–107. https://doi.org/10.1055/S-0034-1366145

Lockie, R. G., Lazar, A., Davis, D. S. L., & Moreno, M. R. (2018). Effects of Postactivation Potentiation on Linear and Change-of-Direction Speed: Analysis of the Current Literature and Applications for the Strength and Conditioning Coach. *Strength and Conditioning Journal*, *40*(1), 75–91. https://doi.org/10.1519/SSC.0000000000000277

Logan, S. W., Ross, S. M., Chee, K., Stodden, D. F., & Robinson, L. E. (2017). Fundamental motor skills: A systematic review of terminology. *Https://Doi.Org/10.1080/02640414.2017.1340660*, *36*(7), 781–796. https://doi.org/10.1080/02640414.2017.1340660

Longstreth, L. E., El-Zahhar, N., & Alcorn, M. B. (1985). Exceptions to Hick's Law. Explorations With a Response Duration Measure. *Journal of Experimental Psychology: General*, *114*(4), 417–434. https://doi.org/10.1037/0096-3445.114.4.417

Lum, D., Barbosa, T. M., Joseph, R., & Balasekaran, G. (2021). Effects of Two Isometric Strength Training Methods on Jump and Sprint Performances: A Randomized Controlled Trial. *Journal of Science in Sport and Exercise*, *3*(2), 115–124. https://doi.org/10.1007/S42978-020-00095-W/METRICS

Lum, D., Haff, G. G., & Barbosa, T. M. (2020). The Relationship between Isometric Force-Time Characteristics and Dynamic Performance: A Systematic Review. *Sports 2020, Vol. 8, Page 63*, *8*(5), 63. https://doi.org/10.3390/SPORTS8050063

Maestroni, L., Read, P., Bishop, C., Papadopoulos, K., Suchomel, T. J., Comfort, P., & Turner, A. (2020). The Benefits of Strength Training on Musculoskeletal System Health: Practical Applications for Interdisciplinary Care. *Sports Medicine*, *50*(8), 1431–1450. https://doi.org/10.1007/S40279-020-01309-5/METRICS

Maffiuletti, N. A., Aagaard, P., Blazevich, A. J., Folland, J., Tillin, N., & Duchateau, J. (2016). Rate of force development: physiological and methodological considerations. In *European Journal of Applied Physiology* (Vol. 116, Issue 6, pp. 1091–1116). Springer Verlag. https://doi.org/10.1007/s00421-016-3346-6

Markwick, W. J., Bird, S. P., Tufano, J. J., Seitz, L. B., & Haff, G. G. (2015). The Intraday Reliability of the Reactive Strength Index Calculated From a Drop Jump in Professional Men's Basketball. *International Journal of Sports Physiology and Performance*, *10*(4), 482–488. https://doi.org/10.1123/IJSPP.2014-0265

Mathern, R. M., Anhorn, M., & Uygur, M. (2019). A novel method to assess rate of force relaxation: reliability and comparisons with rate of force development across various muscles. *European Journal of Applied Physiology*, *119*(1), 291–300. https://doi.org/10.1007/s00421-018-4024-7

McGlory, C., & Phillips, S. M. (2015). Exercise and the Regulation of Skeletal Muscle Hypertrophy. *Progress in Molecular Biology and Translational Science*, *135*, 153–173. https://doi.org/10.1016/BS.PMBTS.2015.06.018

McMahon, J. J., Suchomel, T. J., Lake, J. P., & Comfort, P. (2018). Understanding the key phases of the countermovement jump force-time curve. *Strength and Conditioning Journal*, *40*(4), 96–106. https://doi.org/10.1519/SSC.0000000000000375

Mendez-Rebolledo, G., Morales-Verdugo, J., Orozco-Chavez, I., Habechian, F. A. P., Padilla, E. L., & de la Rosa, F. J. B. (2021). Optimal activation ratio of the scapular muscles in closed kinetic chain shoulder exercises: A systematic review. *Journal of Back and Musculoskeletal Rehabilitation*, *34*(1), 3–16. https://doi.org/10.3233/BMR-191771

Methenitis, S., Spengos, K., Zaras, N., Stasinaki, A. N., Papadimas, G., Karampatsos, G., Arnaoutis, G., & Terzis, G. (2019). FIBER TYPE COMPOSITION AND RATE OF FORCE DEVELOPMENT IN ENDURANCE- AND RESISTANCE-TRAINED INDIVIDUALS. *Journal of Strength and Conditioning Research*, *33*(9), 2388–2397. https://doi.org/10.1519/JSC.0000000000002150

Miller, J. D., Lippman, J. D., Trevino, M. A., & Herda, T. J. (2020). Neural Drive is Greater for a High-Intensity Contraction Than for Moderate-Intensity Contractions Performed to Fatigue. *Journal of Strength and Conditioning Research*, *34*(11), 3013–3021. https://doi.org/10.1519/JSC.0000000000003694

