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MECHANICAL CAPACITIES OF THE DIFFERENT MUSCLE GROUPS ASSESSED USING "TWO-VELOCITY" METHOD

Doctoral Dissertation

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PROCENA MEHANIČKIH SVOJSTAVA RAZLIČITIH MIŠIĆNIH GRUPA PRIMENOM METODE „DVE BRZINE”

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The present thesis could not be possible without my close collaborators, friends and family members. I will be always eternally grateful for your help, and I would like to personally thank to…

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Procena mehaničkih svojstava različitih mišićnih grupa primenom metode „dve brzine”

Rezime

Iako su široko prisutni u sportu i rehabilitaciji, rezultati izokinetičkih protokola ne mogu da diskriminišu između različitih maksimalnih mehaničkih mišićnih kapaciteta (maksimalne sile [F_0], maksimalne brzine [V_0]), maksimalne snage [P_{max}] i nagiba relacije sila-brzina [a]). Relacija sila-brzina modelovana korišćenjem samo dve eksperimentalne tačke (metod „dve tačke”) je predložena za istovremenu procenu svih pomenutih kapaciteta. Međutim, mogućnost korišćenja ovog metoda tokom izokinetičkog testiranja nije dovoljno istražena. Stoga, sprovedene su dve studije sa ciljem da se ispitaju validnost i osetljivost metode „dve tačke”. Za potrebe prve studije su izmerene sile ekstenzora i fleksora koje deluju u zglobu kolena i lakta na uzorku od 22 ispitanika, koristeći osam ugaonih brzina (30-240°/s), dok su za potrebe druge studije izmerene sile mišića koje deluju kao ekstenzori i fleksori u zglobu kolena, kuka, lakta i ramena na uzorku od 40 ispitanika, koristeći dve ugaone brzine (60 and 180°/s). Rezultati su pokazali da je relacija sila-brzina snažna i linearna (svi $r \geq 0.969$), da je validnost modela da proceni maksimalnu mišićnu silu visoka, ali niža za ostale parametre relacije (medijana $r = F_0 = 0.96$; $V_0 = 0.71$; $a = 0.78$; i $P_{max} = 0.78$). Osetljivost metode „dve tačke” je visoka za mišiće koji deluju u zglobu kolena, umerena za mišiće koji deluju u zglobu kuka i ramena i niska za mišiće koji deluju u zglobu lakta. Povezanost između istih parametara relacije sila-brzina je u proseku bila niska do umerena u obe studije. Generalno, rezultati podržavaju korišćenje metode „dve tačke” kao validne i osetljive metode za procenu maksimalnih kapaciteta različitih mišićnih grupa da generišu silu, dok je za dobijanje kompletne slike o mišićnoj funciji ispitanika potrebno testirati veći broj mišićnih grupa.

Ključne reči: Relacija sila-brzina, izokinetička dinamometrija, testiranje, rehabilitacija, sport

Naučna oblast: Fizičko vaspitanje i sport

Uža naučna oblast: Nauke fizičkog vaspitanja, sporta i rekreacije

UDK broj: 796.012.1:612.74(043.3)

Mechanical capacities of the different muscle groups assessed using "two-velocity" method

Resume

Although widely applied in sport and rehabilitation, individual isokinetic testing protocols are ineffective to discern between maximal mechanical capacities of the muscles (i.e., maximal force [F_0], maximal velocity [V_0]), maximal power [P_{max}] and force-velocity slope [a]). Force-velocity [F-V] relationship modelled using just two distinctive experimental points ("two-velocity" method) has been proposed for determining these capacities at once. However, its application during isokinetic testing is not well explored. Therefore, two studies were conducted with an aim to validate the two-velocity method and to explore its sensitivity. For the first study knee and elbow flexors and extensors of the 22 participants were tested implementing eight angular velocities (30-240º/s), while for the second study, force of flexosr and extensors acting on the knee, hip, elbow and shoulder of the 40 men were recorded at two angular velocities (60 and 180°/s). Results show that the F-V relationships were linear and strong (all $r \geq 0.969$), validity of F_0 was high but lower for the other F-V relationship parameters (median r: $F_0 = 0.96$; $V_0 = 0.71$; $a = 0.78$; and $P_{max} = 0.78$). Sensitivity of the two-velocity method was high for the knee, moderate for the hip and shoulder, and low for the muscles that act in the elbow joint. Association between the same F-V relationship parameters was generally poor to moderate in both studies. Generally, findings support the two-velocity method as a valid and sensitive procedure for determining the maximal capacity of the selected muscles to produce F_0, while more muscles should be tested to comprehensively evaluate the participants' muscular function.

Keywords: F-V relationship, isokinetic dynamometry, testing, rehabilitation, sport

Scientific field: Physical Education and Sport

Scientific subfield: Science of Physical Education, Sports and Recreation

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Table of Content:

Abbreviations:

a, slope of the force-velocity relationship
ANOVA, analysis of variance
EE, elbow extension
EF, elbow flexion
ES, effect size
F_0, maximal theoretical force
F-V, force-velocity
HE, hip extension
HF, hip flexion
KE, knee extension
KF, knee flexion
P_{max}, maximal theoretical power
r, Pearson's correlation coefficient
SD, standard deviation
SE, shoulder extension
SF, shoulder flexion
T, torque
V_0, maximal theoretical velocity
ω, angular velocity

1. Introduction

Human muscles are composed from muscle fibres which have very complex structure. Specifically, muscle fibres are merged into groups that are covered with connective tissue (Rothwell & Rothwell, 1994). The movement is enabled by muscle proteins that slide past each other (Squire, 2016), which enables muscle shortening and force production. Muscle function depends from the activation of different mechanical, physiological and neural processes which are necessary for executing any type of movement. Although these processes are interdependent, they are generally explored separately due to their high complexity. From all mentioned processes (i.e., mechanical, physiological and neural) the scope of this dissertation mainly involves mechanical capacities of the muscles and corresponding mechanisms which both enable and limit human performance. The term mechanical capacities refers to the muscle capabilities to generate force (F), velocity (V) and power (P).

Maximal force and power production depend on variety of factors, among which are: biochemical, histological, biological, anatomical, etc. (Pincivero, Coelho, & Campy, 2004). More specifically, those factors are: (1) length and diameter of muscle fibres; (2) muscle structure; (3) fibre types; (4) number of cross-bridges; (5) developed force in every cross-bridge; (6) force-velocity (F-V) relationship; (7) shortening velocity of muscle fibres etc. (Fitts, McDonald, & Schluter, 1991). The ability to produce force influence power production in a quite extent. In this regard, strong correlations between maximal force production and power variables (i.e., maximal values of rate of force development and power) indicate the importance of strength development (i.e., ability to produce force) (Stone, Moir, Glaister, & Sanders, 2002).

Generally, the capacity of the muscles to produce velocity depends of the muscle fibre structure. The most important factor to delineate muscle fibre types are particular myosin profiles. Specifically, from 11 known myosin isoforms, muscle fibres could contain single myosin heavy chain isoform (“pure fibre types”) or two or more (“hybrid fibre types”) (Pette & Staron, 2000). Even though relatively permanent, muscle fibres are known as the structures which are capable to modify their phenotype under specific circumstances (e.g. mechanical loading or unloading, aging, increasing or decreasing neuromuscular activity, etc.) (Pette & Staron, 2000). Consequently, implementing different exercise regimes could lead to shortening velocity changes due to the muscle fibre transitions. Besides muscle fibre structure, variety of mechanical factors influence shortening velocity (i.e., range of motion, pre-stretch, etc.) (Bober, Putnam, & Woodworth, 1987). However, little information exists regarding systematic classification of the all possible mechanisms which could influence shortening velocity of the muscles.

The power depends both on the capacity of the muscles to produce force and velocity (i.e., it represents the product of velocity and force) (Lindstedt, 2016). As a result of the direct dependency from the force and velocity capabilities, power capability could be increased by increasing only force, while keeping velocity at the same level, by incrementing velocity and keeping force output at the same level, or by simultaneously increasing both force and velocity output. Since all muscle fibres can develop equal isometric force per cross-sectional unit (Lindstedt, 2016), from a force standpoint power output could be increased by incrementing cross sectional unit. On the other hand, power output could be incremented by increasing velocity capability (i.e., inducing alterations of fibre types).

Assessing force, velocity and power capabilities is extremely important for the sports, recreation and rehabilitation purposes. Specifically, different types of standardised tests are being used in order to evaluate different physiological and biomechanical characteristics of muscles, to set norms for various individuals, for sport selection, assessing effects of different training and rehabilitation procedures, preventing injuries, etc. (Knežević & Mirkov, 2011; Wilson & Murphy, 1996). Methods for assessing those capacities are diverse and can be divided into field (usually indirect) and laboratory (usually direct) methods. The results of field or indirect methods are used for concluding (i.e., predicting) about muscle capabilities, while laboratory or direct methods are used for measuring some mechanical quantity which enables more precise assessment of the muscle mechanical capacities.

For example, direct methods for measuring force output could be done during different contraction modes (i.e., isometric, isoinertial or isokinetic) (Abernethy, Wilson, & Logan, 1995). As it has been stated in the paper of Knezevic and Mirkov (2011) „the isometric strength assessment is based on a measurement of maximal force (Fmax) exerted during maximal voluntary contraction (i.e., against external load), in a specific joint angle, while the isoinertial strength assessment involves exertion of concentric, eccentric or concentric/eccentric contractions against constant external load". Isokinetic mode is based on measuring force output during constant velocity with the specific equipment (i.e., isokinetic dynamometers).

In the scope of this dissertation is isokinetic dynamometry, a method which represents the gold standard for evaluating muscle capacities during single-joint movements. As a method, it has been widely used for decades (Hislop & Perrine, 1967), which has led to the development of a variety of testing protocols and procedures. Note that isokinetic dynamometry has been considered as a safe, objective and reliable method (Land & Gordon, 2011; Mayhew, Rothstein, Finucane, & Lamb, 1994). The general aim of current dissertation is to assess validity and sensitivity of the two-velocity method (discussed later in the text), which could be developed and implemented during routine testing procedures for comprehensive analysis of the single-joint muscle function.

2. Muscle mechanical capacities

2.1. Strength

In biomechanics, there are two types of forces, those that act within body (e.g. transmitting force from tendon to bone) and outside of the body (e.g. interaction of the subject with the environment) (Zatsiorsky & Kraemer, 2006). People cannot directly influence the magnitude of the forces which are acting inside of our bodies and, therefore, the term force will reflect only forces that are acting outside of our bodies. Instead of force, the appropriate term for naming muscle capacity is strength. Muscle strength refers to the capability of the muscles to develop high forces in isometric conditions (i.e., when there is no movement) or to develop high forces during slow movement velocities. Developing muscle force is related with the increments in the cross sectional area, muscle length, changes of the muscle length (and shortening velocity), etc. (Kukolj, 2006).

The force that a muscle can produce increases in parallel with its cross sectional area (Bruce, Phillips, & Woledge, 1997). This relationship between muscle strength (i.e., exerted force) and cross-sectional area is positive and high. In addition, level of the developed force is directly related with the time available for muscle contraction. This can be explained by the well-known fact that specific time is needed both for attaching and detaching of actin and myosin chains (Cormie, McGuigan, & Newton, 2011). Relationship which describes association between force and available time is so called force-time relationship. Maximal forces are developed during isometric contractions, while the capacity to generate maximal force decreases with increment of the velocity of the movement (Hill, 1938). In order to achieve maximal force 3-5 seconds are needed (Abernethy et al., 1995). What needs to be noted is that resistance and magnitude of the exerted force are proportional, so when the external resistance increases so does the muscle force.

The magnitude of force achieved during some activity can be described using absolute or/and relative indicators. More specifically, absolute force refers to the maximal load lifted, or force applied (in kg or N) without considering weight of the subject. On the other hand, relative force is described as force developed per kg of the subject's weight (kg/kg, N/kg). In fact, Jaric (2002) has shown that the association between developed force and body weight is non-linear and suggested using alometric scale for this purpose (N/kg$^{\wedge 2/3}$).

2.2. Velocity

High velocity of the movement is the main prerequisite for successful performance in many sports. Factors that are influencing velocity of the multi-joint movements are: (1) muscle structure (i.e., percent of slow and fast twitched fibers of the muscles involved in the movement), (2) age, (3) force and power capacities, (4) level of sports technique (Nešić, 2002). As a multi-joint characteristic, velocity is defined as ability to perform movement(s) as quickly as possible, while external resistance is not big, activity of the movement is not coordinative demanding and activity does not last long. More, it can be divided into speed of the reaction time, velocity of the single movement and frequency of the movement (Kukolj, 2006). Depending of the sport discipline, most important type of speed can and should be developed during specific trainings.

Heterogeneous muscle structure is undoubtable one of the crucial factors that affect velocity of the movement. Different muscle fibre types that make muscle structure heterogeneous are tightly connected with the velocity capacity of the individual muscles, and thus velocity capacity of the multi-joint movements. To date, 4 different "pure" muscle fibre types are known, with specific abilities to produce maximal velocity. Specifically, lowest maximal velocity of shortening can be achieved in type I fibres, type IIB are the fastest, while IIA and IID types display comparable values, but lower than IIB (Pette & Staron, 2000). These "pure" muscle fibre types are composed of single myosin heavy chain isoform. Additionally, few "hybrid" fibre types are known (i.e., composed of two or more myosin heavy chain isoforms) making the muscle tissue even more heterogeneous (Pette & Staron, 2000). It has been suggested that muscles can be shortened with a speed of 3 length per second (Jarić, 1997), depending of the muscle structure, while most of the single-joint movements are faster than 200 °/s (Pereira & Gomes, 2003).

Shortening velocity is a muscle capacity which is predominantly influenced by genetics, which means that it can be slightly improved with training (Kukolj, 2006). Even though relatively persistent, muscle fibres are structures that are capable of changing their phenotype under specific circumstances (e.g. training). Thus, implementing different training regimes might increase shortening velocity due to the muscle fibre transitions. For years, it was generally accepted that for improving specific sport performance, exercises during training should be performed at a specific velocity. Opposite to this, Cronin et al. (2002) indicated that increasing muscle capabilities such as strength, rate of force development and power would lead to better improvements in sport performance in comparison to training at a specific velocity.

2.3. Power

Power can be described as the capability of the muscles to generate force rapidly (Lima & Rodrigues de Paula, 2012). Power should be considered as the "product of velocity and force of the movement" (Kukolj, 2006). Based on this, it can be concluded that if the aim is to increase power, force or/and velocity should be increased. More, power output is zero when the force is zero and/or shortening velocity is zero, while during multi-joint movements it reaches a maximum at an intermediate force (i.e., one half of the maximal force) and associated velocity (Josephson, 1993). Maximal power depends on several factors (described below) which are interdependent:

Mechanical factors

Mechanical factors upon which maximal power capacity of the muscle depends on are numerous, while some of the most important are: time available to exert force, velocity of the movement and type of the muscle contraction (Cormie et al., 2011). Peak power is influenced by the F-V relationship in a way that it is maximised around $^1/_3$ of the maximal velocity during single-joint, and around $^1/_2$ during multi-joint movement (Jarić, 1997). In addition, power depends on time available to attach cross bridges, while it is higher during eccentric-concentric (stretch shortening cycle) in comparison to power which could be developed in pure concentric-only movement (Cormie et al., 2011). More, during stretching of the muscle-tendon complex potential energy is saved in tendons, cross bridges and aponeurosis, which could be used in next contractions (Cormie et al., 2011).

Morphological and neural factors

Percent of slow and fast twitch fibres is the main morphological factor which influences power. A person with more fast twitch fibres will demonstrate an improved capacity to produce muscle power

(Cormie et al., 2011; Wilmore & Costill, 1994). Indirectly, power depends on muscle length, and physiological cross-sectional area. Neural factors which are influencing muscle power are “firing frequency, motor unit recruitment, synchronisation and inter-muscular coordination” (Cormie et al., 2011).

3. The assessment of muscle mechanical capacities

Testing muscle capabilities is widely applied in sport (Singh, Chengappa, & Banerjee, 2002), recreation (Gissis et al., 2006) and rehabilitation (Bohannon, 2001). Results of these tests can reveal current state of the muscle system, while same result should be used with precaution for predicting sport results (Singh et al., 2002). Testing can be performed in laboratory or in field conditions. As it is well known, laboratory testing allows obtaining more precise information, with a higher internal validity, while field tests are more ecologically valid. Particular tests are conducted to assess mainly one motor capability. However, it is generally thought that strength, power and velocity are inter-related to some extent.

3.1. Strength assessment

Strength can be assessed using direct and indirect methods. Direct methods are the one that provide real force mechanical output, using dynamometers. Formulas that are used for indirect estimation of the force are "based on the assumption that number of repetitions against loads lighter than a maximal (i.e., some % of the *one repetition maximum* [1RM]) does not change under training" (Knežević & Mirkov, 2011). In the next two paragraphs, isometric test will be described (as a representative of direct, laboratory testing methodology) as well as 1RM testing procedure (which represents indirect, field force assessment methodology).

So, as it has been emphasized previously, one group of testing procedure consists of tests during which muscles act against static resistance (i.e., isometric dynamometry). Capability that has been assessed in this manner is sometimes called static strength, and represents capacity to produce force or torque (T) under maximal volitional isometric conditions (Caldwell et al., 1974). Test usually lasts 3-5 seconds (Caldwell et al., 1974). Even though it has evident internal validity, reliability and sensitivity, the ecological validity is low due to the fact that this kind of movements are extremely rare in everyday life (Nedeljkovic, 2016).

The other testing procedure consists of tests during slow velocity of the movements, and the most common type of it is 1RM test. 1RM type of test pertains to group of the tests which are known as isoinertial dynamometry (i.e., resistance is constant). As the name says, this testing protocol requires performing one repetition with the resistance which can be lifted only once. Velocity of the movement during this kind of tests is different for different movements/exercises (García-Ramos, Pestaña-Melero, Pérez-Castilla, Rojas, & Haff, 2018). As it has been shown, irrespective of the sex or muscle group, 1RM testing protocol is a reliable method for assessing muscle strength capacities as long as it is performed after familiarisation period and short warm-up (Seo et al., 2012). Ecological validity of this kind of testing procedure is higher in comparison to isometric testing, as the muscles act both in eccentric and concentric conditions, which is common to regular activities such as walking, running, jumping, etc.

3.2. Velocity assessment

Regarding sport performance velocity assessment can be carried out with a goal to discover maximal velocity capacity. What is important to emphasize when assessing maximal velocity is that some basic prerequisite needs to be fulfilled. Namely, test should be conducted in a way that the movement is simple, resistance minimal and that activity does not last long. Tests for assessing maximal velocity capacity can be divided into 3 different groups (1) tests for reaction time: different kind of movements performed from a variety of starting positions (on audio or visual, predetermined or unexpected signal), (2) speed of the single movement: different kind of throwing, jumps, short maximal accelerations, etc., and (3) frequency of the movement: hand tapping, running, etc. (i.e., selection of the test depends on specific sports activity) (Kukolj, 2006).

Besides revealing maximal velocity capacity, velocity assessment could be used for controlling intensity during resistance training. For instance, velocity assessment gain massive popularity as it has been reported that during typical resistance exercise in isoinertial conditions (i.e., assuming that repetitions are performed with maximal volitional effort) velocity decreases as fatigue increases (González-Badillo, Marques, & Sánchez-Medina, 2011). Prescribing and controlling exercise intensity based on the measured velocity is well known as *velocity-based training.* According to García-Ramos et al., (2019) "velocity-based training requires the measurement of velocity in real-time and provides at least three important practical applications: (I) load can be adjusted on a daily basis to match the desired intensity (commonly expressed as a percentage of the 1RM) due to the strong relationship between movement velocity and the load lifted (González-Badillo & Sánchez-Medina, 2010), (II) the volume of the training session (e.g., the number of exercises per session, sets per exercise or repetitions per set) can be prescribed based off the magnitude of velocity loss due to its close relationship with markers of fatigue, and (III) the administration of real-time velocity feedback improves motivation and enables the maintenance of higher movement velocities during resistance training".

3.3. Power assessment

As it was previously mentioned power is maximised when the muscles are acting against optimal load, and the intention to perform the movement is as fast as possible. Generally, optimal load for power production (i.e., and consequently power assessment) depends from exercise and type of the sport in which athlete is involved, and it is usually defined as a percentage of 1RM. For example, "power output is maximised at 0% of 1RM in the jump squat, 56% of 1RM in the squat, and 80% of 1RM in the power clean for strength and power athletes" (Cormie, McBride, & McCaulley, 2007). Most common tests for power assessment are: Wingate test (30 sec) on bicycle ergometer, different types of jumps (i.e., 30-kg jump squat, countermovement, and drop jumps (Cronin & Hansen, 2005)), and throws (ballistic exercises), Margaria test (Nedeljkovic, 2016), seated shot put, medicine ball chest pass (Falvo, Schilling, & Weiss, 2006), etc. Besides choosing specific exercise, choosing an appropriate equipment is one of the important requisites of every power assessment. For example, in the study of Cormie et al (2007) power measurement techniques were validated utilising different kinetic and kinematic devices (i.e., different combination of the linear positioning transducers and force plates) during squat jump, squat and power clean. The results of the study showed that both the analysis procedures and data collection affect the power output as well as the load-power relationship.

3.4. Open and closed kinetic chain

There is continuous debate over selection of "open" versus "closed" kinetic chain exercises and tests both in scientific literature and in everyday practice. The term open kinetic chain (OKC) refers to a movement in which the terminal limb segment is free, while during closed kinetic chain (CKC) movement distal or terminal limb segment meets external resistance (Mayer et al., 2003). Typical examples of the OCK movements are throwing, golfing, volleyball strike, etc., while typical examples of the CKC are squatting, deadlift, push-up, etc. Even though it seems that there is simple delimiter between OKC and CKC movements, it has been argued that everyday activities are usually composed of the successive interchange between OKC and CKC movements (i.e., walking, running, jumping, stair climbing, swimming, etc.).

More, exercises are divided by different additional criteria into OKC or CKC group. For example, from the biomechanical standpoint, OKC movements are the ones during which proportion of shear forces are grater, while CKC movements are characterised by the greater proportion of compression forces. On the other hand, from the neurophysiological standpoint, OKC are characterised by the involvement of the single muscle group (i.e., single-joint movements), while CKC movements are movements that require controlled co-contraction of the multiple muscles/ muscle groups and joints (i.e., multi-joint movements) (Mayer et al., 2003). Additional delimiters between OKC and CKC are provided in the table below (Table 1).

Table 1. Classification characteristics for open kinetic chain (OKC) and closed kinetic chain (CKC) exercises (Reprinted and modified with permission from George J. Davies from "*Orthopaedic physical therapy home study course 98A"*, 1998)

Table 1. Common classification characteristics for OKC and CKC exercises. Seated knee flexion/extension serves as the model for OKC, while a standing squat movement is the CKC model

Characteristic	**OKC**	**CKC**
Distal segment	free	fixed
Movement pattern	rotatory	linear
Movement plane	single	multiple
Moving joints	one	multiple
Muscle recruitment	single group	multiple groups
Joint compressive forces	slight	yes
Joint shear forces	yes	slight
Equipment	often time extensive	minimal

Based on the all introduced criteria, isokinetic exercises generally pertain to the OKC group since the tests involve single joint movements, single muscle group, movement pattern is rotatory and the portion of the shear forces are higher. However, classifying isokinetic exercises/tests as purely OCK movements is a bit misleading. Specifically, distal segment of the extremity is semi-free since movements are predetermined by the lever arm and attachment between load cell and extremity. More, additional resistance can be very high during testing/training. Lack of free movement and additional external load are the characteristics of the CKC movements. In this aspect, isokinetic testing/training could be essentially classified as OKC, however not always as a purely OKC movements. Maybe the best definition is the one proposed by Steindler, who defined OKC activities as the activities undertaken to create high velocities or acceleration, while CKC are activities with a focus of generating high levels of strength (Steindler, 1977). In this manner, isokinetic exercise performed under higher angular velocities (i.e., 180 °/s) could be defined as OKC, while the ones under low angular velocities (i.e., 60 °/s) could be defined as CKC.

3.5. Force-velocity relationship

Muscles could shorten faster when they act against light resistances, in comparison to when they act against heavy ones (Seow, 2013). In other words, assuming that an individual performs the movement with maximal effort, movement velocity will be decreased when the resistance is increased. First researchers that investigated the relationship between force and velocity of the movement were conducted at the beginning of the previous century (Fenn & Marsh, 1935; Gasser & Hill, 1924). Dr. Archibald Hill conducted his first research on isolated muscle of the frog (m. sartorius). Namely, he measured the change of heating energy, which was influenced by the velocity of the shortening, and concluded that these two variables have a direct and proportional relationship. First mathematical formulation of the F-V relationship (equation 1) was formulated 1938 by the Dr. Archibald Hill, and it describes relationship between muscle force and shortening velocity of the muscles and it has a hyperbolic shape.

$$(V + b) \cdot (F + a) = (F0 + a) \cdot b \quad \textit{(equation 1)}$$

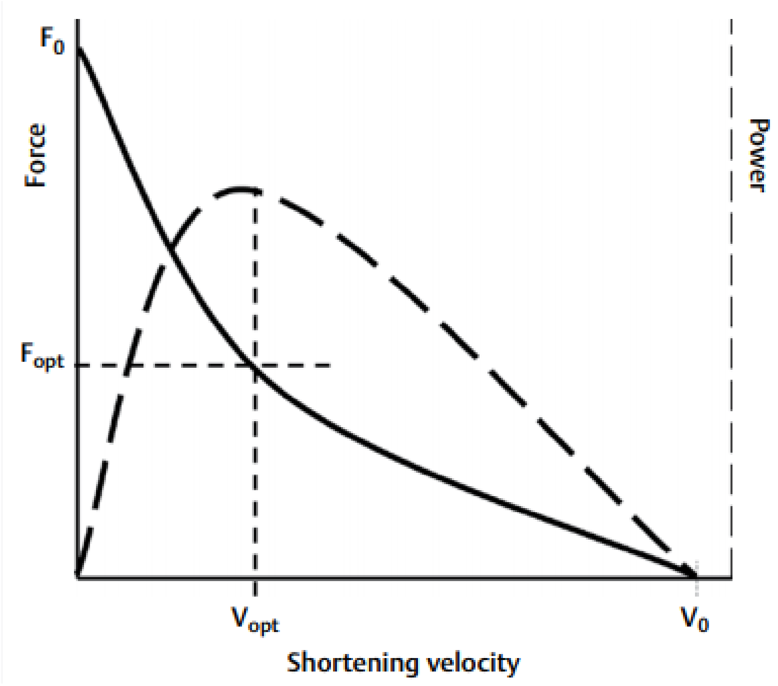

Figure 1. Force-velocity relationship of single-joint movement (Reprinted with permission from: *Force-velocity Relationship of Muscles Performing Multi-joint Maximum Performance Tasks,* Jaric, S., 2015)

Studies were firstly conducted on animals, isolated muscles, and later on single- and multi-joint movements. However, proliferation of scientific literature regarding F-V relationship and its use for a testing and training purposes started with the study of Jaric (2015), who suggested that the F-V relationship during multi-joint movements could follow a linear shape, making calculations of the F-V parameters relatively simple using following equation:

$$F(V) = F_0 - aV \quad \textit{(equation 2)}$$

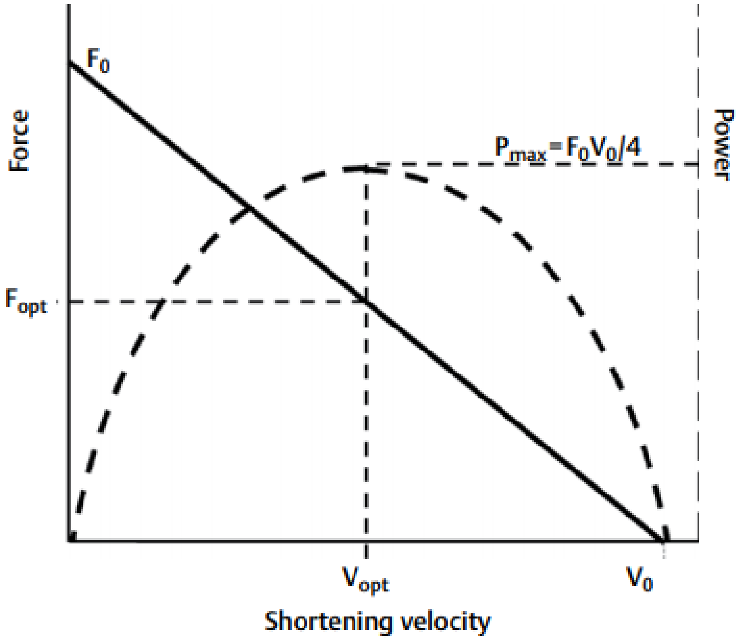

Figure 2. Force-velocity relationship during multi-joint movements (Reprinted with permission from: *Force-velocity Relationship of Muscles Performing Multi-joint Maximum Performance Tasks,* Jaric, S., 2015)

where F_0 represents y-intercept (maximal theoretical force), V_0 is x-intercept (maximal theoretical velocity), a is the slope of the F-V relationship, and it represents the ratio between F_0 and V_0, while P_{max} is the maximal power which, as a direct consequence of the F-V linearity, can be calculated in this manner:

$$P_{max} = F_0 \times V_0 / 4 \quad \textit{(equation 3)}$$

After the proposal of Jaric (2015), modelling the F-V relationships during multi-joint movement was commonly done by recording more than two experimental point (i.e., more than two pairs of force and velocity data; multiple-point method) (Cuk et al., 2016; García-Ramos, Jaric, Padial, & Feriche, 2016; Giroux, Rabita, Chollet, & Guilhem, 2016). Although precision of determining F-V relationship parameters increases as the number of experimental points increases, it has been argued that this procedure could be fatiguing and time-consuming. A study of Jaric (2016) and Perez-Castilla et al. (2018), showed that implementing only two most distant experimental points could be viable solution to increase time-efficiency and to decrease possible negative effect of fatigue. Worth mentioning is that reliability of the V_0 parameter is the lowest, when compared to other F-V relationship parameters, regardless of the method applied (i.e., two- or multiple-point method).

Based on everything mentioned above, F-V relationship depends on four F-V parameters (i.e., F_0, V_0, P_{max} and a,) which have true physiological meaning. F_0 is the parameter of F-V relationship which represents maximal theoretical isometric force (e.g. force applied while velocity of the movement is 0 m/s), V_0 represents maximal theoretical velocity (e.g. when there is no additional resistance), while P_{max} represents maximal theoretical power. And lastly, *a* describes the ability to maintain force production despite increasing movement velocity (Morin & Samozino, 2016). Consequently, F-V relationship has some very important implications which will be presented in the text below.

Firstly, the fact that modelling of the F-V relationship could be done relatively simple opened a possibility to a body of studies to explore shape and slope of the F-V relationship during various exercises, experimental conditions and sports, and primary for assessing maximal muscle capacities of athletes. For example, linearity of the F-V relationship has been confirmed during multi-joint movements as for example during vertical jumps (Samozino et al., 2014), cycling (Zivkovic, Djuric, Cuk, Suzovic, & Jaric, 2017b), and various upper body movements (Nikolaidis, 2012). Very interesting study was conducted by the French scientific couple (Morin & Samozino, 2016) who showed that modelling F-V relationship might be used for monitoring training program on an individual plain, since single program could not fit the needs of the group of athletes. Moreover, they demonstrated that F-V relationship modelling could be also used for assessing imbalances between muscle mechanical capacities (i.e., whether athlete needs to optimize individual F-V profile by increasing force or velocity, etc.). It is important to keep in mind that individual F-V relationship could be used to individualize training stimuluses, since it has been shown that F-V profiles differ more between individual athletes than between athletes of different sports (Haugen, Breitschädel, & Seiler, 2019). Consequently, Jiménez-Reyes, et al. (2017) tested hypothesis that F-V relationship could be implemented for optimising training programs. Specifically, they applied two types of training programs (i.e., training that is based on the individual imbalances in the F-V profile, and resistance training that is common to every participant), and showed that for improving jump performance training program that took into account imbalances and differences in the initial individual F-V profiles had greater success.

Thirdly, F-V relationship modelling found its place in the robotic and prosthetic development, where one of the most challenging part is to build artificial muscles. In the relatively recent study of Schmitt et al. (2012) authors proposed a simple bio-inspired functional artificial muscle that could be used in the prosthetic and robotic industry, and which is grounded on the F-V relationship model. However, it is important to keep in mind that used F-V relationship models are based on the hyperbolic Hill model, and not linear, as it is lately proposed for multi-joint movements. Although utilisation of the F-V models is relatively new approach in the biomedical prosthetic engineering, previous studies have implemented different isokinetic tests and isokinetic F-V modelling to assess post-operative status of the patients with prosthetics (Horstmann et al., 1994; Ryser, Erickson, & Cahalan, 1988).

Finally, it is a matter of time when the F-V relationship modelling would be used in some new area. A potential new direction of the use of the F-V relationship might be as a method for deciding about future specialization of young athletes. Keeping in mind that chronic engagement in specific sport lead to a differently balanced force-velocity profiles (Giroux et al., 2016), young athletes with specific F-V profile might be directed toward suited sport/discipline.

3.6. "Two-point method": a novel method for F-V relationship modelling

As it has been previously mentioned, F-V relationship was shown to follow linear shape when it was assessed from different functional tasks. This feature of the F-V relationship was the initial premise for dr. Slobodan Jarić, to propose F-V relationship modelling using just two distinctive experimental points (i.e., “two-point” method) (Jaric, 2016). In his opinion “two-point method” might be able to discriminate between maximal muscle capacities in a less time and without negative influence of the fatigue in comparison to method that was routinely used for F-V relationship modelling, more popularly known as “multiple-point method” (i.e., more than two experimental pairs of force and velocity values are used for F-V relationship modelling). Even though the “two-point method” was proposed few years ago (Figure 3), a number of papers have been published, confirming hypothesis proposed by Jarić (2016). Importantly, it has been shown that the farthest pair of loads (i.e., the points closest to the intercepts) could provide the highest reliability and validity among all two-point methods evaluated (Pérez-Castilla et al., 2018), so when possible, researchers should try to use most distinct points for modelling.

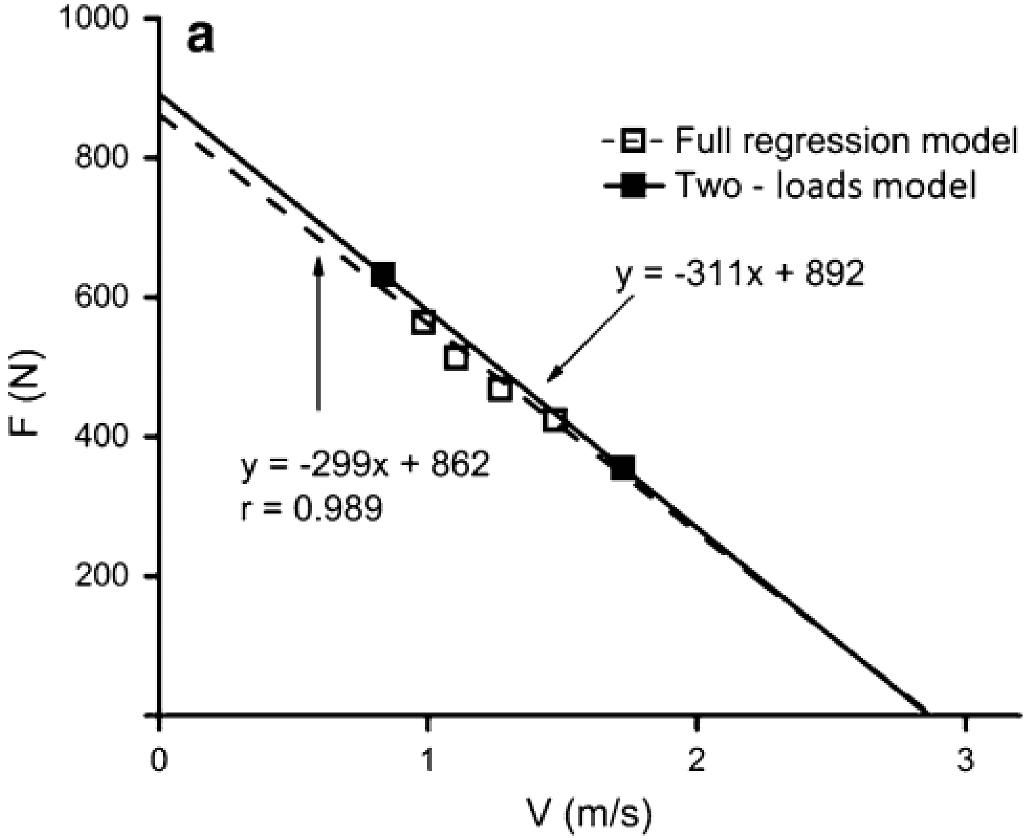

Figure 3. Linear force–velocity relationships modelled applying multiple- (dashed line, solid and empty squares) or two-point method (solid line and solid squares) during bench press exercise.
(Reprinted with permission from: *Two-load method for distinguishing between muscle force, velocity, and power-producing capacities*, Jaric, S., 2016)

Specifically, this method was validated with respect to “multiple-point method” and during specific tasks such as motorized treadmill test (Dobrijevic, Ilic, Djuric, & Jaric, 2017), electronically braked cycle ergometer (García-Ramos, Torrejón, Pérez-Castilla, Morales-Artacho, & Jaric, 2018), squat jumps (Janicijevic et al., 2019), etc. Additionally, it has been also used for assessing upper body muscle capacities (García-Ramos et al., 2017), and for various exercises in the single study (i.e., bench pull, vertical jumps, bench press throws, and cycling) (Zivkovic et al., 2017b). Generally, these studies suggested that the two-point method is a fatigue free and time-effective procedure able to discriminate between muscle mechanical capacities. These characteristics make the two-point method valuable tool for monitoring athletes' capabilities during training program.

Regarding the ability of this method to predict 1 RM, the study of García-Ramos and Jaric (2018) gave some crutial implications and steps that need to be fullfiled to validly obtain 1RM using this method. Specifically, besides above-mentioned requisite that experimental points need to be close to the intercepts (i.e., force and velocity intercepts) it is recomendable that load close to the force intercept used for L-V modelling should represent approximately 70–80% of self-reported 1RM, because higher loads were shown to have lower reliability. More, two trials with the same loads could be suficient and both avaraged or maximal values of recorded variables could be used for modelling, while the rest periods between trials are test-, and load-specific.

Although majority of the studies assessed validity of the "two-point method" during multi-joint movements, Grbić et al. (2017) validated this method for assessing maximal mechanical capacities during isokinetic knee extension (KE) task. This study was an important step forward, since it opened a possibility to quickly evaluate maximal mechanical capacities applying isokinetic dynamometry, which is known to be an important assessment tool during rehabilitation. Since during isokinetic testing one of the requisites is to pre-set velocity, “two-velocity” instead “two-point” method will be used further in the text in the context of isokinetic testing.

4. Muscle mechanical capacities of the single-joint movement assessed using isokinetic dynamometry

4.1. Isokinetic testing

4.1.1. The concept of isokinetic testing

The concept of isokinetic dynamometry was proposed by Perrine and Hislop in the 1967 (Hislop & Perrine, 1967). The term *'isokinetic'* literally means *same, constant* velocity, and therefore isokinetic testing could be considered as a testing employed under constant velocity of the movement. More specifically, during isokinetic test “muscle or muscle group contracts against a controlled accommodating resistance, which causes a limb segment to move at a constant angular velocity (ω) within a prescribed sector of its range of motion” (Dvir, 2004). Long before the development of the isokinetic devices, muscle function was evaluated using manual muscle testing, which has shown to be useful tool for clinical assessment of the muscle strength, while scientific validation and application needed to be employed (Cuthbert & Goodheart, 2007). After developing, concept of isokinetic dynamometry gain massive popularity, since it enables assessing muscle function during conditions that are highly objective, reliable and valid (Land & Gordon, 2011; Mayhew et al., 1994).

Until isokinetic testing gained popularity, two different concepts of resistive exercise were used (i.e., isotonic and isometric) (Hislop & Perrine, 1967). Isotonic exercises involve movements against an additional load which is constant, and isometric against an immovable load. Although external load is constant, resistance is variable during isotonic exercises. In comparison to this, lever arm of the isokinetic dynamometer allows applying maximal resistance throw whole range of movement by modifying resistance of the lever arm (i.e., so that isokinetic velocity could be achieved). This specifically means that the resistance accommodates the external forces which are created by tested muscles (i.e., force output is maximised) during the whole movement.

Even though term "isokinetic" means that velocity of the movement is constant, there are phases during the movement when limb accelerates (beginning of the movement) and decelerates (end of the movement). The higher the velocity, acceleration and deceleration phases take greater part of the movement, limiting duration of the “true” isokinetic phase (i.e., sometimes referred as the isokinetic sector) of the movement. It has been argued that velocities above 180°/s have a very short isokinetic phase (Iossifidou & Baltzopoulos, 1996) and that this could decrease the accuracy of the measurement (Brown, Whitehurst, Findley, Gilbert, & Buchalter, 1995). Example of isokinetic force-time curves recorded during KE (Figure 4) and elbow flexion (EF) (Figure 5) test recorded under 30, 60, 90, 120, 150, 210 and 240 °/s in male subjects. More specifically, Iossifidou and Baltzopoulos (1996) stated that duration of isokinetic sector could be somewhere from 76.5 to 20.9% for the Biodex (during angular velocities ranging from 30 to 150 °/s), while for the KinCom between 66.7 and 28.1 % (from 30 to 250 °/s). If higher velocities were applied, this movements can be considered as ballistic rather than isokinetic (Dvir, 2004).