Miller, M. S., Bedrin, N. G., Ades, P. A., Palmer, B. M., & Toth, M. J. (2015). Molecular determinants of force production in human skeletal muscle fibers: Effects of myosin isoform expression and cross-sectional area. *American Journal of Physiology - Cell Physiology*, *308*(6), C473–C484. https://doi.org/10.1152/AJPCELL.00158.2014/ASSET/IMAGES/LARGE/ZH00061576950010.JPEG

Minetti, A. E. (2002). On the mechanical power of joint extensions as affected by the change in muscle force (or cross-sectional area), ceteris paribus. *European Journal of Applied Physiology*, *86*(4), 363–369. https://doi.org/10.1007/S00421-001-0554-4

Minshull, C., Gallacher, P., Roberts, S., Barnett, A., Kuiper, J. H., & Bailey, A. (2021). Contralateral strength training attenuates muscle performance loss following anterior cruciate ligament (ACL) reconstruction: a randomised-controlled trial. *European Journal of Applied Physiology*, *121*(12), 3551–3559. https://doi.org/10.1007/S00421-021-04812-3/METRICS

Mirkov, D. M., Knezevic, O. M., Maffiuletti, N. A., Kadija, M., Nedeljkovic, A., & Jaric, S. (2016). Contralateral limb deficit after ACL-reconstruction: an analysis of early and late phase of rate of force development. *Https://Doi.Org/10.1080/02640414.2016.1168933*, *35*(5), 435–440. https://doi.org/10.1080/02640414.2016.1168933

Mirkov, D. M., Nedeljkovic, A., Milanovic, S., & Jaric, S. (2004). Muscle strength testing: Evaluation of tests of explosive force production. *European Journal of Applied Physiology*, *91*(2–3), 147–154. https://doi.org/10.1007/S00421-003-0946-8/METRICS

Moir, G. L., Gollie, J. M., Davis, S. E., Guers, J. J., & Witmer, C. A. (2012). The effects of load on system and lower-body joint kinetics during jump squats. *Sports Biomechanics*, *11*(4), 492–506. https://doi.org/10.1080/14763141.2012.725426

Morin, J. B., & Samozino, P. (2016). Interpreting Power-Force-Velocity Profiles for Individualized and Specific Training. *International Journal of Sports Physiology and Performance*, *11*(2), 267–272. https://doi.org/10.1123/IJSPP.2015-0638

Mota, J. A., Gerstner, G. R., & Giuliani, H. K. (2019). Motor unit properties of rapid force development during explosive contractions. *The Journal of Physiology*, *597*(9), 2335. https://doi.org/10.1113/JP277905

Mujika, I., Rønnestad, B. R., & Martin, D. T. (2016). Effects of Increased Muscle Strength and Muscle Mass on Endurance-Cycling Performance. *International Journal of Sports Physiology and Performance*, *11*(3), 283–289. https://doi.org/10.1123/IJSPP.2015-0405

Murlasits, Z., Kneffel, Z., & Thalib, L. (2017). The physiological effects of concurrent strength and endurance training sequence: A systematic review and meta-analysis. *Https://Doi.Org/10.1080/02640414.2017.1364405*, *36*(11), 1212–1219. https://doi.org/10.1080/02640414.2017.1364405

Murphy, A. J., Wilson, G. J., Pryor, J. F., & Newton, R. U. (1995). Isometric Assessment of Muscular Function: The Effect of Joint Angle. *Journal of Applied Biomechanics*, *11*(2), 205–215. https://doi.org/10.1123/JAB.11.2.205

Naqvi, U., & Sherman, A. l. (2022). Muscle Strength Grading. *StatPearls*. https://www.ncbi.nlm.nih.gov/books/NBK436008/

Nessler, T., Denney, L., & Sampley, J. (2017). ACL Injury Prevention: What Does Research Tell Us? *Current Reviews in Musculoskeletal Medicine*, *10*(3), 281–288. https://doi.org/10.1007/S12178-017-9416-5/METRICS

Nishida, S., Kunugi, S., Maehara, K., & Miyakawa, S. (2021). Association between passive stiffness of hamstring and eccentric knee flexion angle-torque relationship. *The Journal of Physical Fitness and Sports Medicine*, *10*(4), 205–211. https://doi.org/10.7600/JPFSM.10.205

Onken, M. (2019). *Sprint characteristics and proportion of the horizontal performance of the lower extremities of a one man push start in bobsledding through field testing*. https://doc.rero.ch/record/327865/files/TM_Onken_Melanie.pdf

Owens, E. M., Ramsey, M. W., Lamont, H. S., Sato, K., & Williams, D. A. (2011). *Use of Isometric Mid-Thigh Pull to Determine Asymmetrical Strength Differences in NCAA D-I Athletes*.

Palmieri-Smith, R. M., & Lepley, L. K. (2015). Quadriceps Strength Asymmetry After Anterior Cruciate Ligament Reconstruction Alters Knee Joint Biomechanics and Functional Performance at Time of Return to Activity. *Https://Doi.Org/10.1177/0363546515578252*, *43*(7), 1662–1669. https://doi.org/10.1177/0363546515578252

Pardos-Mainer, E., Lozano, D., Torrontegui-Duarte, M., Cartón-Llorente, A., & Roso-Moliner, A. (2021). Effects of Strength vs. Plyometric Training Programs on Vertical Jumping, Linear Sprint and Change of Direction Speed Performance in Female Soccer Players: A Systematic Review and Meta-Analysis. *International Journal of Environmental Research and Public Health 2021, Vol. 18, Page 401*, *18*(2), 401. https://doi.org/10.3390/IJERPH18020401

Pérez-Castilla, A., Jaric, S., Feriche, B., Padial, P., & García-Ramos, A. (2018). Evaluation of Muscle Mechanical Capacities Through the Two-Load Method: Optimization of the Load Selection. *Journal of Strength and Conditioning Research*, *32*(5), 1245–1253. https://doi.org/10.1519/JSC.0000000000001969

Perriman, A., Leahy, E., & Semciw, A. I. (2018). The effect of open-versus closed-kinetic-chain exercises on anterior tibial laxity, strength, and function following anterior cruciate ligament reconstruction: A systematic review and meta-analysis. *Journal of Orthopaedic and Sports Physical Therapy*, *48*(7), 552–566. https://doi.org/10.2519/JOSPT.2018.7656/ASSET/IMAGES/LARGE/JOSPT-552-FIG005.JPEG

Pethick, J., Winter, S. L., & Burnley, M. (2015). Fatigue reduces the complexity of knee extensor torque fluctuations during maximal and submaximal intermittent isometric contractions in man. *The Journal of Physiology*, *593*(8), 2085–2096. https://doi.org/10.1113/JPHYSIOL.2015.284380

Petridis, L., Tróznai, Z., Pálinkás, G., Kalabiska, I., & Szabó, T. (2017). Modified Reactive Strength Index in Adolescent Athletes Competing in Different Sports and Its Relationship with Force Production. *American Journal of Sports Science and Medicine*, *5*(2), 21–26. https://doi.org/10.12691/ajssm-5-2-2

Petrovic, M., Garcia-Ramos, A., Janicijevic, D., Perez-Castilla, A., Knezevic, O. M., & Mirkov, D. M. (2021). Force-Velocity Profile of Competitive Kayakers: Evaluation of a Novel Single Kayak Stroke Test. *Journal of Human Kinetics*, *80*(1), 49–59. https://doi.org/10.2478/HUKIN-2021-0100

Presland, J. D., Opar, D. A., Williams, M. D., Hickey, J. T., Maniar, N., Lee Dow, C., Bourne, M. N., & Timmins, R. G. (2020). Hamstring strength and architectural adaptations following inertial flywheel resistance training. *Journal of Science and Medicine in Sport*, *23*(11), 1093–1099. https://doi.org/10.1016/J.JSAMS.2020.04.007

Prieske, O., Behrens, M., Chaabene, H., Granacher, U., & Maffiuletti, N. A. (2020). Time to Differentiate Postactivation "Potentiation" from "Performance Enhancement" in the Strength and Conditioning Community. *Sports Medicine*, *50*(9), 1559–1565. https://doi.org/10.1007/S40279-020-01300-0/FIGURES/2

Ramírez-delaCruz, M., Bravo-Sánchez, A., Esteban-García, P., Jiménez, F., & Abián-Vicén, J. (2022). Effects of Plyometric Training on Lower Body Muscle Architecture, Tendon Structure, Stiffness and Physical Performance: A Systematic Review and Meta-analysis. *Sports Medicine - Open 2022 8:1*, *8*(1), 1–29. https://doi.org/10.1186/S40798-022-00431-0

Robichaud, J. A., Pfann, K. D., Vaillancourt, D. E., Comella, C. L., & Corcos, D. M. (2005). Force control and disease severity in Parkinson's disease. *Movement Disorders*, *20*(4), 441–450. https://doi.org/10.1002/MDS.20350

Rodríguez-Rosell, D., Pareja-Blanco, F., Aagaard, P., & González-Badillo, J. J. (2018). Physiological and methodological aspects of rate of force development assessment in human skeletal muscle. *Clinical Physiology and Functional Imaging*, *38*(5), 743–762. https://doi.org/10.1111/CPF.12495

Salonikidis, K., Amiridis, I. G., Oxyzoglou, N., De Villareal, E. S. S., Zafeiridis, A., & Kellis, E. (2009). Force variability during isometric wrist flexion in highly skilled and sedentary individuals. *European Journal of Applied Physiology*, *107*(6), 715–722. https://doi.org/10.1007/S00421-009-1184-5/TABLES/2