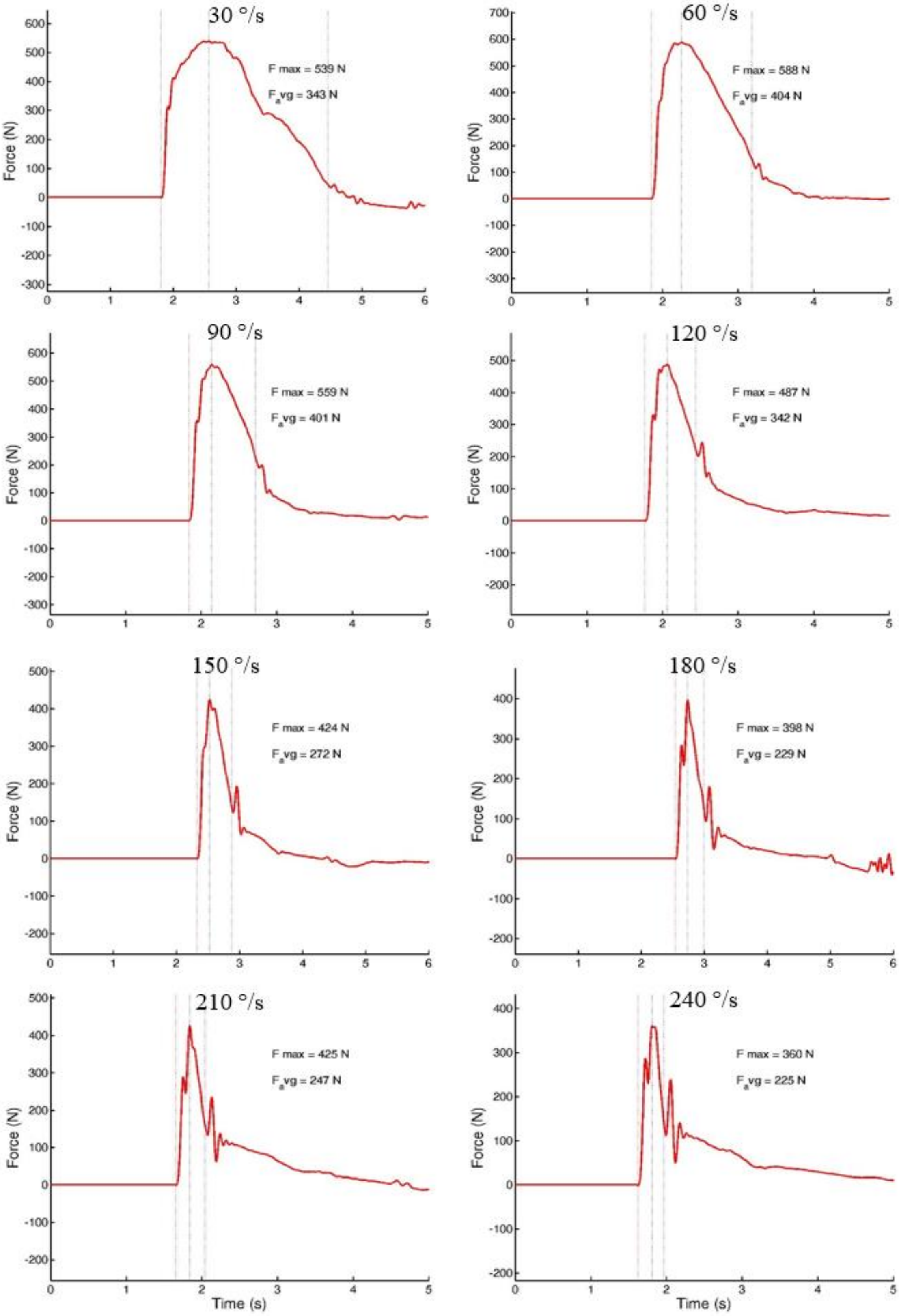

Figure 4. Force-time curves of the knee extensors recorded during 30, 60, 90, 120, 150, 180, 210 and 240 °/s.

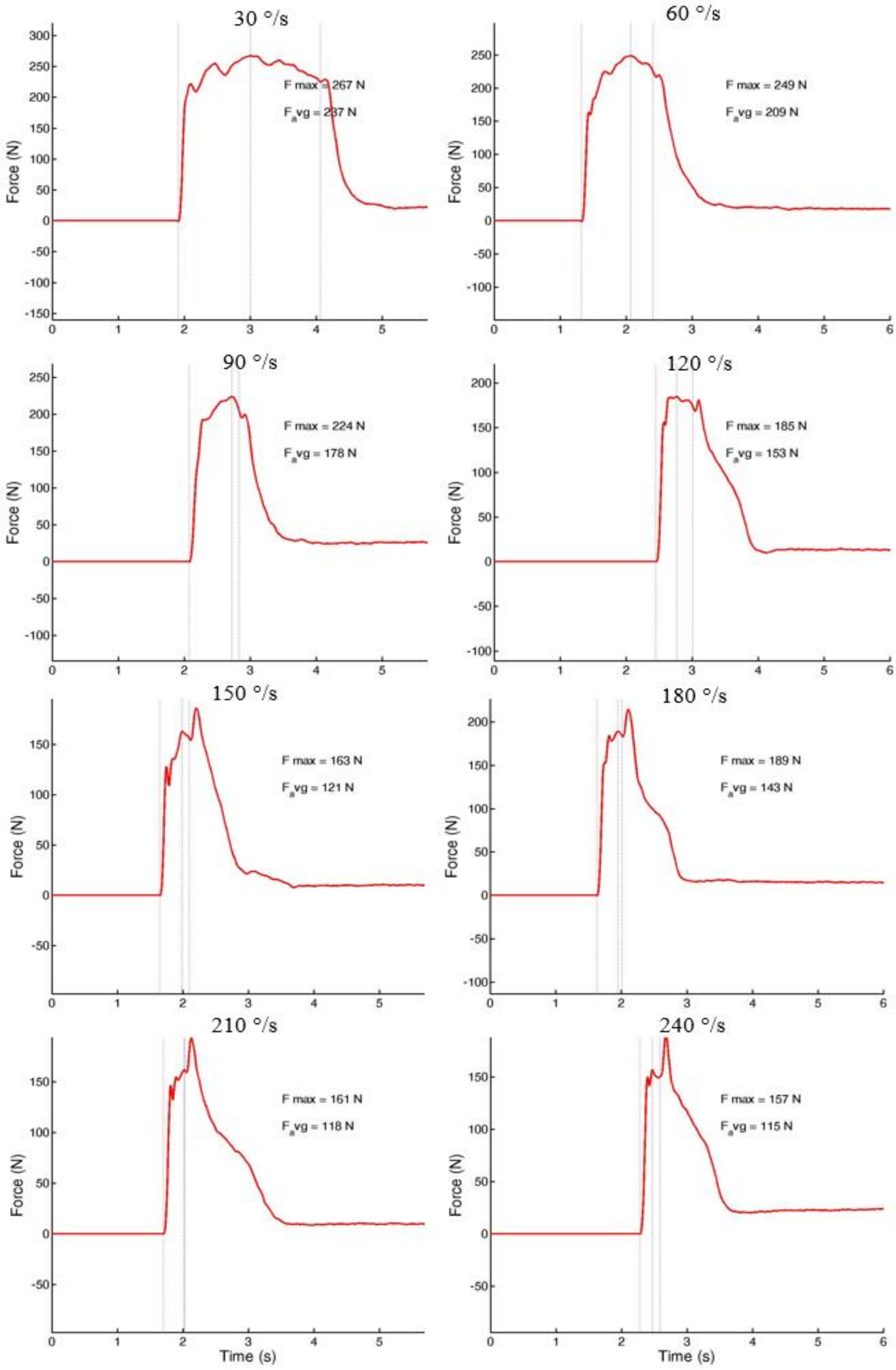

Figure 5. Force-time curves of the elbow flexors recorded during 30, 60, 90, 120, 150, 180, 210 and 240 °/s.

4.1.2. Hardware, software and common testing variables

Isokinetic dynamometers are robust and multipart. Even though there are different types of dynamometers, basic parts are the same. According to Dvir (2004) parts of dynamometers are:

1. *The head assembly*- contains a motor that enables constant velocity of the movement by producing a same amount of force as the tested muscle/muscle group, but in the opposite direction.
2. *Lever arm*- solid part that is attached to the head assembly and which can be moved radially around immovable axis.
3. *The load cell*- enables collecting data regarding changes of the exerted muscle force over time.
4. *The "force acceptance attachment*- is the interface between the subject and the system". Specifically, it is accessory which is attached on the lever arm through the load cell. This *"force acceptance attachment"* could be positioned according to the individual anthropometric characteristics.

Screen of the computer enables real time feedback which is shown to be important factor for additional motivation of the subjects (Weakley et al., 2018). Afterwards, signal can be processed using software such as LabView, MathLab, etc.

Picture 1. Isokinetic setting

Prior testing some basic prerequisite needs to be fulfilled:

1. Selection of the range of motion (ROM),
2. Angular velocity(ies),
3. Subject positioning,
4. Aligning the axis of the dynamometer with the subject's joint,
5. Contraction mode.

Signal obtained during isokinetic testing represents exerted force during specified ROM at a given angular velocity. From this force-time signal following variables can be determined (Dvir, 2004):

1. *Peak torque/force*- maximal value of force/torque obtained during whole ROM, does not involve specification of its location (Brown et al., 1995; Castro et al., 2018);
2. *Average torque/force*- mean value of force/torque obtained during whole isokinetic spectrum (constant velocity part of the velocity-time curve), does not require specification of its location (Calmels, Nellen, van der Borne, Jourdin, & Minaire, 1997);
3. *The angle of a maximal torque/force*- reveals specific angle during which force reached its maximum, and it varies as a function of pre-selected velocity (Castro et al., 2018);
4. *Torque/force at a given angle*- torque/force value of the specific angle of interest;
5. *Work*- in biomechanics, in a context of isokinetic testing, work "refers to the product of muscular force exerted through specific ranges of movement" (Hislop & Perrine, 1967). It can be presented as total work (Brown et al., 1995; Castro et al., 2018), peak work (Sarig Bahat, Blutich, & Kodesh, 2019) or average work;
6. *Power*- usually defined as the rate of doing work. In biomechanics, it represents the product of force and velocity (i.e., torque and angular velocity). Similar to other variables, it can be presented using its maximal or average values (Ellenbecker & Roetert, 2003);
7. *Impulse*- quantifies the overall torque/ force during movement time $I= F * t$ (Ns), $I=M*T$ (Nms).

Since force applied on the load cell is usually exerted during angular movement (Land & Gordon, 2011), and since sensor of the dynamometer which measures force is set at some distance from the centre of rotation, torque (e.g., product of the length of the lever arm and generated force) is usually reported. Since the body segments are relatively short, torque measurement error of 1 cm decrease reliability only 2.5-5% (Dvir, 2004). All mentioned reported variables could be presented as average and/or peak values. Additionally, single muscle group or ratios between antagonistic muscle groups or extremities could be reported depending on the needs. More, values could be presented as an absolute or as a relative (i.e., per kg of body mass).

Besides measuring force under movement of a constant velocity, there is possibility of measuring muscle force under isometric conditions (i.e., against immobile lever of the dynamometer), which is an important indicator of maximal strength capacity of a tested muscle. Additionally, explosive torque/force production of human skeletal muscle is usually evaluated under isometric conditions being that the different angular velocities, joint angles and acceleration interact with torque in a non-linear fashion, that would certainly lead to the confound measures and inconsistent results (Maffiuletti et al., 2016). Figure 6 depict force output change during isokinetic test which has been obtained using isokinetic dynamometer with an initial position set at 120° (180° represents full extension).

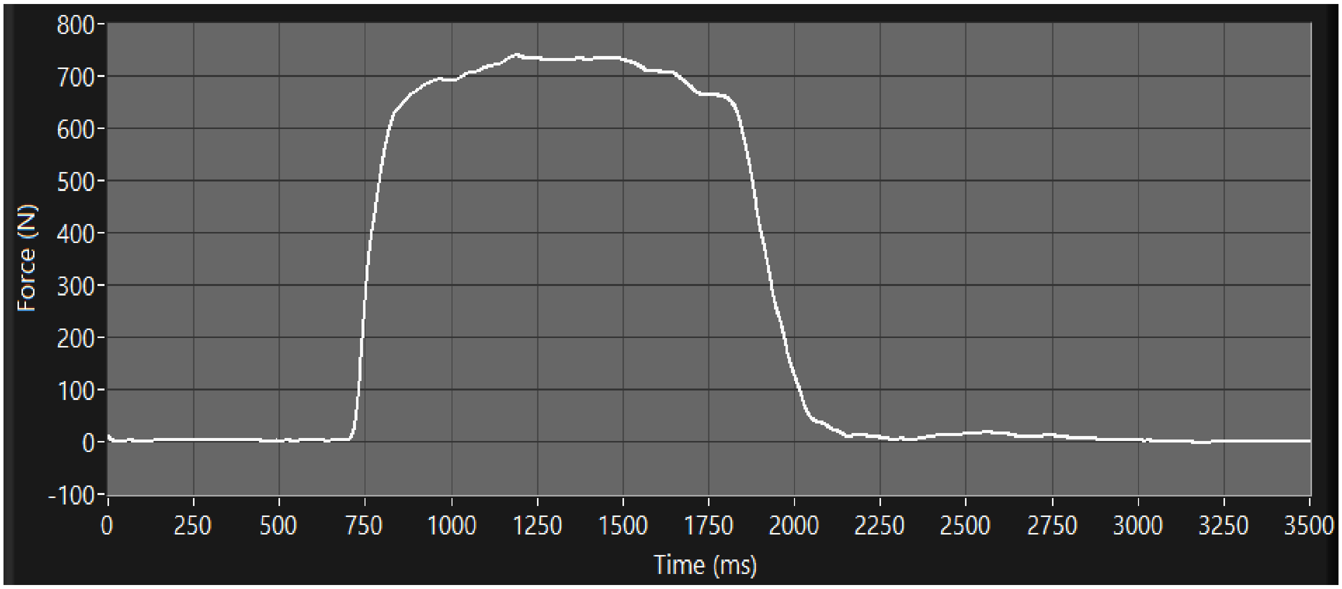

Figure 6. Force-time curve of knee extensors recorded under isokinetic conditions.

Isokinetic testing is possible during both eccentric and concentric contractions (Zemach, Almoznino, Barak, & Dvir, 2009), and if the muscles are tested in the cyclic mode they can be performed in concentric-concentric, concentric-eccentric and eccentric-eccentric regime of the work. On the other hand, numerous studies have explored the strength of antagonist muscle pairs and their corresponding ratios using isokinetic dynamometry (Brown et al., 1995; Grbic et al., 2017; Land & Gordon, 2011; Michael, König, Bertram, Heßling, & Eysel, 2005). Reporting the strength ratio between antagonist muscles is generally recommended because it could provide valuable additional information (Campbell & Glenn, 1982). Most common angular velocity for reporting strength ratios is 60°/s (Land & Gordon, 2011), and for extensors and flexors acting in knee, hip, elbow and shoulder joint, reported values favoured knee extensors (KE) (Kurdak et al., 2005), hip extensors (HE) (Castro et al., 2018), elbow flexors (EF) (Lategan & Krüger, 1995) and shoulder extensors (SE) (Cahalan, Johnson, & Chao, 1991) in comparison to their antagonistic muscle pairs (knee flexors [KF], hip flexors [HF], elbow extensors [EE] and shoulder flexors [SF], respectively). However, it should be noted that strength ratios have always been assessed against individual angular velocities (Land & Gordon, 2011).

4.1.3. Outcomes of isokinetic testing

From its origin, outcomes of the isokinetic testing had been used for assessing maximal muscle capacities, asymmetries between limbs (Daneshjoo, Rahnama, Mokhtar, & Yusof, 2013), ratios between antagonistic muscle groups (Kong & Burns, 2010), as well a method for injury prediction (Bennell et al., 1998). Regardless of the purpose, it is important to mention that applying submaximal warm-up decreases possibility of injury and increases the reliability of obtained results during isokinetic testing (Osternig, 1986). Different testing procedures could significantly affect results obtained during isokinetic testing (Gleeson & Mercer, 1996), emphasizing necessity of having testing procedures as uniform as possible. But before discussing about possible outcomes of isokinetic testing, emphasize will be put on the metric characteristics of its outcomes.

Numerous studies have shown that isokinetic dynamometry is a reliable method for force assessment, specifically it has been shown using different isokinetic devices such as KinCom (Farrell & Richards, 1986), Biodex (Feiring, Ellenbecker, & Derscheid, 1990), Cybex (Cockburn & Hayes, 2010), etc. Worth mentioning is that reliability of the force outcome generally decreases as the pre-set angular velocity increases (Montgomery, Douglass, & Deuster, 1989), while the test-retest of the knee extension and flexion exercise has been used most frequently for assessing reliability (Cockburn & Hayes, 2010; Feiring et al., 1990), with the knee extension being the more reliable test (Montgomery et al., 1989).

Regarding validity, the study of Drouin et al. (2004) reported near-perfect agreement between variables that were measured with the Biodex System 3 and criterion measures of velocity, torque and position. However, this holded the truth for the velocities lower than 300 °/s, while for the some variables recorded during velocities higher than 300°/s, validity systematically decreased. More, isokinetic dynamometry, as a testing procedure, has been commonly referred to as the "gold standard". With evident logical validity for assessing power and strength capacities, it has also been used as a method for validating other tests (Mondin, Owen, Negro, & D'Antona, 2018) due to its costly nature.

Although the aspect of sensitivity was not in the centre of research attention of the isokinetic community, study of Knezevic et al. (2014) showed that force output produced at 60 and 180 °/s were sensitive enough to discriminate the neuromuscular function of the injured leg during three occasions before ACL reconstruction, and after 4 and 6 months. Additionally, same parameters of the uninvolved leg did not change during this period, which additionally confirms sensitivity of the applied isokinetic test. More, Mirkov et al. (2017a) proposed utilisation of the two-velocity method for assessing neuromuscular function of the injured leg using isokinetic testing (i.e., force output during 60 and 180 °/s). Specifically, the authors demonstrated that F_0 and V_0 parameters were higher 6 months in comparison to 4 months after surgery for quadriceps, while for hamstrings differences were noted only for $F_{0.}$

Going back to the benefits of isokinetic outcomes, it is of paramount importance to gain knowledge about the maximal muscle capacities, because they have a great impact on sports performance (Jiménez-Reyes et al., 2017) and rehabilitation process (Mendiguchia et al., 2016). Although isokinetic dynamometry has been criticised due to a lack of specificity, it has been used massively for assessing maximal capacities. In this regard, 60 °/s have been considered as velocity under which muscles could produce maximal torque/force output, while 180 °/s has been thought to be velocity which enables production of the maximal muscle power (Raj, Bird, & Shield, 2010). Despite the existence of wide range of velocities, these two values (i.e., 60 and 180 °/s) have been usually selected for exploring these capacities (Grbic et al., 2017; Michael et al., 2005).

Due to the possibility to adjust isokinetic assembly for testing different muscle groups, numerous designs had been developed to assess possible asymmetries of the body applying different ranges of movement and velocities which could go up to 500 °/s (Baltzopoulos & Brodie, 1989). Specifically, force of the same muscles of the different limbs are measured to assess bilateral asymmetries (Daneshjoo et al., 2013). For example. the phenomenon of between-leg asymmetries received consistent attention from the strength and conditioning community over the last decades (Bishop et al. 2016), and it refers to the difference in the performance and mechanical outputs between two legs. It has been argued that the presence of between-leg asymmetries can affect jumping performance, ability to quickly change direction, provoke injuries, etc. (Bishop et al. 2016). Even though regularly defined as a percentile difference between stronger and weaker, non-dominant and dominant or right and left leg, Exell et al.

(2012) suggested that between leg asymmetries exist only when between leg difference is bigger than variability of the single leg. Between-leg asymmetries has been assessed in a various ways including unilateral (Kobayashi et al., 2013) and bilateral (Jordan, Aagaard, & Herzog, 2015) tests, as well as using less (i.e., isokinetic, isometric) and more functional testing procedures (Menzel et al., 2013).

Beside this, contrasting results obtained between isokinetic and performance (e.g. isokinetic testing shows no relative differences in strength between legs, but functional test shows or vice versa), implied that not only strength, but also different movement patterns influence asymmetries. For example, although Impellizzeri et al. (2007) reported significant correlations between results obtained from isokinetic testing and vertical jump, Menzel et al. (2013) showed that variables obtained during isokinetic and vertical jump testing cannot be used interchangeably and do not portray same origin of the imbalances.

4.2. Isokinetic F-V relationship during single-joint movements

Even though it has been shown that F-V relationship is polynomial (Hill, 1938), recent studies showed that if maximal isometric force is excluded from the regression model, this relationship can be presented using linear regression model. Besides, it has been shown that isokinetic relationship in *in-vivo* conditions is less steeper than in *in-vitro* conditions (Osternig, 1986). Even though isokinetic testing has been considered as a gold standard with high internal validity, the fact that the testing procedure can occupy significant amount of time should not be neglected. A study of Zemach, et al. (2009) is a typical representative of a study with a general aim to increase time-efficiency during isokinetic testing. These researchers recommended that therapists or researchers should not use very slow or very high angular velocities since they can provoke pain, and that implementing isokinetic test under single or two angular velocities could portray unilateral muscle imbalances. Namely, group of subjects who participated in this study was a group which was recovering from knee injury, and the test was KE. Angular velocities which were used were 30, 60, 90 and 120 °/s, while the interpretation break was 5s, and inter-velocity brake was 30s.

Prior to the study of Hislop & Perrine (1967), who introduced isokinetic concept of exercise and testing, different measurement systems were used to explore F-V relationship. For example, Wilkie (1949) used triangular lever and cables which transmitted resistance from an attached load, while velocity was estimated from a charge accumulated on a condenser (i.e., condenser was charged during the movement). In this manner, F-V relationship shape could be modelled and examined during elbow flexion exercise. During the eighties important study was conducted in which authors very carefully demonstrated differences in the force output during dynamic and isometric contraction and influence of the acceleration phase during the isokinetic exercise (Thorstensson, Grimby, & Karlsson, 1976). Besides exploring the shape of the F-V relationship, they added significant knowledge about the differences between dynamic and isometric force output, influence of the acceleration phase and their dependence from the movement velocity during single joint movement. Namely, they showed that isometric output for specific angles is always higher than dynamic output, regardless of the angular velocity. While they investigated force-time output for 180°/s they noticed that acceleration part of the movement could last up to 10°, which can be observed as a sudden drop in the force when the acceleration phase ends.

In the following text relevant studies related to the F-V or T-ω relationship and isokinetic testing will be presented. Difference between torque and force is that torque is defined as a twisting force that tends to cause rotation and can be computed as the product of the perpendicular distance from the centre of rotation and the force applied. Therefore, when torque is used lever arm length (i.e., anthropometric characteristics of the subjects are taken into account) is taken into account, while when F is used only a linear quantity of the movement is considered. Therefore, it should be emphasized that for modelling T-ω relationships angular velocity should be used, while for modelling F-V relationships linear velocity should be used.

Interest for accessing F-V relationship during isokinetic testing is present several decades now. For example, study of James et al. (1994) was assessing characteristics of F-V curves of quadriceps muscle and demonstrated that different contraction protocols (i.e., volitional or no volitional) seems to provide different F-V curves for the same muscle group. More, Taylor et al. (1991) explored differences in torque-angular velocity relationships modeled separately for 'power trained athletes' and 'endurance trained athletes', evaluating differences in their shapes, while de Koning et al. (1985) explored F-V relationship of arm flexor muscles in subjects that are 'arm-trained' and untrained with an aim to find differences between different F-V relationship parameters. Additionally, Knapik and Ramos (1980) explored the decrease in force values with the increase of movement velocity (i.e., 30, 90 and 180 °/s) during isokinetic testing (i.e., KF, KE, EF and EE), and obtained high correlations between isometric force and force achieved during low angular velocities, and suggested that low velocities could be used for predicting maximal voluntary isometric force. Nevertheless, none of these or many other studies explored the F-V relationship that was modelled using linear regression model. However, the studies that did explore weather F-V relationship could be modeled using linear regression model were orientated towards flexors and extensors of the trunk and knee and are discussed in detail below.

Ripamonti et al. (2008) were one of the pioneers in the utilisation of the linear regression model for examining T-ω relationship. Specifically, they were the first that demonstrated that T-ω relationship of trunk flexors and extensors can be modelled using linear regression model. Even though T-ω relationships were linear during these movements, when muscles were tested without proper rest (e.g., trunk extension right after flexion) the T-ω relationship was polynomial, which was attributed to the fatigue. More, it is important to mention that angular velocities were not randomised, with an implication that during rehabilitation subjects usually perform exercises with gradual increment of the resistance. The following study of the same research group focuses on the ability of the linearly modelled F-V relationship to evaluate low back pain, which has known to be one of the major public health problem and it refers to a pain that is localized between the 12th rib and the inferior gluteal folds. Specifically, the results of the theoretical maximal T was shown to be related to the results of the DALLAS pain questionnaire (Ripamonti, Ritz, Colin, & Rahmani, 2011), and showed that linear isokinetic F-V relationship can be used as a complementary information for the regular low back pain evaluation. And finally, in their third study they described differences in the T-V and P-V relationships of the trunk muscles in patients that are suffering from chronic lower back pain and healthy individuals, and showed that lower back pain does not provoke differences in the F-V relationship shapes and that P_{max} assessed from this relationship can be used as a relevant factor of lower back pain (Ripamonti, Colin, & Rahmani, 2011). In described studies subjects were tested on isokinetic dynamometer using six different angular velocities (45, 60, 75, 90, 105 and 120 °/s), the ROM was set to 60° and flexors and extensors of the trunk were tested in two non-consecutive days.

Muscle group that has been in the centre of attention of the isokinetic evaluation is quadriceps femoris (i.e., knee extensors). Using the four velocities (30, 90, 120, 180 °/s) and with an aim to explore the F-V relationship during submaximal concentric and eccentric contractions Kues & Mayhew (1996) tested thirty females. The authors demonstrated that F-V relationship is linear and strong, although, mentioned results should be taken with precaution since the authors used narrow range of movement (50-70°, 90° corresponds to the full extension) and the participants were stimulated electrically at 30% of their individual maximal volitional isometric force. However, one of the first significant steps forward in the utilisation of the linear isokinetic F-V relationship for the volitional KE assessment was made by Lemaire et al. (2014) who showed that the F-V parameters did not differ when the F-V relationships were modelled using eight or just three experimental points. The authors of this study were the first who started lowering down the number of experimental points for modelling linear F-V relationship and calculating corresponding parameters. Specifically, they tested 16 males on isokinetic dynamometer at eight angular velocities (60, 90, 120, 150, 180, 210, 240 and 270 °/s) during KE test. Afterwards, they modelled F-V relationships using eight and three experimental points (forces obtained during 90, 180, 240 °/s) and compared obtained F-V relationship parameters. The parameters of the F-V relationships modelled using only three and eight experimental points did not differ, implying that F-V relationship could be confidently modelled using only three experimental velocities. Even though research of Lemaire and co-workers (2014) tried to decrease the number of angular velocities applied during isokinetic testing, the only study that have used just two angular velocities to model the F-V relationship is the research of Grbic et al. (2017). Using the same test (i.e., KE) the validity of the parameters of the F-V relationship was high when obtained from the two-velocity method (force recorded at 60 and 180º/s) compared to the multiple-point method (force recorded at five velocities: 30, 60, 120, 180, 240º/s). Therefore, the two-velocity method is a promising approach since it could provide more meaningful information (i.e., F_0, V_0, and P_{max}) than the standard isokinetic test (which allows drawing conclusion only about single muscle capacity).

4.3. Shortcomings of previous studies

As it has been mentioned, nowadays isokinetic dynamometry as a testing method has a massive popularity in sport and rehabilitation settings. Due to the fact that it has been proposed as a method in the seventies of the past century, numerous protocols have been developed. Choosing the right protocol can be tricky and the testing results can reveal information only about individual muscle capacity. When the term *protocol* is mentioned, it refers to the type of contraction, range of movement, angular velocities, etc. (Zemach et al., 2009). So, if specific muscle group is tested during low angular velocities, muscle capacity to produce maximal force will be revealed, while implementing high angular velocities during isokinetic testing will dominantly reveal capacity of the muscles to develop maximal power. In addition, the standard isokinetic test (i.e., force output recorded against a predetermined velocity) cannot reveal the maximal velocity capacity because (I) the velocity cannot be voluntarily changed during the movement, and (II) the maximal velocity of the muscles is considerably higher than the velocities typically used during isokinetic tests. More, most common testing protocol consists of measuring velocities during consecutive contractions which prolongs testing procedure even more.

Besides, there is no consensus about the threshold of low and high angular velocity during the single-joint isokinetic testing. Even though it has been reported in the review paper of Pereira & Gomes (2003) that angular velocities ranging from 20-96 °/s could be defined as low and from 100–300 °/s could be defined as high, it seems that this question is still an open debate. It has been recommended that angular velocities higher than 180°/s should not be used because the time at a constant velocity is very short and this compromises the accuracy of the measurement (Brown et al., 1995), while it has been argued that maximal power is obtained during velocities that are higher than 180°/s.

Isokinetic dynamometry is of vital importance for rehabilitation process. People that are recovering from injuries need to be tested using specific angular velocities and range of movement. Literature suggests that very slow angular velocities as well as very high are not recommendable for isokinetic testing for this population, since they can provoke pain (Zemach et al., 2009). Therefore, it should be possible to predict maximal capacities of the muscles, taking into consideration current abilities of the convalescents (i.e., intensity of exercises applied during rehabilitation should be set with respect to the real maximal capacities).

Even though it is shown that F-V relationship modelling has higher informative value, there is very little studies that were exploring the sensitivity of the model to discriminate between genders, muscles, different populations etc. More, there is no study with the aim to explore the possibility to generalize same parameters of the F-V relationship between muscles tested under isokinetic conditions. Previous studies showed inconsistent results for multi-joint movements (Prebeg et al., 2013; Zivkovic et al., 2017b).

5. Problem, scope and aims of the research

Problem of the research is evaluation of the maximal mechanical capacities of the muscles using isokinetic dynamometry. Often applied isokinetic testing protocols does not provide information regarding all muscle capacities at the same moment. There is a need to develop less time-consuming and fatiguing procedure for evaluation of the maximal mechanical muscle capacities.

Scope of the research is the isokinetic F-V relationship modelled using “two-velocity” method to determine maximal mechanical capacities of the muscles.

Aim of the research: In particular, two studies have been conducted, first one with a general aim to validate the two-velocity method, and second for exploring sensitivity of F-V relationship to discriminate between different muscle groups and populations.

Specific aims of the first study: **(1)** to evaluate the shape and strength of the F-V relationship obtained from four different muscle groups, **(2)** to explore the concurrent validity of the two-velocity method (based on two representative angular velocities: 60 and 180°/s) with respect to the standard multiple-velocity method (based on eight angular velocities ranging from 30 to 240°/s), **(3)** to test the sensitivity of the F-V relationship to discriminate between different muscle groups and genders, **(4)** to explore the possibility of generalizing the same F-V parameters between different muscle groups, and **(5)** to explore the association between maximal isometric force and theoretical maximal force obtained using two- or multiple-velocity method.

Specific aims of second study: assessing the sensitivity of the F-V relationship obtained using the two-velocity method to discriminate between **(1)** flexor and extensor muscles working at the same joints (knee, hip, elbow and shoulder), and **(2)** men with different levels of physical activity, while the last aim was **(3)** to examine the generalizability of the same F-V relationship parameters between different antagonist muscle pairs.

6. Hypotheses of the research

Based on available literature, hypotheses were set for both studies. For the first study it was hypothesized that:

(1) All F-V relationships would be highly linear;

(2) Comparable magnitudes and strong relationships would be observed for the F-V parameters obtained from the multiple- and two-velocity methods;

(3) The F-V relationship parameters would be higher for knee than for the elbow muscles, as well as in men when compared to women;

(4) The association between the same F-V parameters across different muscle groups would be generally low;

(5) Association between maximal isometric F and F_0 obtained using two- or multiple-velocity method will be high.

Hypotheses set for the second study are:

(1) The F_0 and P_{max} relationship parameter obtained for KE, HE, EF, SE would be higher than for their antagonistic muscle groups (KF, HF, EE, SF);

(2) The F_0 and P_{max} relationship parameters of all muscles would be higher for active compared to non-active males;

(3) The association between the same F-V parameters across different muscle groups will be low.

Study 1

7. Feasibility of the two-velocity method for assessing the force-velocity relationship during lower-body and upper-body isokinetic tests (Study 1)[1]

7.1. Introduction

Monitoring maximal muscle capacities is of paramount importance for the sports performance (Jiménez-Reyes et al., 2017) and rehabilitation (Mendiguchia et al., 2016). Maximal muscle capacities refer to the ability of the muscles to produce force (F), velocity (V) and power (P). However, most of the standardised tests are ineffective to discern between these capacities (Hamilton, Shultz, Schmitz, & Perrin, 2008; Hansen, Cronin, Pickering, & Newton, 2011; Raj et al., 2010). One of the most important testing methodologies during rehabilitation process is isokinetic dynamometry, and it is considered reliable, valid and safe for testing muscle capacities (Farrell & Richards, 1986). The concept of isokinetic dynamometry has been developed in the seventies, and since then numerous protocols have been developed for assessing mainly F and P capacities. However, most usually, testing procedure consists of assessment of F under two distinct velocities, one that is in the range of low velocities (60°/s), and one that is in the range of high ones (180°/s) (Grbic et al., 2017; Lemaire et al., 2014). Usually, lower angular velocities has been consider as a velocities that are able to discover maximal capacity of the muscles to produce F capacity, while higher angular velocities has been considered to reveal P capacity (Raj et al., 2010). It has been argued that revealing P capacities could be done only by testing muscle capacities implementing angular velocities that are higher than the range of testing velocities of isokinetic dynamometers (Grbic et al., 2017). Consequently, the F recorded against a single angular V does not allow to determine the actual maximal capacities of the muscles to produce F, V and P (Jaric, 2015). The solution of this problem could be modelling of the F-V relationship (Jaric, 2015).

Although it has been accepted for decades that the F-V relationship of individual muscles has approximately a hyperbolic shape (Hill, 1938), recent studies suggest that it fits a linear shape for isoinertial multi-joint exercises (Jaric, 2015). The advantage of the linear F-V relationship is that determining the theoretical maximal capacities of the muscles to produce F (F_0), V (V_0) and P (P_{max}) through a linear regression model is simplified:

$$F(V) = F_0 - aV \quad (eq.1)$$

where F_0 represents the F-intercept (i.e., theoretical maximal F), a is the slope that corresponds to F_0/V_0, and V_0 is the V-intercept (i.e., theoretical maximal V). As a direct consequence of the F-V relationship linearity, P_{max} can be calculated as $P_{max} = F_0 \cdot V_0/4$. There is also evidence that the F-V relationship of single-joint tasks could follow a linear pattern. More specifically, Grbic et al. (2017) revealed that the F-V relationship for the knee extension (KE) task obtained in an isokinetic dynamometer fits a linear shape ($r > 0.96$). However, a more robust set of data is needed to support the linearity of the F-V relationship of single-joint isokinetic tests performed by different muscle groups.

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[1] This text presents complemented and partially modified publication of the paper published in the Journal of Sports Sciences (Janicijevic, D., García-Ramos, A. Knezevic, O., Mirkov, D. Feasibility of the two-point method for assessing the force-velocity relationship during lower-body and upper-body isokinetic tests, *Journal of Sports Sciences 37*(6). In press. doi: 10.1080/02640414.2019.1636523)

Most frequently, the F-V relationship has been modelled using the direct measures of F and V under more loading or velocity conditions (*multiple-point method*) (Garcia-Ramos, Feriche, Perez-Castilla, Padial, & Jaric, 2017). Modelling F-V relationship implementing multiple-point method can be, however, fatiguing and time-consuming procedure (García-Ramos & Jaric, 2018). Potential solution for this issue, Jaric (2016) proposed a quicker and less fatigue-prone method based on the application of only two loads/velocities (i.e., *two-velocity method*). The concurrent validity and reliability of the F-V relationships obtained implementing two-point method have been confirmed in previous studies that have involved multi-joint exercises (García-Ramos, Torrejón, et al., 2018; Zivkovic, Djuric, Cuk, Suzovic, & Jaric, 2017a). To our knowledge, less studies have been conducted with an aim to explore validity and reliability of the F-V relationship obtained using isokinetic dynamometry (i.e., testing single-joint muscle capacities) either by implementing multiple- or two-point method. To our knowledge, only Grbic et al. (2017) have demonstrated a high validity of the outcomes obtained from the two-velocity method as compared to the same outcomes obtained from the multiple-point method during the isokinetic KE task ($r > 0.76$). It could be also of importance to elucidate whether the F-V relationships modelled using two-velocity method are sensitive to differentiate between muscle groups of lower and upper extremities, and between female and male participants.

It could be of importance to elucidate if the outcomes of the F-V profile could be generalised across different tasks since previous studies have found inconsistent results for multi-joint tasks (Zivkovic et al., 2017b), while to our knowledge the generalizability of the F-V relationship parameters has not been explored between isokinetic single-joint tasks. A high sensitivity and generalizability of the F-V parameters could further motivate using the F-V relationship in routine isokinetic testing. And finally, most common way of exploring maximal strength capacities of the muscles is by measuring isometric F and by assessing the one-repetition maximum (1RM). In this regard, very high *r* correlations coefficients were obtained between F_0 parameter and isometric F and F recorded during 1RM test in bench press throws and squat jump exercise (Cosic et al. 2019). However, t-test performed on the same dataset showed that these values do significantly differ, except in case of comparison between F_0 and F recorded under isometric condition in squat exercise. It should be noted that from these two strength measures only isometric F could be recorded during isokinetic testing. Although there are controversies regarding the capability of the isometric testing to portray and monitor changes of the sports activities, it has been argued that isometric tests do portray basic characteristic of the muscles. To our knowledge, no previous study compared the association between F_0 and maximal isometric F within single-joint movement using isokinetic dynamometry. Therefore, it would be interesting to explore validity of the F_0 in respect to the F recorded under isometric condition.

To fill mentioned research gaps, the F-V relationships has been modelled for 4 different isokinetic muscle tasks (KE, knee flexion [KF], elbow extension [EE] and elbow flexion [EF]) using multiple- and two-velocity method. We aimed to (1) evaluate the shape and strength of the F-V relationship obtained from four different muscle groups, (2) explore the concurrent validity of the two-velocity method (based on two representative angular velocities: 60 and 180°/s) with respect to the standard multiple-point method (based on eight angular velocities ranging from 30 to 240°/s), (3) test the sensitivity of the F-V relationship to discriminate between different muscle groups and genders, (4) explore the possibility of generalizing the same F-V parameters between different muscle groups and (5) to explore the association between maximal isometric force and theoretical maximal force obtained using two- or multiple-velocity method. It was hypothesised that (1) all F-V relationships would be highly linear, (2) strong relationship and high agreement would be observed for the F-V parameters obtained from the multiple- and two-velocity methods, (3) the F-V relationship parameters would be higher for knee than for the elbow muscles, as well as in men compared to women, (4) the association between the same F-V parameters across different muscle groups would be generally low as it has been described for multi-joint tasks (5) association between maximal isometric force and theoretical maximal force obtained using two- or multiple-velocity method will be high.

7.2. Methods

7.2.1. Participants

Twenty-two physical education students (12 women [age: 21.5 ± 2.2 years; body height: 1.69 ± 0.07 m; body mass: 60.9 ± 9.7 kg] and 10 men [age: 22.7 ± 2.5 years; body height: 1.86 ± 0.06 m; body mass: 80.6 ± 5.9 kg]) volunteered to participate in this study. Data regarding their habitual physical activities was assessed using International Physical Activity Questionnaire (IPAQ). Based on the results of the IPAQ tests, the average weekly activity of the participants was 10 hours, which was described as moderate to highly intensive. The criteria for including participants into study was that they were no professional athletes and that they did not have musculoskeletal pain or injuries that can negatively affect the outcomes of this study. Participants were introduced with the procedures and aims of the study and were informed that they can withdraw from the study anytime. The study was approved by the Institutional Review Board and protocol adhered to the tenets of the Declaration of Helsinki.

7.2.2. Study design

Present study was designed to explore the feasibility of the two-velocity method for assessing muscle mechanical capacities within variety of isokinetic tasks. All measurements were performed within two sessions that were organised in two different non-consecutive days. The implemented testing sessions as well as the task within one testing session were randomised. Additionally, implemented angular velocities within each test were also randomised. Both sessions were organised at the similar time for each participant (±1 hour).

7.2.3. Testing procedures

All testing sessions were performed with an using an isokinetic dynamometer (Kin-Kom AP125, Chatex Corp., Chattanooga, Tennessee, USA) in the university research laboratory. According to the manufacturer`s instructions the height and the chair of the dynamometer were adjusted to the individual anthropometric characteristics and the axis of the dynamometer was aligned with the lateral femoral condyle (for the tasks performed with lower extremities) and with the lateral epicondyle of the humerus (for the tasks performed with the upper extremities). All tests and instructions were given by the same examiner who was in charge to verbally encourage participants to exert maximal values of F.

Afterwards, participants performed three maximal voluntary isometric contractions (MVC) of the assessed muscles (i.e., KE, KF, EE, or EF) at 120° of knee/elbow extension (180° corresponding to full extension) that lasted 5 s (Table 3). The trials were separated by a rest period of 1 min and only the trial with the highest F was used for statistical analyses. Following, the F during eight angular velocities (30, 60, 90, 120, 150, 180, 210, 240°) was measured during isokinetic tasks. Both during isometric and isokinetic tests, participants were instructed to exert maximal force. Three trials were performed during isometric tests and respecting each angular velocity. First trial of each contraction (isometric or isokinetic) was used as a familiarization trial, while the trial with highest force output was used for statistical analyses. Implemented pauses between consecutive trials, different velocities during isokinetic tests were 30 seconds and 60 seconds, respectively (Blazquez, Warren, O'Hanlon, & Silvestri, 2013). Pause between two different regimes was set to 5 minutes. All tasks were performed with the dominant limb (i.e., the one they would use for kicking a ball [knee exercises] and writing [elbow exercises]) (Aagaard et al., 2000).

Description of the isokinetic tests was provided bellow:

Knee extension (KE):

Participants were fastened in the chair of the dynamometer with the straps around pelvis, chest and tie. Starting position was set to 90°, while ending position was 170° (180° corresponding to complete extension). Participants were instructed to extend their lower leg from starting to ending position.

Knee flexion (KF):

Participants were fastened in the chair of the dynamometer in the same manner as for KE test. Range of motion was also the same, however, starting position was set to 170°, while final position was 90°. Participants were instructed to flex the lower limb from the starting to the ending position.

Elbow extension (EE):

Participants were fastened in the chair of the dynamometer with the straps around pelvis and chest. Starting position was set to 70°, while the ending position was 135°. Participants were instructed to extend their forearm from starting to ending position.