Šarabon, N., Čeh, T., Kozinc, Ž., & Smajla, D. (2020). Adapted protocol of rate of force development and relaxation scaling factor for neuromuscular assessment in patients with knee osteoarthritis. *Knee*, *27*(6), 1697–1707. https://doi.org/10.1016/j.knee.2020.09.023

Šarabon, N., Knezevic, M. O., Mirkov, M. D., & Smajla, D. (2020). Introduction of dynamic rate-of-force development scaling factor in progressive drop jumps. *Journal of Biomechanics*, *110*, 109980. https://doi.org/10.1016/J.JBIOMECH.2020.109980

Schilling, D. T., & Elazzazi, A. M. (2021). Shoulder Strength and Closed Kinetic Chain Upper Extremity Stability Test Performance in Division III Collegiate Baseball and Softball Players. *International Journal of Sports Physical Therapy*, *16*(3), 844. https://doi.org/10.26603/001C.24244

Schoenfeld, B. J., Contreras, B., Krieger, J., Grgic, J., Delcastillo, K., Belliard, R., & Alto, A. (2019). Resistance Training Volume Enhances Muscle Hypertrophy but Not Strength in Trained Men. *Medicine and Science in Sports and Exercise*, *51*(1), 94. https://doi.org/10.1249/MSS.0000000000001764

Seitz, L. B., Villarreal, E. S. D., & Haff, G. G. (2014). The temporal profile of postactivation potentiation is related to strength level. *Journal of Strength and Conditioning Research*, *28*(3), 706–715. https://doi.org/10.1519/JSC.0B013E3182A73EA3

Sharifmoradi, K., Karimi, M. T., & Hoseini, Y. (2021). Evaluation of the Asymmetry of Leg Muscles Forces in the Subjects with Anterior Cruciate Ligament Reconstruction. *Journal of Knee Surgery*, *34*(4), 357–362. https://doi.org/10.1055/S-0039-1695703/ID/JR190001OA-24/BIB

Sivokhin, H. I., Skotnikov, P. V., Professor Fedorov, A. A., Khlystov, P. M., & Kalashnikov, A. (2020). SIMULATION OF WEIGHTLIFTING TRAINING PROCESS. *Theory and Practice of Physical Culture*, *9*. https://cyberleninka.ru/article/n/simulation-of-weightlifting-training-process

Smajla, D., Knezevic, O. M., Mirkov, D. M., & Šarabon, N. (2020). Interlimb asymmetries and ipsilateral associations of plantar flexors and knee extensors rate-of-force development scaling factor. *Symmetry*, *12*(9). https://doi.org/10.3390/sym12091522

Smajla, D., Kozinc, Ž., & Šarabon, N. (2020). Elbow Extensors and Volar Flexors Strength Capacity and Its Relation to Shooting Performance in Basketball Players—A Pilot Study. *Applied Sciences 2020, Vol. 10, Page 8206*, *10*(22), 8206. https://doi.org/10.3390/APP10228206

Smajla, D., Spudić, D., & Šarabon, N. (2021). Influence of load and phase of contraction on lateral symmetries in flywheel squats. *Symmetry*, *13*(1), 1–14. https://doi.org/10.3390/SYM13010111

Smajla, D., Žitnik, J., & Šarabon, N. (2021). Advancements in the Protocol for Rate of Force Development/Relaxation Scaling Factor Evaluation. *Frontiers in Human Neuroscience*, *15*, 159. https://doi.org/10.3389/FNHUM.2021.654443/BIBTEX

Soria-Gila, M. A., Chirosa, I. J., Bautista, I. J., Baena, S., & Chirosa, L. J. (2015). Effects of variable resistance training on maximal strength: A meta-analysis. *Journal of Strength and Conditioning Research*, *29*(11), 3260–3270. https://doi.org/10.1519/JSC.0000000000000971

Spiteri, T., Cochrane, J. L., Hart, N. H., Haff, G. G., & Nimphius, S. (2013). Effect of strength on plant foot kinetics and kinematics during a change of direction task. *Https://Doi.Org/10.1080/17461391.2013.774053*, *13*(6), 646–652. https://doi.org/10.1080/17461391.2013.774053

Spiteri, T., & Nimphius, S. (2013). Relationship between timing variables and plant foot kinetics during change of direction movements. *Research Outputs 2013*. https://ro.ecu.edu.au/ecuworks2013/285

Spitz, R. W., Bell, Z. W., Wong, V., Yamada, Y., Song, J. S., Buckner, S. L., Abe, T., & Loenneke, J. P. (2020). Strength testing or strength training: considerations for future research. *Physiological Measurement*, *41*(9), 09TR01. https://doi.org/10.1088/1361-6579/ABB1FA