Elbow flexion (EF):

Participants were fastened in the chair of the dynamometer in the same manner like for the EE test. The range of motion was the same like for EE, while the starting position was set to 135° and ending to 70°.

Picture 2. Testing set-up for elbow extension and elbow flexion test
(Modified and reprinted with permission from: *Relationships between force and rate of force development of different muscle groups as assessed thought various strength tests*, Prebeg, G., 2015)

Picture 3. Testing set-up for knee extension and knee flexion test

7.2.4. Data acquisition and analysis

All F-time signals were collected at 500 Hz, using an isokinetic dynamometer (Kin-Kom AP125, Chatex Corp., Chattanooga, Tennessee, USA). Afterwards, signals were filtered using low-pass (10Hz) second-order (zero-phase lag) Butterworth filter. The program used to collect, filter and calculate necessary variables was written using LabView software (National Instruments, 13.0). Once recorded forces were corrected for the gravity effect, and normalised by body mass using an alometric scale ($N\cdot kg^{2/3}$) (Jaric, 2002). To avoid computation errors, acceleration and deceleration artefacts phases were neglected, and all variables were calculated from the isokinetic part of the F-time curves (Brown et al., 1995). Although angular velocities (°/s) were the same for all subjects, they were multiplied by the length of the individuals' lever arms to obtain linear velocities ($m\cdot s^{-1}$). Thereafter, obtained linear velocities and maximal values of F were used to model F-V relationships by fitting both second order polynomial and linear regression models, using F recorded during all eight velocity conditions (i.e., multiple-point method) and using F recorded during just two most commonly used ones (60 and 180°/s; i.e., two-velocity method). And finally, both multiple- and two-point methods were used for calculating parameters of the F-V relationships (i.e., F_0, V_0, a, and P_{max})(Jaric, 2016).

7.2.5. Statistical analyses

Descriptive data of all F-V relationship parameters are presented as mean and standard deviation since they were normally distributed (Shapiro-Wilk test: $p > 0.05$), while the Pearson's correlation coefficients (r) are presented through their median and interquartile range. The standard error of the estimate (SEE) expressed in absolute values and as a coefficient of variation (CV %) was used to explore the validity of the two-velocity method with respect to the multiple-point method. The validity was determined based on the following scale: very high (CV < 5%), high (CV = 5%–10%), acceptable (CV > 10%–15%), and low (CV > 15%). Student's paired-sample t-tests and Cohen's d effect size (ES) were used to compare the magnitude of the F-V relationship parameters (F_0, V_0, a, P_{max}) between the multiple- and two-velocity methods. The association between the same F-V relationship parameters obtained from the multiple- and two-velocity methods was quantified through the r coefficients. The r coefficients were calculated to determine the relationship between the same F-V relationship parameters obtained from the four different muscles. The level of agreement between F_0 and the maximal measured isometric F was quantified through r coefficients. Qualitative interpretations of the r coefficients as defined by Hopkins, Marshall, Batterham, & Hanin (2009) (0.00–0.09 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; 1.00 perfect) are provided for all significant correlations. A mixed model ANOVA with Bonferroni corrections was applied to each F-V relationship parameter with the "gender" (women and men) as between- and "method" (multiple-point method and two-velocity method) and muscle (KE, KF, EE, and EF) as within-participants factor. All statistical analyses were performed using SPSS software version 20.0 (SPSS Inc., Chicago, IL, USA) and statistical significance was set at an alpha level of 0.05.

7.3. Results

7.3.1. Linearity of the F-V relationship

All F-V relationships were strong and linear independently from whether obtained either from the data averaged across the participants ($r \geq 0.969$; Figure 7) or from the individual F and V data (all $r \geq 0.893$; Figure 8). However, the advantage of the higher polynomial fit (i.e., second order *vs.* linear model) proved to be inconsistent. Namely, half of the r coefficients of polynomial regressions were above the 95% CI of the corresponding linear regressions (KE men, KF women, EE women, EF men), but no significant differences were observed for KE and EF in women and KF and EE in men.

7.3.2. Validity of the two-velocity method

Figure 9 shows both the SEE and correlation coefficients of the parameters obtained from the multiple- and two-velocity methods. No significant differences and only trivial to small ES were obtained for all parameters (all $P > 0.118$ and ES ≤ 0.50). Very large to nearly perfect correlations were observed between the magnitudes of the F-V relationship parameters obtained from the multiple- and two-velocity methods (median r and range: $F_0 = 0.96$ [0.91, 0.99]; $V_0 = 0.71$ [0.35, 0.93]; $a = 0.78$ [0.65, 0.96]; and $P_{max} = 0.78$ [0.21, 0.94]). However, the CV only showed a high to very high validity for F_0 (range: 4.1-9.3%), while a lower validity was observed for the other F-V relationship parameters (range: V_0= 10.8-27.5%; a=*10.3*- 30.4%; P_{max} = 10.8-29.2%).

7.3.3. Sensitivity of the F-V relationship

The ANOVAs conducted on F_0, V_0 and P_{max} revealed significant main effect of muscle group (F_0: F = 186.4, $P < 0.001$; V_0: F = 16.6, $P < 0.001$; P_{max}: F = 85.8, $P < 0.001$) and gender (F_0: F = 11.8, $P = 0.001$; V_0: F = 18.4, $P < 0.001$; P_{max}: F = 46.2, $P < 0.001$), while the ANOVA conducted on a parameter only revealed a significant main effect of muscle group (F = 23.9, $P < 0.001$). Neither the main effect of method nor the interactions reached statistical significance for any of the F-V relationship parameters. Regardless of the method, men showed higher values of F_0, V_0 and P_{max} than women. Similarly, both methods revealed larger values of P_{max} for knee muscles than for elbow muscles due to higher values of F_0, while no clear difference between muscles was observed for V_0. Note that the F and P data were previously normalised for the difference in body size between men and women.

7.3.4. Generalizability of the F-V relationship

To assess the generalizability of the findings, the same F-V relationship parameters across the different tasks were correlated (Table 2). The results proved to be inconclusive. The *r* coefficients were generally low (median *r* and range: F_0 = 0.04 [-0.43, 0.88], V_0 = 0.04 [-0.68, 0.85], *a* = -0.02 [-0.45, 0.71], and P_{max} = 0.08 [-0.48, 0.66]) (Table 2). Only 8 out of 96 coefficients were significant and those were not particularly related either to specific test, or the parameter, or the participant group.

7.3.5. Agreement between theoretical maximal force (F_0) and maximal isometric force

To assess the association between maximal isometric force and theoretical maximal force (F_0) when it was obtained implementing two- or multiple-velocity method. The results were inconclusive and r coefficient ranged from moderate to very large for both females and males and both methods (r range two-velocity method [0.41, 0.87], multiple-velocity method [0,37, 0.85]) (Figure 10). In 9 out of 16 cases r values resulted to be significant.

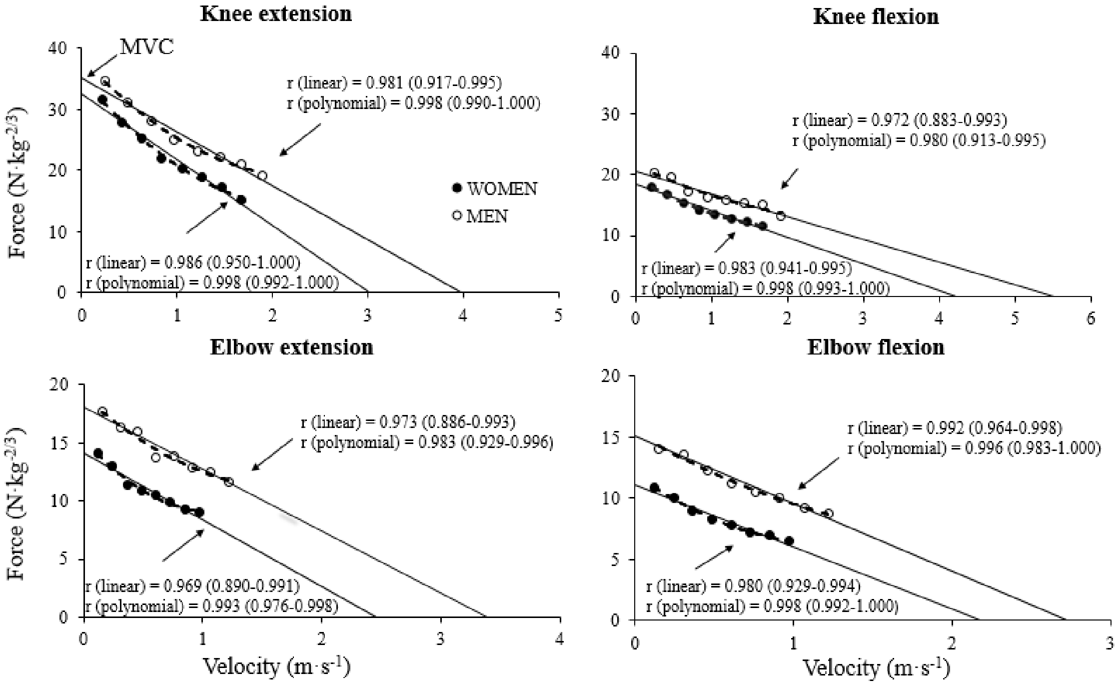

Figure 7. Linear and polynomial regression models obtained from the force and velocity data averaged across the participants during the isokinetic knee extension (upper-left panel), knee flexion (upper-right panel), elbow extension (lower-left panel) and elbow flexion (lower-right panel) tasks. The Pearson's correlation coefficients with corresponding 95% confidence intervals are presented for both the linear and polynomial regression models obtained in women (filled circles) and men (empty circles). Triangles represent the directly measured maximal voluntary isometric contraction (MVC).

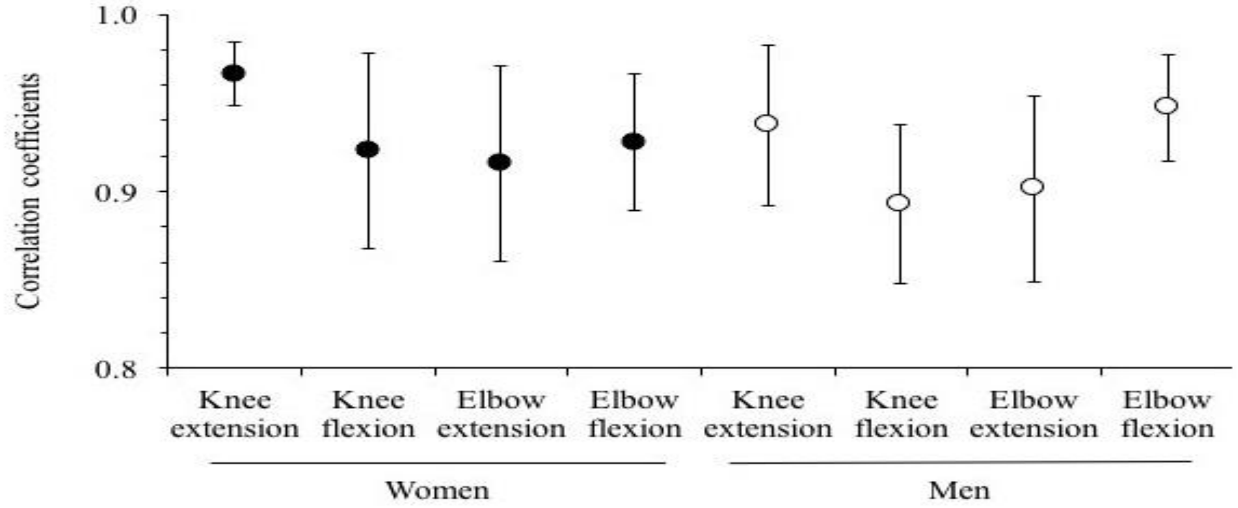

Figure 8. Pearson's correlation coefficients (medians with SD error bars) obtained from individual linear F-V relationships of four isokinetic tasks in women (filled circles) and men (empty circles).

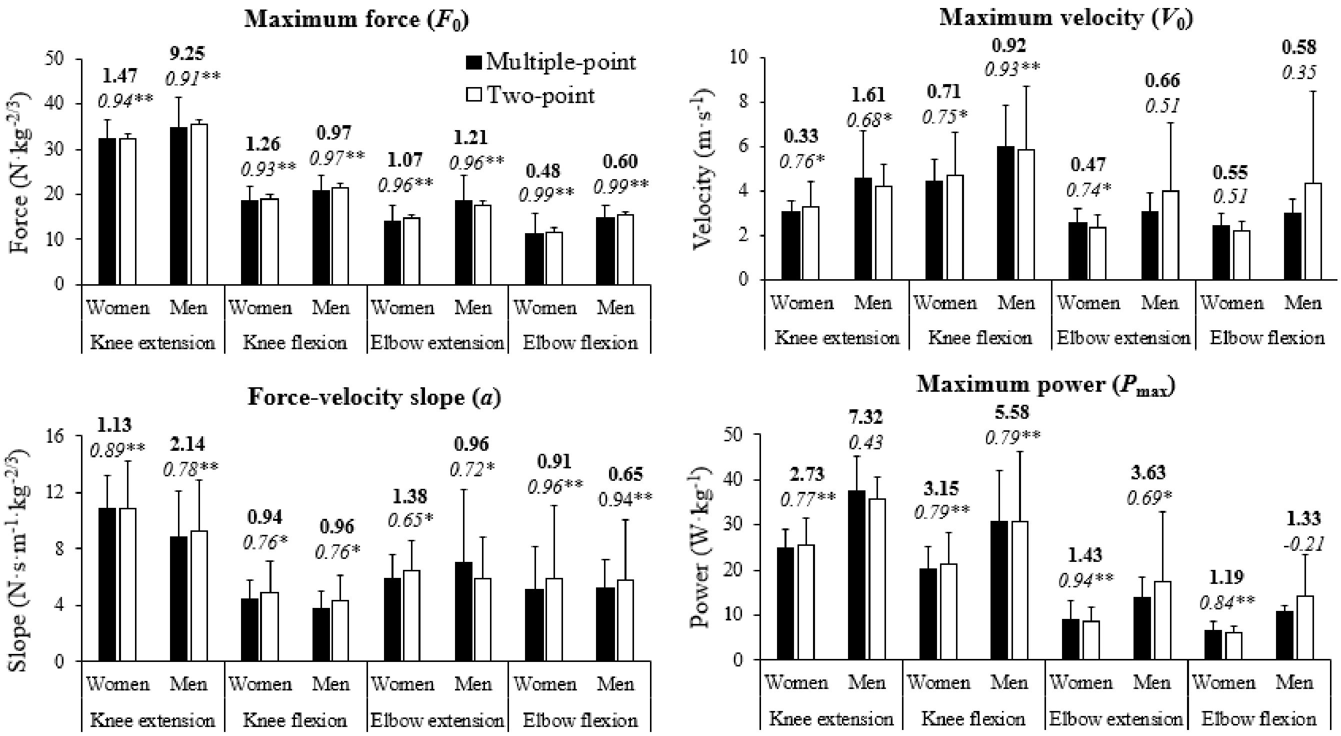

Figure 9. Comparison between the same force-velocity relationship parameters obtained from the multiple-point (filled bars) and two-velocity (empty bars) methods during the four isokinetic tasks. The Cohen's d effect size ([multiple-point mean – two-velocity mean] / SD both; bold numbers) and the Pearson's correlation coefficient (italic numbers) are indicated. Statistical significance: * $P < 0.05$, ** $P < 0.01$. Data are presented as means and standard deviations.

Table 2. Correlations between the same parameters obtained from 4 different tasks by means of the multiple-point and two-point methods

Parameter		Women						Men					
		Multiple-point			Two-point			Multiple-point			Two-point		
		KF	EE	EF	KF	EE	EF	KF	EE	EF	KF	EE	EF
F_0	KE	0.29	-0.06	-0.32	0.42	-0.05	-0.34	**0.70***	**0.65***	-0.18	0.59	-0.01	-0.30
	KF		0.08	-0.39		0.14	-0.43		**0.88****	-0.23		0.44	-0.10
	EE			0.53			0.48			-0.09			0.30
V_0	KE	0.39	0.02	0.09	0.55	-0.33	-0.09	0.10	0.02	0.21	0.33	-0.51	-0.37
	KF		0.47	0.04		0.26	-0.33		0.09	-0.12		0.08	-0.21
	EE			0.04			-0.48			**-0.68***			**0.85****
a	KE	0.14	-0.09	-0.33	0.32	-0.30	-0.38	**0.71***	0.26	-0.18	0.57	-0.45	-0.24
	KF		0.50	-0.39		0.36	-0.34		0.43	-0.26		0.03	-0.07
	EE			0.03			0.05			-0.39			0.24
P_0	KE	**0.66***	0.12	0.20	0.55	-0.17	0.21	0.03	-0.48	0.27	0.38	-0.48	-0.43
	KF		-0.00	0.03		-0.14	-0.17		0.17	0.18		0.00	-0.29
	EE			0.45			0.24			-0.29			**0.86****

F_0, theoretical maximal force; V_0, theoretical maximal velocity; *a*, force-velocity slope; P_0, theoretical maximal power, KE, knee extension; KF, knee flexion; EE, elbow extension; EF, elbow flexion. Statistical significance: * $P < 0.05$, ** $P < 0.01$.

Table 3. Descriptive data of the isometric dynamometry

	KE	***KF***	***EE***	***EF***
Men	39.60 ± 7.49	19.26 ± 3.98	19.75 ± 5.05	18.38 ± 3.68
Women	37.42 ± 4.68	16.35 ± 2.93	17.49 ± 4.03	12.96 ± 2.07

Data are presented as means ± standard deviations for men and women. KE, knee extension; KF, knee flexion; EE, elbow extension; EF, elbow flexion.

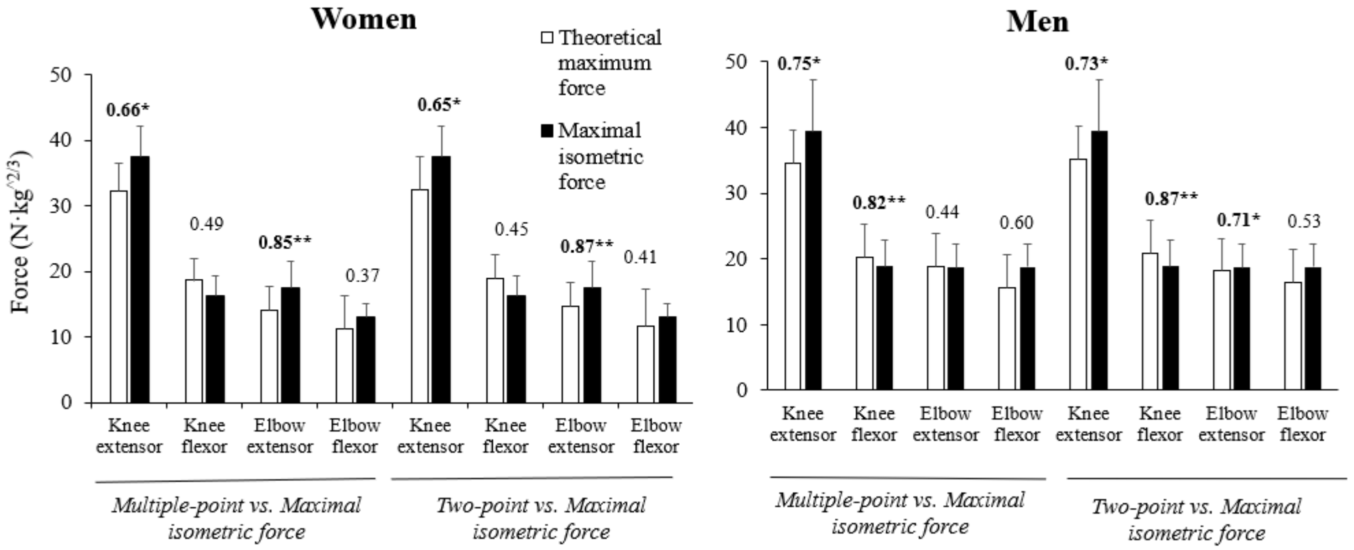

Figure 10. Correlations between theoretical maximum force (empty bars) and maximal measured isometric force (full bars) for women (left panel) and men (right panel). Correlations with the maximal isometric force and theoretical maximum force were made when it was obtained using multiple point method (left part of panels) and two-velocity method (right parts of panels).

7.4. Discussion

This study explored the validity, sensitivity and generalizability of the F-V relationship parameters, obtained from the multiple- and two-velocity methods, during isokinetic testing of various muscles involving both the lower- and upper-body ones. The main findings of this study revealed (1) strong and linear F-V relationships of tested muscle groups (KE, KF, EE, and EF), (2) a high concurrent validity of F_0, but lower for the other F-V relationship parameters, when obtained from the two-velocity method compared to the multiple-point method, (3) the outcomes of both multiple- and two-velocity methods were sensitive to the gender and muscle groups tested (i.e., higher values of F_0, V_0, and P_{max} were generally obtained for men and knee muscles compared to women and elbow muscles, respectively), (4) the magnitude of the same F-V parameters obtained from different muscles were on average poorly correlated, and (5) moderate to very large association was obtained between F_0 and maximal isometric F. The three first findings collectively support the two-velocity method as a valid and sensitive procedure for determining the maximal capacity of the muscles to produce F, but not V, during isokinetic testing. The fourth finding highlights that the F-V relationship parameters cannot be generalised across different muscles.

Linear shape of the F-V relationships obtained from the number of multi-joint movements (i.e., squat jumps, bench press, bench press throws, etc.) was reported in numerous studies (Janicijevic et al., 2019; García-Ramos et al., 2016; Lu, Boyas, Jubeau, & Rahmani, 2017; Zivkovic et al., 2017b). However, polynomial regression models have been usually used for modelling F-V relationships during isokinetic tasks (Carvalho, 2015; Raj et al., 2010). Nevertheless, there are some indication that experimental points (F and corresponding V data) obtained during isokinetic tasks could be used for linear F-V relationship modelling. More specifically, some previous studies that have aimed to explore the shape of the isokinetic F-V relationships demonstrated that if maximal isometric F is excluded from the model, F-V relationship could be modelled using linear model (Grbic et al., 2017; Lemaire et al., 2014; Ripamonti et al., 2008). Confirming our first hypothesis, previous studies have reported high linearity of the F-V relationship modelled for the isokinetic KE task (Grbic et al., 2017; Lemaire et al., 2014; Ripamonti et al., 2008). What is important to emphasize is that this study add additional knowledge about the shape of the F-V relationships modelled during various isokinetic tasks (KF, EE, EF). Specifically, results of the current study demonstrated that F-V relationships are strong and linear, however, it should be noted that half of the r coefficients of polynomial regressions were above the 95% CI of the corresponding linear regressions. Possibly, higher linearity of the F-V relationship obtained for the KE task could be explained by the higher prevalence of this muscle group in everyday activities (e.g., walking, running, climbing stairs, etc.) (Gates, Walters, Cowley, Wilken, & Resnik, 2016). Possible direction of the future studies could be to evaluate the shape of the F-V relationships during other isokinetic tasks.

As a result of the strong linearity of the F-V relationships observed during isokinetic tasks, application of the two-velocity method, which represents less time-consuming and less fatiguing approach, might be used for the F-V relationships modelling. However, when modelled using two-velocity method different F-V relationship parameters demonstrate different level of the concurrent validity in respect to the multiple-point method. Specifically, the most valid parameter has shown to be the F_0, regardless of the isokinetic task (low SEE and high r coefficients), while other parameters (V_0, a, and P_{max}) have shown lower validity, suggesting that the two-velocity method is less valid to estimate these parameters. It seems that findings of the present study contradict the findings obtained in the previous studies that investigated concurrent validity of the F-V parameters during different multi-joint movements (García-Ramos & Jaric, 2018; Zivkovic et al., 2017b). Possible explanation regarding lower validity of the V_0 (and parameters which calculation directly depends from the magnitude of the V_0, a and P_{max}) might be that our experimental data were F-biased, meaning that higher extrapolation was needed to the V-intercept. In his recent paper, Pérez-Castilla et al. (2018) emphasized the importance of selecting the appropriate experimental points and recommended utilization of the experimental points that are closer to the intercepts, especially to the axis intercept. Although it stands that the two angular velocities used for two-velocity modelling are the velocities most commonly used during isokinetic testing (i.e., 60 and 180°/s) (Raj et al., 2010; Zemach et al., 2009), the concurrent validity of the F-V relationship parameters could be increased by selecting higher angular velocities. Future studies should try to widen the range of the preselected angular velocities, in order to identify which is the combination of the angular velocities that can be used for obtaining more valid F-V relationship parameters.

It has been generally considered that within general population men and lower-body muscles are stronger than woman and upper body muscles, respectively (Miller, MacDougall, Tarnopolsky, & Sale, 1993). However, possible differences in the magnitude of the F-V relationship parameters between different groups was not in the scope of the research attention (García-Ramos, Torrejón, et al., 2018). The results of the present study supported our third hypothesis. As it has been expected, both methods (i.e., multiple- and two-point method) presented higher values of the F_0, V_0 and P_{max} relationship parameters for men in comparison to the women and higher P_{max} for lower- in comparison to upper-body muscles. Differences between lower- and upper-body muscles originate more from the differences in their maximal F, rather than from the differences in their maximal V. Therefore, it seems that F-V relationship assessment is sensitive enough to distinguish among maximal muscle capacities (i.e., F, V and P) between different muscle groups and gender.

Rejecting our fourth hypothesis, the correlations observed between the same F-V relationship parameters were shown to be low. Although the possible generalisation between the same parameters might save time, the inconclusive and generally low correlations were observed between tasks. Although this is the first study that investigated this issue within single-joint movements, the findings of the present study are in consent to the study of Zivkovic et al. (2017) who assessed the correlations across different isoinertial multi-joint tasks. This is also in agreement with the study of Prebeg et al., (2013) who demonstrated that maximal mechanical capacities differ more between muscles than between variables obtained from the same muscle/muscle group. Therefore, sports practitioners, therapist and coaches should evaluate single muscle group/exercise to obtain valid information about muscle mechanical capacities of their subjects.

Although isometric F portrays an important quality of the musculoskeletal system, association between F_0 parameter of the F-V relationship and maximal isometric F was moderate to very large regardless of the gender or muscle group. The inconclusive results indicate that F_0 parameter cannot be used as a predictor of the maximal isometric F value during isokinetic tasks. Contrary to our findings, Cosic et al. (2019) obtained high correlations between F_0 and both maximal isometric F and 1RM (0.84, 0.92, respectively). However, possible explanation for this discrepancy in the results could be found in the type of the performed task. Specifically, in the present study, muscles acting in the single-joint were tested, while in the study of Cosic et al. (2019) task was squat jump performed on a Smith machine. Therefore, it seems that F_0 and maximal isometric F share the same variance to some extent, however this shared variance is more pronounced within multi-joint tasks.

Respecting possible future directions and limitations of the current study, few things should be acknowledged. Firstly, our experimental points are somewhat F-biased (i.e., nearer to the ordinate) that influenced decrement in the concurrent validity of the V_0 parameter, and in parameters that directly depend on it (i.e., a and P_{max}). Secondly, the F-biased experimental points can partially explain the low generalizability between some of the F-V relationship parameters, because the accuracy of the two-velocity method could be diminished due to the higher distance to the axis. And finally, future studies should try to seek for an optimal combination of the experimental points that might increase the accuracy of the F-V relationship and its parameters (Pérez-Castilla et al. 2018).

7.5. Conclusions

Generally, the findings of the current study reinforce utilisation of the two-velocity method, a fast, valid and sensitive procedure for determination of the maximal muscle capacity to generate F (i.e., F_0). At the same time its implementation is somewhat limited for rest of the muscle capacities (V_0, a and P_{max}). For obtaining comprehensive analysis of the individual`s general muscle function, F-V should be modelled for every tested muscle/muscle group. Therefore, for increasing time efficiency and decrease fatigue associated to the testing procedures, two-velocity method could be confidently used for assessing maximal muscle capacity to produce F_0, while future studies should seek for the more optimal combination of the experimental points to increase the preciseness of the V_0, a and P_{max} for isokinetic tasks.

Study 2

8. Isokinetic testing: sensitivity of the force-velocity relationship assessed through the two-velocity method to discriminate between muscle groups and participants' physical activity levels (Study 2)

8.1. Introduction

Muscle isokinetic strength tests are considered safe, valid and reliable (Land & Gordon, 2011). Therefore, they have been widely used to assess the state of individual muscle groups and the asymmetries between them (Holmes & Alderink, 1984; Michael et al., 2005). A basic requisite of isokinetic testing is to record force output at a constant movement velocity, that may range from 0-500 °/s depending on the device (Land & Gordon, 2011). In this regard, it has been argued that angular velocities above 180 °/s should be avoided because the range of motion (ROM) under the constant velocity is very small and this might decrease measurement accuracy (Brown et al., 1995). The two velocities most commonly used during isokinetic testing procedures are 60 and 180°/s (Janicijevic et al., 2019; Grbic et al., 2017; Lemaire et al., 2014), which have been suggested to reveal the maximal capacities of the muscles to produce force and power, respectively (Raj et al., 2010; Zapparoli & Riberto, 2017). However, it is known that higher values of force can be achieved under lower angular velocities , while maximal power could be attained at higher angular velocities (Raj et al., 2010). In addition, the standard isokinetic test (i.e., force output recorded against a predetermined velocity) cannot reveal the maximal velocity capacity because (I) the velocity cannot be voluntarily changed during the movement, and (II) the maximal movement velocity is considerably higher than the velocities typically used during isokinetic tests (Bober et al., 1987).

The linear regression has been recommended for modelling of the force-velocity (F-V) relationship during multi-joint movements because it has been suggested that the F-V relationship during these tasks follows a linear shape (Jaric, 2015). However, previous studies implied that the F-V relationship may also be linear when obtained from single-joint isokinetic tasks (Grbic et al., 2017; Lemaire et al., 2014; Ripamonti et al., 2008). A benefit of the strong linearity of the F-V relationship is that it provides a possibility to estimate maximum force (F_0), velocity (V_0) and power (P_{max}) producing capacities within a single testing procedure. In this manner, additional tests for separate evaluation of the V_0 and P_{max} capacities could be avoided. Furthermore, recording force values against only two angular velocities could provide enough information to accurately determine the F-V relationship (i.e., two-velocity method) (García-Ramos & Jaric, 2018; Jaric, 2016; Petronijevic et al., 2018). In this regard, Grbic et al. (2017) reported a high validity of the F-V relationship parameters (F_0, V_0, and P_{max}) obtained through the two-velocity method (force recorded at 60 and 180 º/s) compared to the multiple-point method (force recorded at five velocities: 30, 60, 120, 180, 240 º/s) during the isokinetic knee extension (KE) task. Previously, Lemaire et al. (2014) reported a high agreement between torque- and power-velocity relationships when three angular velocities were used in comparison to eight for its modelling. However, to date, no study has evaluated the feasibility of the two-velocity method in isokinetic settings (e.g., 60 and 180º/s).

It may be important to elucidate if the F-V relationship assessed through the two-velocity method is able to discriminate between participants of different physical activity levels (active vs. non-active) as well as between antagonistic muscle groups (e.g., knee, hip, elbow and shoulder). Although Cuk et al., (2016) reported sensitivity of the F-V parameters to discriminate between participant of different activity level, no previous studies have compared magnitudes of the F-V relationship parameters assessed by isokinetic dynamometry between antagonistic muscle groups. It has been proposed that quantitative relation of the antagonist muscles strength could present valuable additional information to strength values of individual muscles (Campbell & Glenn, 1982). In this regard, higher force values have been reported for extensor muscles acting on the knee (Kurdak et al., 2005) and hip (Castro et al., 2018), while flexor muscles were stronger at shoulder (Cook, Gray, Savinar-Nogue, & Medeiros, 1987) and elbow joints (Yang et al., 2014). It should keep in mind that F-V relationship modelling can help us discriminate not only between maximal force capacities (F_0), but also between maximal power (P_{max}) and maximal velocity capacities (V_0) of antagonist muscle pairs. In addition, it would be also interesting to determine the possibility of generalizing the outcomes of the F-V relationship between antagonist muscle pairs. It should be kept in mind that the generalizability of the F-V relationship parameters has been shown to be low between different muscle groups assessed during multi-joint task (e.g., jumping and sprinting) (Cuk, Prebeg, Sreckovic, Mirkov, & Jaric, 2017), but no previous study has explored the association between the same F-V relationship parameters obtained from antagonist muscle pairs assessed using isokinetic dynamometry.

Scarce information exists regarding the maximal velocity capacity of individual muscles due to the limitations of isokinetic devices for testing very fast movements. However, other technologies have been used for measuring the maximal velocity of different body segments (Lambert, Beck, & Weeks, 2017; Wagner et al., 2014). Jessop and Pain (2016) used a high-speed video camera to measure the maximal velocity of flexor and extensor muscle groups acting on six joints (ankle, knee, hip, shoulder, elbow and wrist) during movements performed in a standing position. The issue regarding measuring velocity in a standing position is that the gravitational component has a positive and negative effect on maximal velocity during flexion and extension movements, respectively. Therefore, the influence of gravity did not allow to accurately compare maximal velocity capacities between flexor and extensor muscle groups acting on the same joints. Mirkov et al. (2002) showed that when performing the exercise with the arm in an abducted position, elbow flexors and extensors have similar velocities at a ROM from 115 to 165 °, while higher velocity values were obtained for flexors from 65 to 115 ° (180 ° is considered to be maximal extension). That elbow flexors are faster than extensors in a variety of conditions was also confirmed by Jaric (2000). However, very little information exists regarding the comparison of maximal velocity capacity between flexor and extensor muscles acting on other joints (e.g., knee, hip, and shoulder). The issue with comparing maximal velocities between different studies was highlighted by Bober, Putnam and Woodworth (1987) who reported that the maximal velocity of knee extensor muscles was dependent of both the ROM and pre-stretch (velocity values ranged from 213 to 1087 °/s). Therefore, the existing literature does not allow us to hypothesise regarding the possible differences in maximal velocity capacities between antagonist muscle pairs acting on several joints.

Taking all of the above into account, there is an apparent need to explore the feasibility of the two-velocity method (i.e., force output recorded against only two angular velocities) to assess the F-V relationship parameters during isokinetic tasks. Therefore, the main aim of this study was to evaluate the sensitivity of the F-V relationship assessed through the two-velocity method to discriminate between (I) extensor and flexor muscle groups acting on the same joints (knee, hip, elbow and shoulder), and (II) men with different levels of physical activity. The generalizability of the same F-V relationship parameters between antagonist muscle pairs was also examined. It was hypothesized that (I) F_0 and P_{max} obtained during KE, hip extension (HE), elbow flexion (EF), and shoulder extension (SE) would be higher than during the knee flexion (KF), hip flexion (HF), elbow extension (EE), and shoulder flexion (SF), respectively. It was also hypothesized that (II) F_0 and P_{max} of all muscles would be higher for active compared to non-active participants, and (III) the association between the same F-V relationship parameters across different muscle groups would be low. These results could allow better understanding of the benefits of modelling that isokinetic testing procedure of the F-V relationship through the two-velocity method.

8.2. Method

8.2.1. Participants

Forty young men volunteered to participate in this study. The physical activity level was assessed by the International Physical Activity Questionnaire (IPAQ), which was used to divide participants in active (n = 27, age = 23.7 ± 2.9 years [range = 21.0 - 26.0 years], height = 1.83 ± 0.06 m, body mass: 79.8 ± 8.0 kg) and non-active group (n = 13, age = 21.9 ± 4.0 years [range = 17.8 - 26.0 years], height = 1.80 ± 0.06 m, body mass = 68.4 ± 9.9 kg). All participants were free from chronic diseases and musculoskeletal injuries. Participants were introduced with the testing procedures and possible risks associated with isokinetic assessment. The study protocol was approved by the Institutional Review Board and was in accordance with the principles of the Declaration of Helsinki. All participants singed an informed consent form.

8.2.2. Study design

This study was designed to explore the feasibility of the two-velocity method for assessing the muscle mechanical capacities during several isokinetic tasks. The study consisted of four testing sessions separated by 48-72 hours. The flexor and extensor muscle groups of one joint were tested in each session against two angular velocities. The order of testing of the joints (elbow, knee, shoulder and hip), muscles (flexors and extensors), and velocities (60 and 180º/s) was randomised. All testing sessions took part at the same time of the day for every participant (±1 hour) and under similar environmental conditions.

8.2.3. Testing procedures

Measurements were conducted at the Faculty research laboratory, using an isokinetic dynamometer (Kin-Kom AP125, Chatex Corp., Chattanooga, Tennessee, USA). Every testing session started with a standardised 5 minutes warm-up that consisted of cycling on a leg cycle ergometer and stretching exercises. Afterwards, the participants were positioned into the chair of the dynamometer and fixed with Velcro straps in accordance to the manufacturer's guidelines. The axis of the dynamometer was aligned with the axis of the participants' joint using visual inspection and manual palpation. Muscle force was assessed at two angular velocities: 60 and 180°/s. Participants performed three cycles of maximal voluntary contractions (1 cycle = 1 flexion + 1 extension) separated by 30 seconds. The recovery time between different sets was set to 2 minutes. Participants were encouraged by the same experienced examiner to execute the movement as strong and as fast as possible. In addition, participants received visual feedback of force values throughout the whole execution of the exercise. All measurements were performed with the dominant extremity (i.e., extremity that would be used for kicking a ball [knee and hip exercises] and writing [elbow and shoulder exercises]) (Aagaard et al., 2000; Holmes & Alderink, 1984). The ROM was 80º for the knee tasks (from 90° to 170°) (Grbic et al., 2017), 50º for the hip tasks (from 90° to 140°) (Dvir, 2004), 65º for the elbow tasks (from 45° to 110°) (Parr, Yarrow, Garbo, & Borsa, 2009), and 80º for the shoulder tasks (from 90° to 170°) (Dvir, 2004).

8.2.4. Data acquisition and analysis

A custom-made Lab View application was used to provide visual feedback on a computer screen, data acquisition and processing of the force-time signals. Force-time signals were recorded at 500 Hz and low-pass filtered (5 Hz) using a second-order (zero-phase lag) Butterworth filter. The peak force value of each trial was calculated from the isokinetic part of the force-time curve (Brown et al., 1995). The highest peak force of the three trials was used for further analyses. Force data were normalized to the body mass on the power of 2/3 (Jaric, 2002). Linear velocities ($m \cdot s^{-1}$) were calculated as a product of angular velocity and the length of individuals' lever arm. Then, using normalised force and linear velocity, F-V relationships were modelled by fitting the following linear regression model:

$$F(V)= F_0 - aV \; (eq.1)$$

where F_0 represents the force-intercept (i.e., theoretical maximal force), a is the slope that corresponds to F_0/V_0, and V_0 is the velocity-intercept (i.e., theoretical maximal velocity), while P_{max} (i.e., maximal theoretical power) was calculated as $P_{max} = F_0 \cdot V_0/4$.

8.2.5. Statistical analysis

Mean and standard deviations (SD) are used for reporting descriptive data, while the Pearson's correlation coefficients (*r*) are reported through their median and inter-quartile range values. A total of 16 mixed-model ANOVAs with Bonferroni post hoc corrections (4 F-V relationship parameters [F_0, V_0, a and P_{max}] × 4 joints [knee, hip, elbow and shoulder]) were applied with the muscle group (flexor *vs.* extensor) as within- and physical activity level (active *vs.* non-active) as between-participant factors. The Cohen's d effect size (ES) was used to explore the magnitude of the differences and it was computed considering the harmonic mean of the SD of the compared conditions. The following scale was used to interpret the magnitude of the ES: negligible (<0.2), small (0.2–0.5), moderate (0.5–0.8), and large (≥0.8) (Cohen, 1988). The association between the same F-V relationship parameters obtained from flexor and extensor muscle groups acting on the same joint was quantified through the *r* coefficient. Qualitative interpretations of the *r* coefficients were: "0.00–0.09 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; 1.00 perfect" (Hopkins et al. 2009). Magnitude-based inference was performed by means of a custom Excel spreadsheet, while other statistical analyses were performed using the software package SPSS (IBM SPSS version 22.0, Chicago, IL, USA). Statistical significance was set at an alpha level of 0.05.

8.3. Results

Descriptive data (Mean ± SD) for the F-V relationship parameters are provided in Table 4. Linear regression models obtained during the knee, hip, elbow and shoulder tasks were presented in the Figure 11. None of the *muscle group × physical activity level* interactions reached statistical significance ($p \geq 0.093$) (Table 4, Figure 11). A significant main effect of muscle group was obtained for F_0, a and P_{max} in the knee and hip joints (higher values for extensors) as well as in the shoulder joint (higher values for flexors), while for V_0 the main effect of muscle group reached statistical significance only for the knee joint (higher value for flexors) (Figure 12). A significant main effect of physical activity level was obtained for F_0 during the KE and KF tasks and for P_{max} during KF, EE and SE tasks (higher values were always obtained by the active group) (Figure 13).

Table 4. Comparison of the force-velocity (F-V) relationship parameters between muscle groups and physical activity levels for each joint.