Staehli, S., Glatthorn, J. F., Casartelli, N., & Maffiuletti, N. A. (2010). Test–retest reliability of quadriceps muscle function outcomes in patients with knee osteoarthritis. *Journal of Electromyography and Kinesiology*, *20*(6), 1058–1065. https://doi.org/10.1016/J.JELEKIN.2010.07.006

Steindler, A. (1955). KINESIOLOGY OF THE HUMAN BODY under normal and pathological conditions. *The Journal of Bone & Joint Surgery British Volume*, *37-B*(4), 736–737. https://doi.org/10.1302/0301-620X.37B4.736

Stien, N., Vereide, V. A., Saeterbakken, A. H., Hermans, E., Shaw, M. P., & Andersen, V. (2021). Upper body rate of force development and maximal strength discriminates performance levels in sport climbing. *PLOS ONE*, *16*(3), e0249353. https://doi.org/10.1371/JOURNAL.PONE.0249353

Stone, M. H., Sands, W. A., Carlock, J., Callan, S., Dickie, D., Daigle, K., Cotton, J., Smith, S. L., & Hartman, M. (2004). The importance of isometric maximum strength and peak rate-of-force development in sprint cycling. *Journal of Strength and Conditioning Research*, *18*(4), 878–884. https://doi.org/10.1519/14874.1

Suchomel, T. J., Nimphius, S., Bellon, C. R., Hornsby, W. G., & Stone, M. H. (2021). Training for Muscular Strength: Methods for Monitoring and Adjusting Training Intensity. *Sports Medicine 2021 51:10*, *51*(10), 2051–2066. https://doi.org/10.1007/S40279-021-01488-9

Suchomel, T. J., Sato, K., Deweese, B. H., Ebben, W. P., & Stone, M. H. (2016). Potentiation following ballistic and nonballistic complexes: The effect of strength level. *Journal of Strength and Conditioning Research*, *30*(7), 1825–1833. https://doi.org/10.1519/JSC.0000000000001288

Suchomel, T. J., & Sole, C. J. (2017). Force-Time–Curve Comparison Between Weight-Lifting Derivatives. *International Journal of Sports Physiology and Performance*, *12*(4), 431–439. https://doi.org/10.1123/IJSPP.2016-0147

Suchomel, T. J., & Stone, M. H. (2017). The Relationships between Hip and Knee Extensor Cross-Sectional Area, Strength, Power, and Potentiation Characteristics. *Sports 2017, Vol. 5, Page 66*, *5*(3), 66. https://doi.org/10.3390/SPORTS5030066

Sullivan, G. M., & Feinn, R. (2012). Using Effect Size—or Why the P Value Is Not Enough. *Journal of Graduate Medical Education*, *4*(3), 279. https://doi.org/10.4300/JGME-D-12-00156.1

Taber, C., Bellon, C., Abbott, H., & Bingham, G. E. (2016). Roles of maximal strength and rate of force development in maximizing muscular power. *Strength and Conditioning Journal*, *38*(1), 71–78. https://doi.org/10.1519/SSC.0000000000000193

Thomas, C., Jones, P. A., Rothwell, J., Chiang, C. Y., & Comfort, P. (2015). An Investigation Into the Relationship Between Maximum Isometric Strength and Vertical Jump Performance. *Journal of Strength and Conditioning Research*, *29*(8), 2176–2185. https://doi.org/10.1519/JSC.0000000000000866

Tomlinson, D. J., Erskine, R. M., Morse, C. I., Winwood, K., & Onambélé-Pearson, G. (2016). The impact of obesity on skeletal muscle strength and structure through adolescence to old age. *Biogerontology*, *17*(3), 467–483. https://doi.org/10.1007/S10522-015-9626-4/FIGURES/2

Turgut, E., Pedersen, Ø., Duzgun, I., & Baltaci, G. (2016). Three-dimensional scapular kinematics during open and closed kinetic chain movements in asymptomatic and symptomatic subjects. *Journal of Biomechanics*, *49*(13), 2770–2777. https://doi.org/10.1016/J.JBIOMECH.2016.06.015

Uygur, M., de Freitas, P. B., & Barone, D. A. (2020). Rate of force development and relaxation scaling factors are highly sensitive to detect upper extremity motor impairments in multiple sclerosis. *Journal of the Neurological Sciences*, *408*. https://doi.org/10.1016/j.jns.2019.116500

Van Cutsem, M., & Duchateau, J. (2005). Preceding muscle activity influences motor unit discharge and rate of torque development during ballistic contractions in humans. *Journal of Physiology*, *562*(2), 635–644. https://doi.org/10.1113/jphysiol.2004.074567

Van Cutsem, M., Duchateau, J., & Hainaut, K. (1998). Changes in single motor unit behaviour contribute to the increase in contraction speed after dynamic training in humans. *Journal of Physiology*, *513*(1), 295–305. https://doi.org/10.1111/j.1469-7793.1998.295by.x

van der Kruk, E., van der Helm, F. C. T., Veeger, H. E. J., & Schwab, A. L. (2018). Power in sports: A literature review on the application, assumptions, and terminology of mechanical power in sport research. *Journal of Biomechanics*, *79*, 1–14. https://doi.org/10.1016/J.JBIOMECH.2018.08.031

Van Der Woude, D. R., Ruyten, T., & Bartels, B. (2022). Reliability of Muscle Strength and Muscle Power Assessments Using Isokinetic Dynamometry in Neuromuscular Diseases: A Systematic Review. *Physical Therapy*, *102*(10), 1–9. https://doi.org/10.1093/PTJ/PZAC099

Van Melick, N., Van Cingel, R. E. H., Brooijmans, F., Neeter, C., Van Tienen, T., Hullegie, W., & Nijhuis-Van Der Sanden, M. W. G. (2016). Evidence-based clinical practice update: practice guidelines for anterior cruciate ligament rehabilitation based on a systematic review and multidisciplinary consensus. *British Journal of Sports Medicine*, *50*(24), 1506–1515. https://doi.org/10.1136/BJSPORTS-2015-095898

Vecchio, A. Del, Falla, D., Felici, F., & Farina, D. (2019). The relative strength of common synaptic input to motor neurons is not a determinant of the maximal rate of force development in humans. *Journal of Applied Physiology*, *127*(1), 205–214. https://doi.org/10.1152/JAPPLPHYSIOL.00139.2019/ASSET/IMAGES/LARGE/ZDG0071930720008.JPEG

Vesga-Castro, C., Aldazabal, J., Vallejo-Illarramendi, A., & Paredes, J. (2022). Contractile force assessment methods for in vitro skeletal muscle tissues. *ELife*, *11*. https://doi.org/10.7554/ELIFE.77204

Vidmar, M. F., Baroni, B. M., Michelin, A. F., Mezzomo, M., Lugokenski, R., Pimentel, G. L., & Silva, M. F. (2020). Isokinetic eccentric training is more effective than constant load eccentric training for quadriceps rehabilitation following anterior cruciate ligament reconstruction: a randomized controlled trial. *Brazilian Journal of Physical Therapy*, *24*(5), 424–432. https://doi.org/10.1016/J.BJPT.2019.07.003

Wallace, B., & Janz, J. (2009). Implications of Motor Unit Activity on Ballistic Movement. *International Journal of Sports Science & Coaching*, *4*(2), 285–292. https://doi.org/10.1260/174795409788549490

Wang, E., Nyberg, S. K., Hoff, J., Zhao, J., Leivseth, G., Tørhaug, T., Husby, O. S., Helgerud, J., & Richardson, R. S. (2017). Impact of maximal strength training on work efficiency and muscle fiber type in the elderly: Implications for physical function and fall prevention. *Experimental Gerontology*, *91*, 64–71. https://doi.org/10.1016/J.EXGER.2017.02.071

Wang, R., Hoffman, J. R., Tanigawa, S., Miramonti, A. A., La Monica, M. B., Beyer, K. S., Church, D. D., Fukuda, D. H., & Stout, J. R. (2016). Isometric Mid-Thigh Pull Correlates with Strength, Sprint, and Agility Performance in Collegiate Rugby Union Players. *Journal of Strength and Conditioning Research*, *30*(11), 3051–3056. https://doi.org/10.1519/JSC.0000000000001416

Warren, M., Ganley, K. J., & Pohl, P. S. (2016). The association between social participation and lower extremity muscle strength, balance, and gait speed in US adults. *Preventive Medicine Reports*, *4*, 142–147. https://doi.org/10.1016/J.PMEDR.2016.06.005

Weakley, J., Mann, B., Banyard, H., McLaren, S., Scott, T., & Garcia-Ramos, A. (2021). Velocity-based training: From theory to application. *Strength and Conditioning Journal*, *43*(2), 31–49. https://doi.org/10.1519/SSC.0000000000000560

Wierzbicka, M. M., Wiegner, A. W., Logigian, E. L., & Young, R. R. (1991). Abnormal most-rapid isometric contractions in patients with Parkinson's disease. *Journal of Neurology Neurosurgery and Psychiatry*, *54*(3), 210–216. https://doi.org/10.1136/jnnp.54.3.210

Wulf, G., Shea, C., & Lewthwaite, R. (2010). Motor skill learning and performance: a review of influential factors. *Medical Education*, *44*(1), 75–84. https://doi.org/10.1111/J.1365-2923.2009.03421.X

Xaverova, Z., Dirnberger, J., Lehnert, M., Belka, J., Wagner, H., & Orechovska, K. (2015). Isokinetic strength profile of elite female handball players. *Journal of Human Kinetics*, *49*(1), 257–266. https://doi.org/10.1515/HUKIN-2015-0128

Yi, W., Wang, D., Chen, C., & Wu, R. (2022). Acute effects of ballistic and non-ballistic conditioning activities on the punching impact of amateur boxers. *Https://Doi.Org/10.1177/17479541221119390*. https://doi.org/10.1177/17479541221119390