F-V parameter	Joint	Active		Non-active		ANOVA		
		Flexor	Extensor	Flexor	Extensor	Muscle	PAL	Muscle × PAL
F_0 (N·kg$^{-2/3}$)	Knee	20.5±4.0	29.7±5.0*	17.6±3.2#	26.1±4.8#	$p < 0.001$	$p = 0.015$	$p = 0.706$
	Hip	19.4±4.2	37.4±9.8*	19.8±3.1	33.5±8.0	$p < 0.001$	$p = 0.403$	$p = 0.093$
	Elbow	12.3±2.0	12.1±2.4	11.6±2.9	10.7±1.7	$p = 0.192$	$p = 0.127$	$p = 0.387$
	Shoulder	18.7±3.5	14.0±2.8*	17.6±2.8	12.0±2.1	$p < 0.001$	$p = 0.093$	$p = 0.372$
V_0 (m·s^{-1})	Knee	3.20±0.93	2.50±0.51*	3.10±1.59	2.65±1.46	$p = 0.009$	$p = 0.940$	$p = 0.538$
	Hip	4.17±2.40	3.07±2.03	3.45±2.75	3.93±2.78	$p = 0.556$	$p = 0.907$	$p = 0.142$
	Elbow	4.39±1.85	4.76±2.36	4.47±2.25	3.48±1.36	$p = 0.508$	$p = 0.241$	$p = 0.158$
	Shoulder	3.72±1.78	3.35±1.49	3.42±2.50	3.37±2.19	$p = 0.523$	$p = 0.804$	$p = 0.629$
a (N·m·s^{-1}·kg$^{-2/3}$)	Knee	6.17±2.54	10.64±2.82*	5.98±2.75	10.16±4.30	$p < 0.001$	$p = 0.709$	$p = 0.773$
	Hip	5.50±3.40	11.19±5.96*	7.01±3.34	11.34±6.52	$p < 0.001$	$p = 0.543$	$p = 0.487$
	Elbow	2.98±1.11	2.94±1.31	3.28±2.53	3.22±1.21	$p = 0.884$	$p = 0.395$	$p = 0.972$
	Shoulder	5.93±3.07	4.58±2.33*	6.88±3.98	4.11±1.67	$p < 0.001$	$p = 0.770$	$p = 0.168$
P_{max} (W·kg$^{-2/3}$)	Knee	16.1±4.4	18.4±3.8*	12.9±4.8#	16.2±5.2	$p = 0.001$	$p = 0.040$	$p = 0.507$
	Hip	19.6±10.8	29.5±19.0*	16.1±11.1	29.3±14.8	$p = 0.001$	$p = 0.622$	$p = 0.622$
	Elbow	13.4±5.6	14.3±7.5	12.2±5.9	9.4±4.3#	$p = 0.459$	$p = 0.076$	$p = 0.147$
	Shoulder	16.9±7.7	11.3±4.6*	14.1±8.5	9.6±4.7#	$p < 0.001$	$p = 0.244$	$p = 0.623$

Mean ± standard deviation. F_0, maximum force; V_0, maximum velocity; a force-velocity slope; P_{max}, maximum power; PAL, physical activity level. *, significant differences with respect to Flexor; #, significant differences with respect to Active.

Linear regression models obtained from the force and velocity data averaged across the participants during the knee extension and flexion (upper-left panel), elbow extension and flexion (lower-left panel), hip extension and flexion (upper-right panel) and shoulder extension and flexion (lower-right panel) tasks are depicted in Figure 11. The correlations of the F-V relationship parameters between flexor and extensor muscles acting on the same joint are reported in Table 5. Moderate to large correlations were observed in the knee and shoulder joints for all F-V relationship parameters (*r* ranges from 0.349 to 0.571). Hip joint showed significant correlations for F_0 ($r = 0.640$) and *a* ($r = 0.385$), while the elbow joint only showed a significant correlation for F_0 ($r = 0.513$).

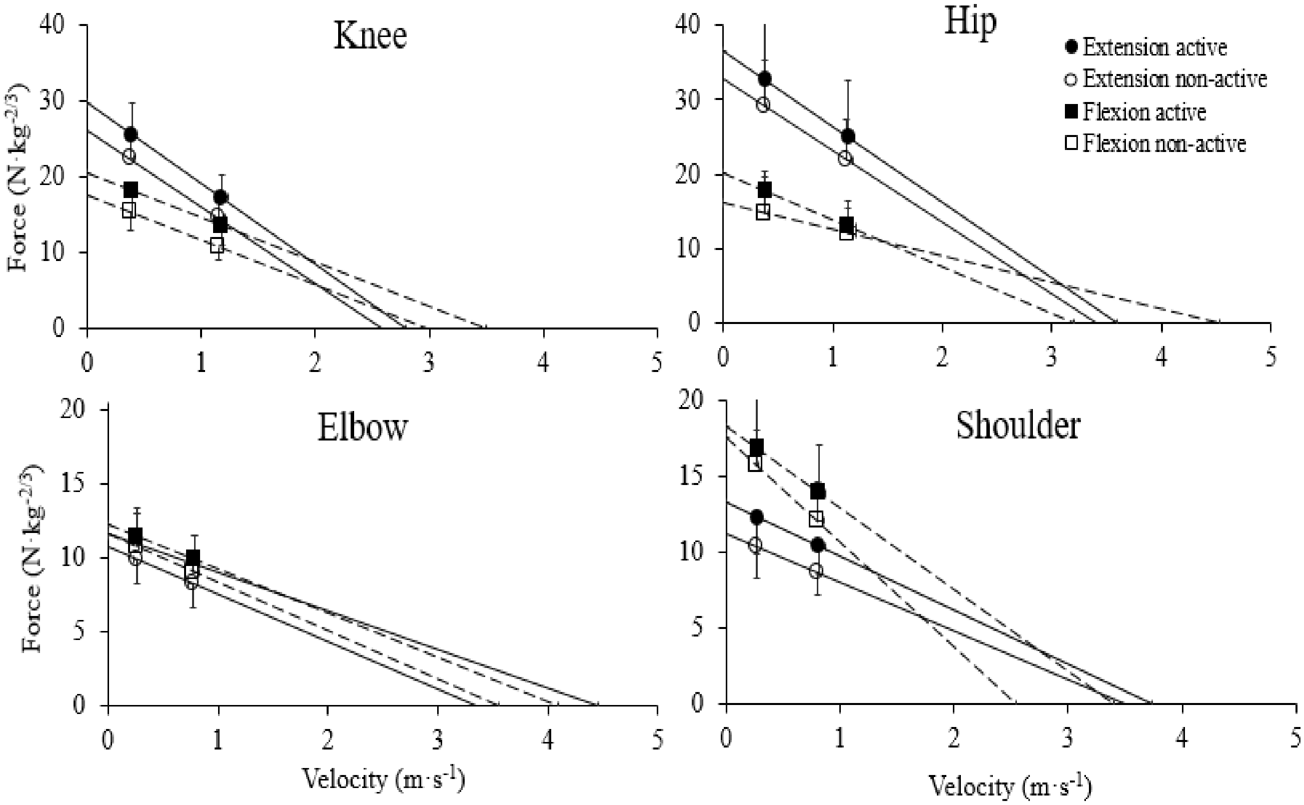

Figure 11. Linear regression models obtained from the force and velocity data averaged across the participants during the knee extension and flexion (upper-left panel), elbow extension and flexion (lower-left panel), hip extension and flexion (upper-right panel) and shoulder extension and flexion (lower-right panel) tasks. Straight and dashed lines represent extensor and flexor muscles, respectively. The error bars depict the standard deviations of flexor (squares) and extensor (circles) muscle groups.

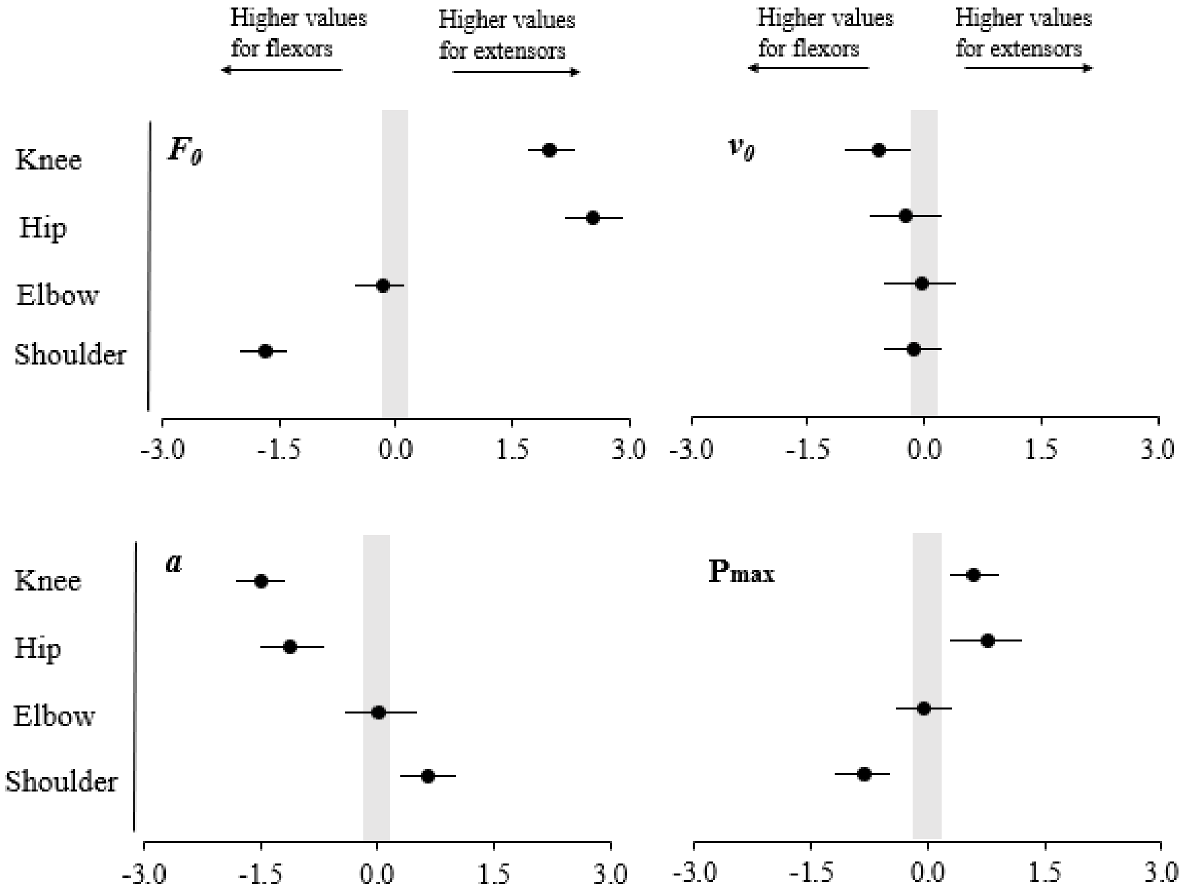

Figure 12. Standardized differences (95% confidence intervals) for maximum force (F_0; upper-left panel), maximum velocity (V_0; upper-right panel), force-velocity slope (a; lower-left panel) and maximum power (P_{max}; lower-right panel) between the antagonist muscle pairs acting on the knee, hip, elbow and shoulder joints (ES = Extensor mean – Flexor mean / SD_{both}).

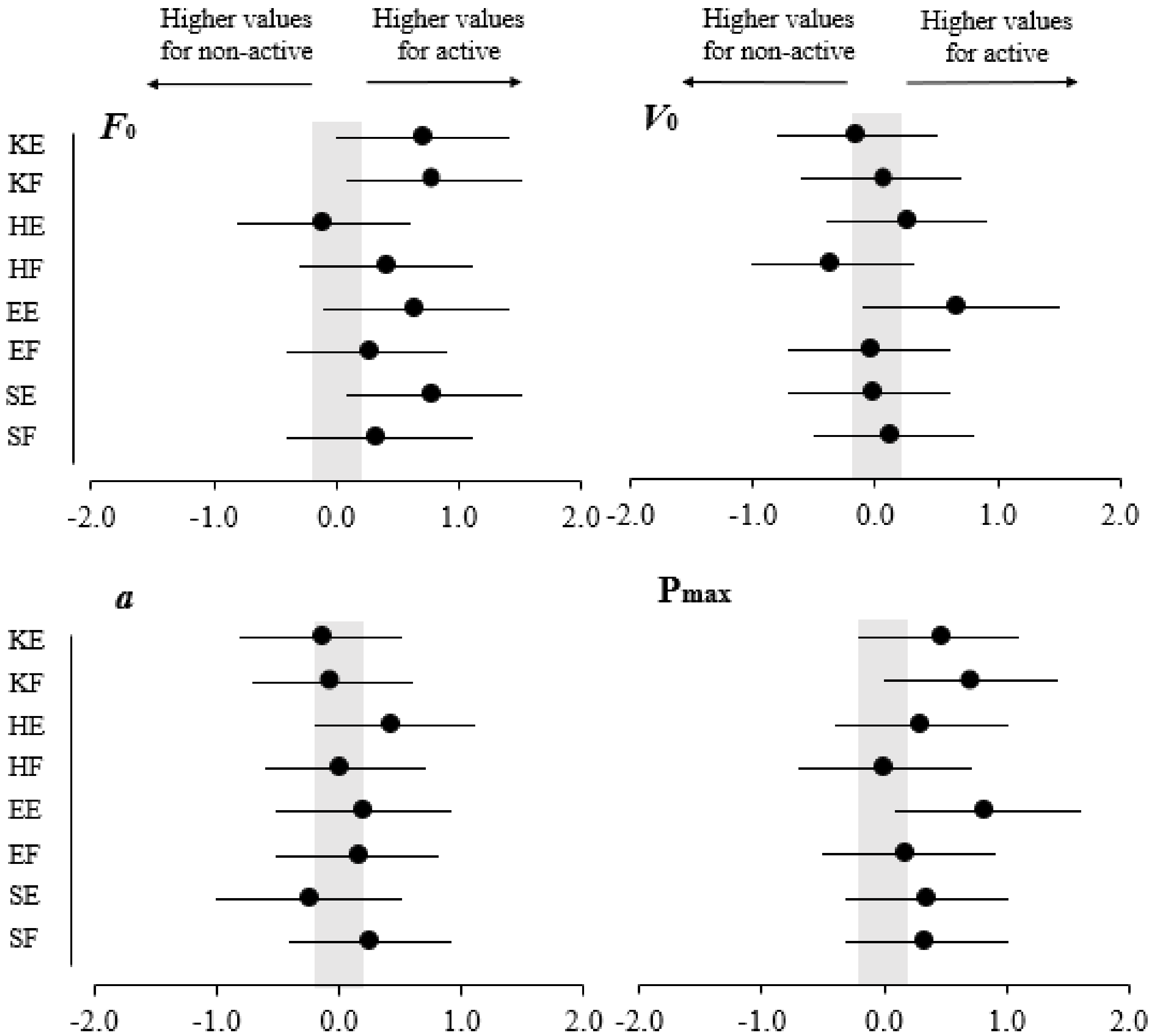

Figure 13. Standardized differences (95% confidence intervals) for maximum force (F_0; upper-left panel), maximum velocity (V_0; upper-right panel), force-velocity slope (a; lower-left panel) and maximum power (P_{max}; lower-right panel) between active and non-active groups for each muscle group. ES, effect size. KE, knee extension; KF, knee flexion; HE, hip extension; HF, hip flexion; EE, elbow extension; EF, elbow flexion; SE, shoulder extension; SF, shoulder flexion.

Table 5. Association of the force-velocity relationship parameters between flexor and extensor muscles acting on the same joint.

	F_0	V_0	a	P_{max}
Knee	0.571**	0.349**	0.554**	0.496**
Hip	0.640**	0.132	0.385*	0.142
Elbow	0.513**	0.057	-0.110	0.275
Shoulder	0.560**	0.467**	0.474**	0.579**

F_0, maximum force; V_0, maximum velocity; a, force-velocity slope; P_{max}, maximum power. Statistical significance: * $p < 0.05$, ** $p < 0.01$.

8.4. Discussion

This study was designed to explore whether the F-V relationship modelled by the two-velocity method could discriminate between antagonist muscle groups and males with different physical activity levels. The main findings revealed that (I) F_0, a and P_{max} were higher for the KE, HE and SF compared to their corresponding muscle pairs (KF, HF, SE), while V_0 was significantly higher for KF compared to KE, (II) F_0 was higher for active compared to non-active males only during the KE and KF tasks, while P_{max} was higher for active males during KF, EE and SE, and (III) the association between the same F-V parameters across different muscle groups were generally moderate to large. The first two findings generally support the two-velocity method as a sensitive procedure for testing muscle capacities during knee, hip and shoulder isokinetic tasks, while a lower sensitivity was observed for the elbow task. The third finding suggests that the association of the F-V relationship parameters between antagonist muscle groups could be higher than the previously reported between different multi-joint exercises.

The function of the muscles acting on the knee joint has been commonly evaluated by isokinetic dynamometry (Grbic et al., 2017). Previous studies have reported higher values of force under isokinetic conditions for KE compared to KF muscles (Holmes & Alderink, 1984; Kabacinski, Murawa, Mackala, & Dworak, 2018). Similarly, higher values of F_0 and P_{max} for the KE compared to the KF were observed. Even though a specific hypothesis regarding V_0 was not formulated, our results demonstrated that KF tends to show a higher V_0 than KE. A plausible explanation might be the different architecture of KE and KF muscles (i.e., KF muscles consist of long and parallel fibres that are expected to allow higher shortening velocities than KE muscles which present a greater pennation angle) (Lieber & Fridé N, 2000). In addition, both F_0 and P_{max} were higher for active males during the KF task, while only F_0 was higher for active males during the KE task. Therefore, as far as the knee joint is concerned, it can be concluded that the two-velocity method was sensitive enough to discriminate between antagonist muscles as well as between males of different physical activity levels.

The weakness of the muscles acting on the hip joint may provoke imbalances of the whole kinetic chain of the lower limbs (Khayambashi, Ghoddosi, Straub, & Powers, 2016). The weakness of the HE evaluated during an isokinetic concentric contraction has also been positively connected with an increased risk of hamstring injury (Sugiura, Saito, Sakuraba, Sakuma, & Suzuki, 2008). In line with other studies (Alexander, 1990; Calmels et al., 1997), both higher F_0 and P_{max} for HE compared to HF were observed, but no significant differences were reported between active and non-active males for any of the F-V relationship parameter. Therefore, while the two-velocity method seems to be effective to discriminate between HE and HF muscle groups, it remains unclear whether it could also be sensitive to discriminate between males of different physical activity levels. Future studies should compare populations with clear differences in the strength of HE and HF (e.g., runners *vs.* taekwondo athletes) to further explore the sensitivity of the two-velocity method to discriminate between different populations.

The repetitive overhead movements which are common for some sports (e.g. throwing and spiking) may be responsible for sport-specific injuries of the elbow (Wilk, Macrina, Cain, Dugas, & Andrews, 2012). Velocities of the elbow can go up to 2300°/s during overhead pitching (Wilk et al., 2012) and 1700°/s for tennis serve (Leon Lategan & Krüger, 2007). These extremely high velocities emphasize the importance of developing the strength of the muscles acting on the elbow. Rejecting our hypothesis, no differences were found for any F-V relationship parameter between the EF and EE muscle groups. This contradicts the results of Jaric (2000) who revealed higher velocities for EF compared to EE under a variety of conditions. In addition, only P_{max} during the EE was significantly higher for active compared to non-active males. The overall lack of significant differences between active and non-active males could be explained because they did not necessarily differ in the activities performed with the upper limbs, or by the fact that isokinetic testing may not be sensitive to discriminate between active and non-active populations (Sarig Bahat et al., 2019). Future studies should explore if the two-velocity method could be sensitive enough to find differences in the F-V relationship parameters between groups that clearly differ in the strength capacity of their elbow muscles. Therefore, based in our findings, the sensitivity of the two-velocity method for assessing the mechanical capacities of EF and EE muscle groups should be questioned.

Shoulder isokinetic testing is commonly used not only for testing participants who are recovering from shoulder injuries, but also for healthy overhead athletes (i.e., those who use their upper limbs in an arc over head to propel a ball) (Ellenbecker & Roetert, 2003). The shoulder joint is one of the most mobile joints of the human body and, therefore, it needs to be surrounded with strong muscles (Veeger & van der Helm, 2007). Confirming our first hypothesis, higher F_0 values were obtained for SF compared to SE muscles. However, significant differences between active and non-active males were obtained only for P_{max} during SE in which active males showed higher values. Previous studies have reported significantly higher force values for active participants compared to non-active participants during both SE and SF tasks (Cook et al., 1987). The absence of significant differences in F_0 in our study could be explained because the level of upper limb activity did not meaningfully differ between the active and non-active groups. Note that the findings related to the shoulder joint are somehow similar to the ones reported for hip muscles, suggesting that the two-velocity method is sensitive to discriminate between flexor and extensor muscles, but a lower sensitivity was observed for discriminating between active and non-active males. Therefore, the recommendation of comparing groups with clear differences in upper-body force capacities could be also applied for the shoulder joint.

The possibility of generalising the F-V relationship parameters between antagonist muscle groups was also explored in the present study. Rejecting our last hypothesis, stronger correlations were found for the magnitude of the same F-V parameters than previous studies that explored the correlations between different isoinertial multi-joint exercises (Marcote-Pequeno et al., 2018; Zivkovic et al., 2017b). Regardless of the higher generalizability of the F-V relationship parameters observed in the current study, it should be noted that significant correlations were not systematically reached, which suggest that a given maximal mechanical capacity cannot be predicted from the value observed in the antagonist muscle group. Regarding the possible limitations of the present study, it should be acknowledged that during the testing procedure the two most commonly used angular velocities (i.e., 60 °/s and 180 °/s) were applied. Because these two velocities are far from the velocity-intercept, it is possible that the precision of the F-V relationship could be improved using velocities nearer to the velocity-intercept by reducing the extrapolation needed to reach V_0 (García-Ramos & Jaric, 2018). In addition, the lack of significant differences between active and non-active males for several F-V relationship parameters and muscle groups could be the consequence of not controlling the type of sport and recreational activity performed by the participants. Therefore, future studies should try to compare participants with more distinctive characteristics regarding the function of the different muscles assessed.