Zampieri, S., Mosole, S., Löfler, S., Fruhmann, H., Burggraf, S., Cvečka, J., Hamar, D., Sedliak, M., Tirptakova, V., Šarabon, N., Mayr, W., & Kern, H. (2015). Physical Exercise in Aging: Nine Weeks of Leg Press or Electrical Stimulation Training in 70 Years Old Sedentary Elderly People. *European Journal of Translational Myology*, *25*(4), 237. https://doi.org/10.4081/EJTM.2015.5374

Zouita, S., Zouita, A. B. M., Kebsi, W., Dupont, G., Ben Abderrahman, A., Ben Salah, F. Z., & Zouhal, H. (2016). Strength training reduces injury rate in elite young soccer players during one season. *Journal of Strength and Conditioning Research*, *30*(5), 1295–1307. https://doi.org/10.1519/JSC.0000000000000920

Supplementary document 1. Ethics committee approval

UNIVERZITET U BEOGRADU
FAKULTET SPORTA I FIZIČKOG VASPITANJA
- ETIČKI KOMITET

УНИВЕРЗИТЕТ У БЕОГРАДУ
ФАКУЛТЕТ СПОРТА И ФИЗИЧКОГ ВАСПИТАЊА
02 - 1854/21-2
14-07-2021 год.
БЕОГРАД Благоја Паровића 156

Predmet: Na zahtev zaveden pod brojem 02-1854/21-1 od 30.06.2021. koji je podneo Života Stefanović kao studenti doktorskih studija, Etički komitet Fakulteta sporta i fizičkog vaspitanja Univerziteta u Beogradu daje

S A G L A S N O S T

Za realizaciju istraživanja pod nazivom " **Procena brzine neuromišićnog odgovora – optimizacija testa i ispitivanje njegove osetljivosti**", koji realizuje grupa istraživača: Života Stefanović, dr Olivera Knežević, dr Slađan Milanović, Suzana Blesić, Iva Prćić i dr Dragan Mirkov .

O b r a z l o ž e n j e

Na osnovu uvida u nacrt istraživanja koje se realizuje pod nazivom nazivom " **Procena brzine neuromišićnog odgovora – optimizacija testa i ispitivanje njegove osetljivosti**", koji realizuje grupa istraživača: Života Stefanović, dr Olivera Knežević, dr Slađan Milanović, Suzana Blesić, Iva Prćić i dr Dragan Mirkov, Etički komitet iznosi mišljenje da se, kako u konceptu tako i u planiranju realizacije istraživanja i primene dobijenih rezultata, polazilo od principa koji su u skladu sa etičkim standardima, čime se obezbeđuje zaštita ispitanika od mogućih povreda njihove psihosocijalne i fizičke dobrobiti.

U skladu sa iznetim mišljenjem Etički komitet Fakulteta daje saglasnost za realizaciju planiranog istraživanja.

Za etički komitet

Članovi

1. prof. dr Dušan Mitić ____________
2. prof. dr Marina Đorđević-Nikić ____________
3. prof. dr Ana Orlić ____________

Supplementary document 2. Online accepted version of the paper

symmetry

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Article

Evaluation of the Reduced Protocol for the Assessment of Rate of Force Development Scaling Factor

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Abstract: The rate of force development scaling factor (RFD-SF) has been used to assess neuromuscular quickness. However, the common protocols are lengthy. This study evaluated the validity and reliability of the reduced protocol to assess the RFD-SF and its validity in detecting inter-limb asymmetries. Eighteen participants (five females and thirteen males; mean age = 20.8 ± 0.6 years) performed the common and reduced RFD-SF protocols (five isometric pulse knee extensions at 30 and 70% of maximal voluntary contraction). A repeat measure design was employed including one test session of the common protocol and two test sessions of the reduced protocol. Correlation analysis was conducted to investigate the association between the two protocols, while a paired-sample *t*-test and a Bland–Altman plot assessed whether the reduced protocol provided valid results. The between-day reliability was assessed using an intra-class correlation coefficient, coefficient of variation, typical error of measurement, and paired-sample *t*-test. The validity to detect asymmetries was checked with the paired-sample *t*-test. The correlation between RFD-SF obtained using two protocols was significant ($p < 0.001$) and very large for the dominant (r = 0.71) and non-dominant (r = 0.80) legs. No significant difference occurred between protocols in the RFD-SF for the dominant ($p = 0.480$, d = 0.17) and non-dominant legs ($p = 0.213$, d = 0.31). The reliability was acceptable for both legs, with no between-day difference for the dominant ($p = 0.393$) and non-dominant legs ($p = 0.436$). No significant difference between the two protocols ($p = 0.415$, d = 0.19) was found in the detection of inter-limb asymmetries. The results of this study suggest that the reduced protocol could be used as a valid and reliable alternative to the common protocol, as well as to identify interlimb asymmetries.

Keywords: neuromuscular quickness; protocol; asymmetries

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1. Introduction

The ability to voluntarily activate muscles and generate forces allows humans to move and execute various movement tasks of different intensities and complexities [1,2], whereby the quality of movement strongly depends on one's neuromuscular characteristics [3]. Thus, an assessment of neuromuscular characteristics is important for a general understanding of the design and function of the muscular system and the routine testing of muscular functions [1]. Neuromuscular quickness refers to the ability of the nervous system to rapidly activate and coordinate muscle contractions in response to stimuli, while influencing factors include the speed of nerve impulses, muscle responsiveness, and strength and coordination between muscle groups [4].

Neuromuscular quickness depends on the inter- and intra-muscular motor unit firing rates across different contraction intensities [5]. Therefore, they could be an indicator of not only some neuromuscular characteristics (i.e., maximal muscle force (Fmax) and rate

Biography

Born on 1st of March in 1996 in Priština, Serbia. In 1999 he moves to Danilovgrad, Montenegro where he finished elementary school “Vuko Jovović” and one of the top secondary schools in country, Gymnasium “Petar I Petrović Njegoš”. In both schools he won prestigious “Luča“ award, given to students who finish their education with an excellent average grade. After finishing secondary school, he moves to Serbia, and starts studying at the “Faculty of sports and physical education, Leposavić, University of Priština”. He finished his Bachelor studies in the year 2018, and a year later Master studies with the highest grades in generation (average grade: 9.91 and 10). During his Bachelor and Master studies, he worked on the mentioned faculty for a year as a demonstrator on the subject “Basics of anthropomotorics”. He also received prestigious “Vidovdan” award, given to the best students of the university. He was awarded with grant of the Ministry of Education, Science and Technological Development, given to the students with the average grade higher of 9.0 in the country. For two years he was awarded with the prestigious grant of “Dositeja – Fund for Young Talents”, given to only 500 best students in the country. In the 2019/20 school year he enrolled into doctoral programme on “Faculty of Sport and Physical Education – University of Belgrade”. Currently he is working as a research associate on the mentioned faculty on the project financed by Ministry of Science, Education and Technological Development of Republic of Serbia called “Muscle and neural factors of human movement and their adaptive changes” (#175037). He is an author of more than 10 papers published in scientific journals as well as publications on scientific conferences.

Изјава о ауторству

Име и презиме аутора: Живота Стефановић

Број индекса: 5003/2019

Изјављујем

да је докторска дисертација под насловом

Neuromuscular quickness assessment – test optimization and sensitivity evaluation (Procena brzine neuromišićnog odgovora – optimizacija testa i ispitivanje njegove osetljivosti)

- резултат сопственог истраживачког рада;
- да дисертација у целини ни у деловима није била предложена за стицање друге дипломе према студијским програмима других високошколских установа;
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Изјава о истоветности штампане и електронске верзије докторског рада

Име и презиме аутора: Живота Стефановић

Број индекса: 5003/2019

Студијски програм: Експерименталне методе изучавања хумане локомоције

Наслов рада: Neuromuscular quickness assessment – test optimization and sensitivity evaluation (Procena brzine neuromišićnog odgovora – optimizacija testa i ispitivanje njegove osetljivosti)

Ментор: Редовни проф. др Драган Мирков

Изјављујем да је штампана верзија мог докторског рада истоветна електронској верзији коју сам предао/ла ради похрањена у **Дигиталном репозиторијуму Универзитета у Београду.**

Дозвољавам да се објаве моји лични подаци везани за добијање академског назива доктора наука, као што су име и презиме, година и место рођења и датум одбране рада.

Ови лични подаци могу се објавити на мрежним страницама дигиталне библиотеке, у електронском каталогу и у публикацијама Универзитета у Београду.

У Београду, ________________________

Потпис аутора

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Изјава о коришћењу

Овлашћујем Универзитетску библиотеку „Светозар Марковић“ да у Дигитални репозиторијум Универзитета у Београду унесе моју докторску дисертацију под насловом:

Neuromuscular quickness assessment – test optimization and sensitivity evaluation (Procena brzine neuromišićnog odgovora – optimizacija testa i ispitivanje njegove osetljivosti)

која је моје ауторско дело.

Дисертацију са свим прилозима предао/ла сам у електронском формату погодном за трајно архивирање.

Моју докторску дисертацију похрањену у Дигиталном репозиторијуму Универзитета у Београду и доступну у отвореном приступу могу да користе сви који поштују одредбе садржане у одабраном типу лиценце Креативне заједнице (Creative Commons) за коју сам се одлучио/ла.

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(Молимо да заокружите само једну од шест понуђених лиценци.

Кратак опис лиценци је саставни део ове изјаве).

У Београду, ________________________

Потпис аутора

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