A new potential benefit of the two-point method could be calculation of the muscle mechanical capacities ratios (i.e., strength ratios, power ratios, velocity ratios). It has been argued that strength ratio between antagonist muscle groups could provide meaningful additional information about strength capacities of antagonistic muscle groups (Tata, Ng, & Kramer, 1993). Strength ratios are typically calculated under isometric (Kong & Burns, 2010) or isokinetic conditions (Aagaard, Simonsen, Magnusson, Larsson, & Dyhre-Poulsen, 1998) dividing the maximal force of flexor muscles by the maximal force of extensor muscles. However, traditional strength ratios do not provide an extensive evaluation of the mechanical imbalances of the tested muscles because other important mechanical capacities (V_0 and P_{max}) are not being evaluated. Therefore, additional tests would be needed to evaluate V_0 and P_{max} capacities which could be time-consuming. A potential solution for shortening the testing procedure could be the use of the two-point method to selectively evaluate all maximal mechanical capacities at the same time (Grbic et al., 2017) and, subsequently, calculate their corresponding ratios.

8.5. Conclusions

The sensitivity of the two-velocity method for testing the maximal mechanical capacities was high for the knee joint, moderate for the hip and shoulder joints, and low for the elbow joint. The F-V relationship assessed through the two-velocity method was able to discriminate better between antagonist muscle groups than between males with different levels of physical activity. The non-systematic correlations between the F-V relationship parameters of antagonist muscle groups suggest that a given maximal mechanical capacity cannot be predicted from the value observed in the antagonist muscle group. Therefore, since different muscle groups should be evaluated to obtain complete information of the function of the whole neuromuscular system, the two-velocity method could be considered as a quick procedure for testing the maximal mechanical capacities to produce force, velocity, and power.

9. General conclusion and significance of the studies

Present thesis was designed with an aim to validate, explore sensitivity and generalizability of the two-point method for applying it during isokinetic testing. Results of the studies demonstrated that F-V relationships obtained during isokinetic tasks were strong and linear (all $r \geq 0.969$), and that validity of the F_0 was high but lower for the other F-V relationship parameters (median r: $F_0 = 0.96$; $V_0 = 0.71$; $a = 0.78$; and $P_{max} = 0.78$) when obtained using two-velocity method. Regarding sensitivity, both the multiple- and the two-velocity method provided higher values of F_0, V_0 and P_{max} for men compared to women, and were able to discriminate better between antagonist muscle groups than between males with different levels of physical activity. In both studies, association between the same F-V relationship parameters were on average poor to moderate. Generally, findings support the two-velocity method as a valid and sensitive procedure for determining the maximal capacity of the selected muscles to produce F_0, while more muscles should be tested to comprehensively evaluate the subject's muscular function.

Until recently, assessing muscle capabilities was performed exclusively using standard isokinetic testing protocols (i.e., applying different angular velocities during isokinetic testing), which enabled drawing conclusions only about individual mechanical capacities (i.e., F or P) of the tested muscles at once. What is important to emphasize is that isokinetic F-V relationship modelling opens a possibility to assess all mechanical capacities (i.e., F, P and V) at once, while two-velocity method additionally shortens this procedure. In this regard, the two-velocity method could be particularly recommended when several muscles should be tested within the same session to minimise testing time.

Besides shortening testing procedure, fatigue associated with the testing protocol is significantly decreased. This quality of two-velocity method is particularly important since the mechanical capacities of both the patients and athletes could be frequently assessed. And what is of great importance is that velocities applied during testing sessions are more comfortable for tested subjects (i.e., enable predicting maximal capacities without directly assessing them) irrespective of the strength level. Finally, two-velocity method could be used to distinguish between antagonistic muscle groups, likely opening possibility to evaluate asymmetries in the F, V, P capabilities of the extremities.

Summing up, designs of the studies presented as a part of this thesis were the first that included assessing validity of the two-point method of the several important muscle groups during isokinetic testing. Also, presented studies were the first to assess sensitivity of the two-velocity method to discriminate between maximal muscle capacities of antagonistic muscle pairs, subjects of different gender and healthy, uninjured males of different strength levels. However, besides its great potential demonstrated within this work, future studies should seek for a different combination of the experimental velocities to optimise the accuracy of the two-velocity method.

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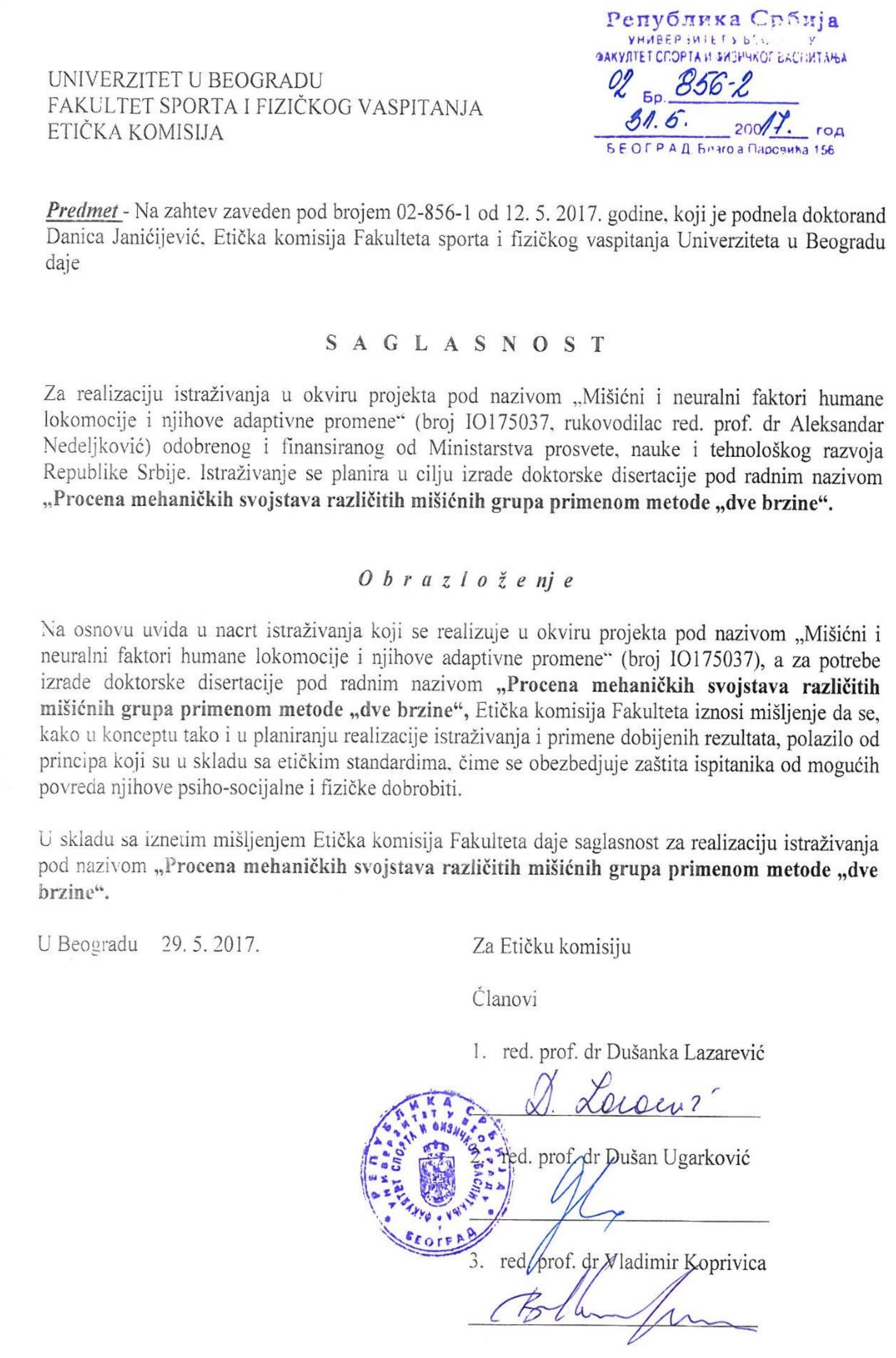
Supplementary document 1. Ethic committee approval



РЕПУБЛИКА СРБИЈА
УНИВЕРЗИТЕТ У БЕОГРАДУ
ФАКУЛТЕТ СПОРТА И ФИЗИЧКОГ ВАСПИТАЊА
02 Бр. 856-2
31. 5. 2017. год
БЕОГРАД Благоја Паровића 156

UNIVERZITET U BEOGRADU
FAKULTET SPORTA I FIZIČKOG VASPITANJA
ETIČKA KOMISIJA

Predmet - Na zahtev zaveden pod brojem 02-856-1 od 12. 5. 2017. godine, koji je podnela doktorand Danica Janićijević, Etička komisija Fakulteta sporta i fizičkog vaspitanja Univerziteta u Beogradu daje

SAGLASNOST

Za realizaciju istraživanja u okviru projekta pod nazivom „Mišićni i neuralni faktori humane lokomocije i njihove adaptivne promene" (broj IO175037, rukovodilac red. prof. dr Aleksandar Nedeljković) odobrenog i finansiranog od Ministarstva prosvete, nauke i tehnološkog razvoja Republike Srbije. Istraživanje se planira u cilju izrade doktorske disertacije pod radnim nazivom **„Procena mehaničkih svojstava različitih mišićnih grupa primenom metode „dve brzine".**

Obrazloženje

Na osnovu uvida u nacrt istraživanja koji se realizuje u okviru projekta pod nazivom „Mišićni i neuralni faktori humane lokomocije i njihove adaptivne promene" (broj IO175037), a za potrebe izrade doktorske disertacije pod radnim nazivom **„Procena mehaničkih svojstava različitih mišićnih grupa primenom metode „dve brzine"**, Etička komisija Fakulteta 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 obezbedjuje zaštita ispitanika od mogućih povreda njihove psiho-socijalne i fizičke dobrobiti.

U skladu sa iznetim mišljenjem Etička komisija Fakulteta daje saglasnost za realizaciju istraživanja pod nazivom **„Procena mehaničkih svojstava različitih mišićnih grupa primenom metode „dve brzine".**

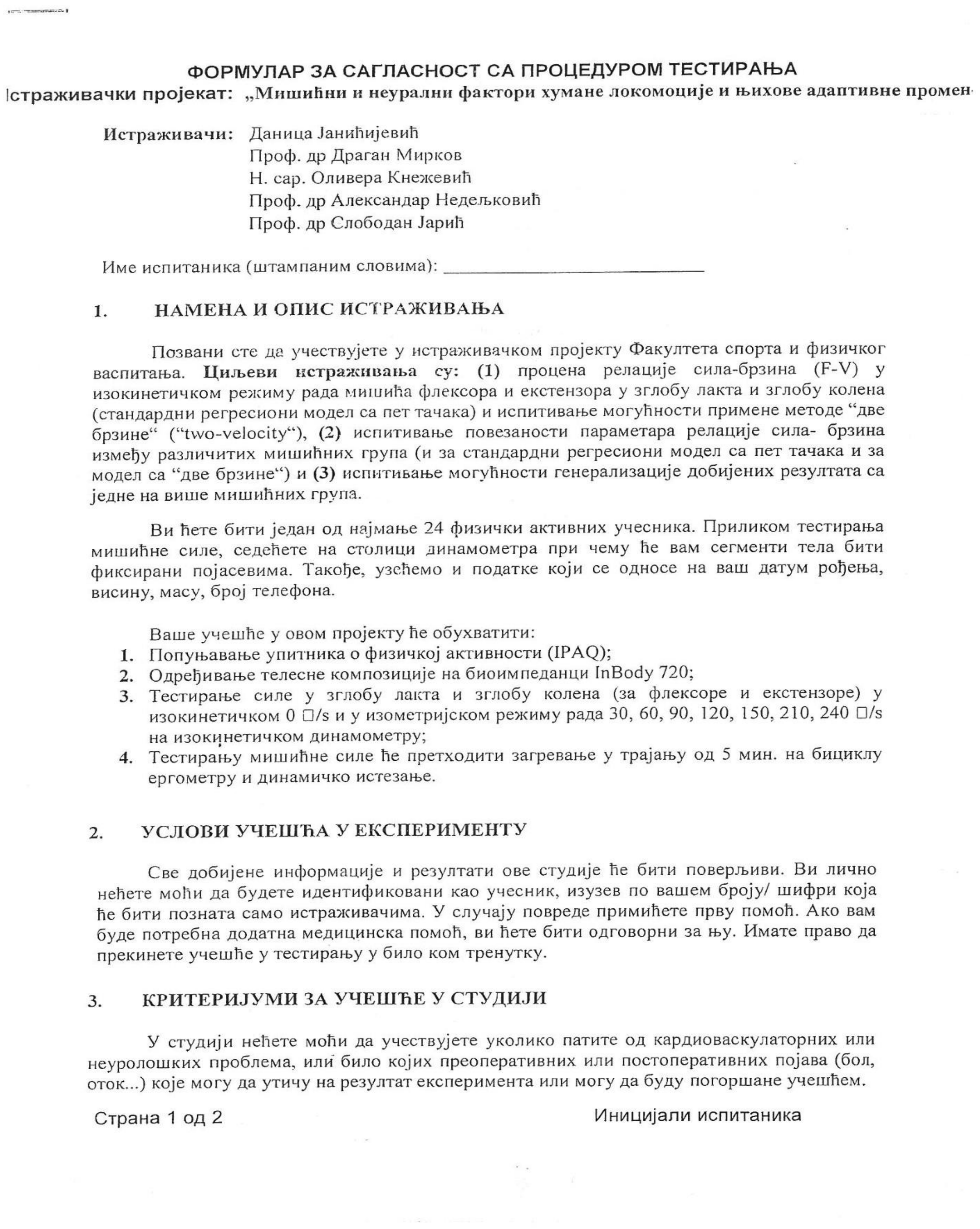
U Beogradu 29. 5. 2017.

Za Etičku komisiju

Članovi

1. red. prof. dr Dušanka Lazarević
   D. Lazarević
2. red. prof. dr Dušan Ugarković
3. red. prof. dr Vladimir Koprivica

Supplementary document 2. Testing protocol agreement file



ФОРМУЛАР ЗА САГЛАСНОСТ СА ПРОЦЕДУРОМ ТЕСТИРАЊА

Iстраживачки пројекат: **„Мишићни и неурални фактори хумане локомоције и њихове адаптивне промен**

Истраживачи: Даница Јанићијевић
Проф. др Драган Мирков
Н. сар. Оливера Кнежевић
Проф. др Александар Недељковић
Проф. др Слободан Јарић

Име испитаника (штампаним словима): ______________________________

1. НАМЕНА И ОПИС ИСТРАЖИВАЊА

Позвани сте да учествујете у истраживачком пројекту Факултета спорта и физичког васпитања. **Циљеви истраживања су: (1)** процена релације сила-брзина (F-V) у изокинетичком режиму рада мишића флексора и екстензора у зглобу лакта и зглобу колена (стандардни регресиони модел са пет тачака) и испитивање могућности примене методе “две брзине“ (“two-velocity“), **(2)** испитивање повезаности параметара релације сила- брзина између различитих мишићних група (и за стандардни регресиони модел са пет тачака и за модел са “две брзине“) и **(3)** испитивање могућности генерализације добијених резултата са једне на више мишићних група.

Ви ћете бити један од најмање 24 физички активних учесника. Приликом тестирања мишићне силе, седећете на столици динамометра при чему ће вам сегменти тела бити фиксирани појасевима. Такође, узећемо и податке који се односе на ваш датум рођења, висину, масу, број телефона.

Ваше учешће у овом пројекту ће обухватити:

1. Попуњавање упитника о физичкој активности (IPAQ);
2. Одређивање телесне композиције на биоимпеданци InBody 720;
3. Тестирање силе у зглобу лакта и зглобу колена (за флексоре и екстензоре) у изокинетичком 0 □/s и у изометријском режиму рада 30, 60, 90, 120, 150, 210, 240 □/s на изокинетичком динамометру;
4. Тестирању мишићне силе ће претходити загревање у трајању од 5 мин. на бициклу ергометру и динамичко истезање.

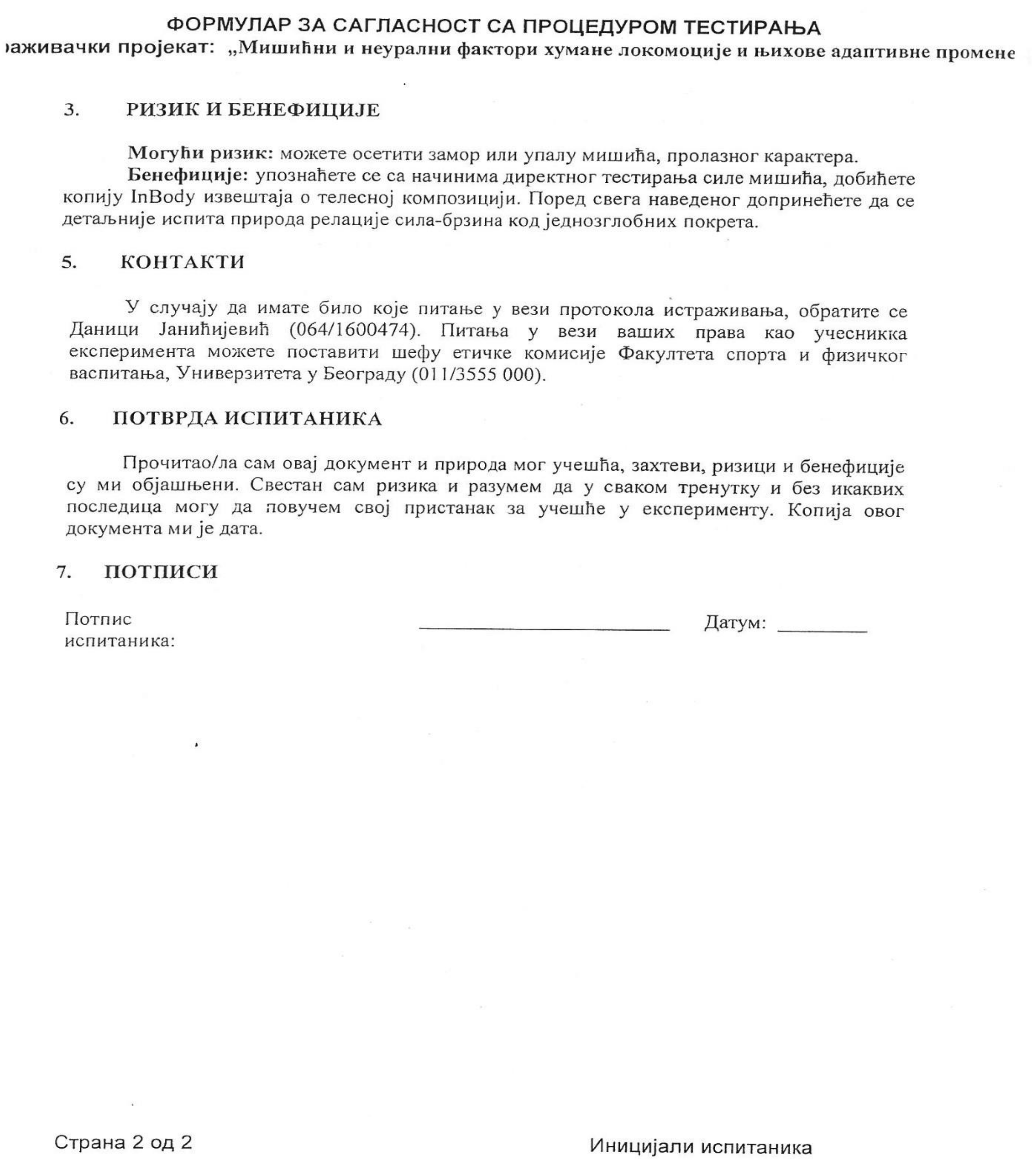
2. УСЛОВИ УЧЕШЋА У ЕКСПЕРИМЕНТУ

Све добијене информације и резултати ове студије ће бити поверљиви. Ви лично нећете моћи да будете идентификовани као учесник, изузев по вашем броју/ шифри која ће бити позната само истраживачима. У случају повреде примићете прву помоћ. Ако вам буде потребна додатна медицинска помоћ, ви ћете бити одговорни за њу. Имате право да прекинете учешће у тестирању у било ком тренутку.

3. КРИТЕРИЈУМИ ЗА УЧЕШЋЕ У СТУДИЈИ

У студији нећете моћи да учествујете уколико патите од кардиоваскулаторних или неуролошких проблема, или било којих преоперативних или постоперативних појава (бол, оток...) које могу да утичу на резултат експеримента или могу да буду погоршане учешћем.

Иницијали испитаника



ФОРМУЛАР ЗА САГЛАСНОСТ СА ПРОЦЕДУРОМ ТЕСТИРАЊА

аживачки пројекат: „Мишићни и неурални фактори хумане локомоције и њихове адаптивне промене

3. РИЗИК И БЕНЕФИЦИЈЕ

Могући ризик: можете осетити замор или упалу мишића, пролазног карактера.

Бенефиције: упознаћете се са начинима директног тестирања силе мишића, добићете копију InBody извештаја о телесној композицији. Поред свега наведеног допринећете да се детаљније испита природа релације сила-брзина код једнозглобних покрета.

5. КОНТАКТИ

У случају да имате било које питање у вези протокола истраживања, обратите се Даници Јанићијевић (064/1600474). Питања у вези ваших права као учесникка експеримента можете поставити шефу етичке комисије Факултета спорта и физичког васпитања, Универзитета у Београду (011/3555 000).

6. ПОТВРДА ИСПИТАНИКА

Прочитао/ла сам овај документ и природа мог учешћа, захтеви, ризици и бенефиције су ми објашњени. Свестан сам ризика и разумем да у сваком тренутку и без икаквих последица могу да повучем свој пристанак за учешће у експерименту. Копија овог документа ми је дата.

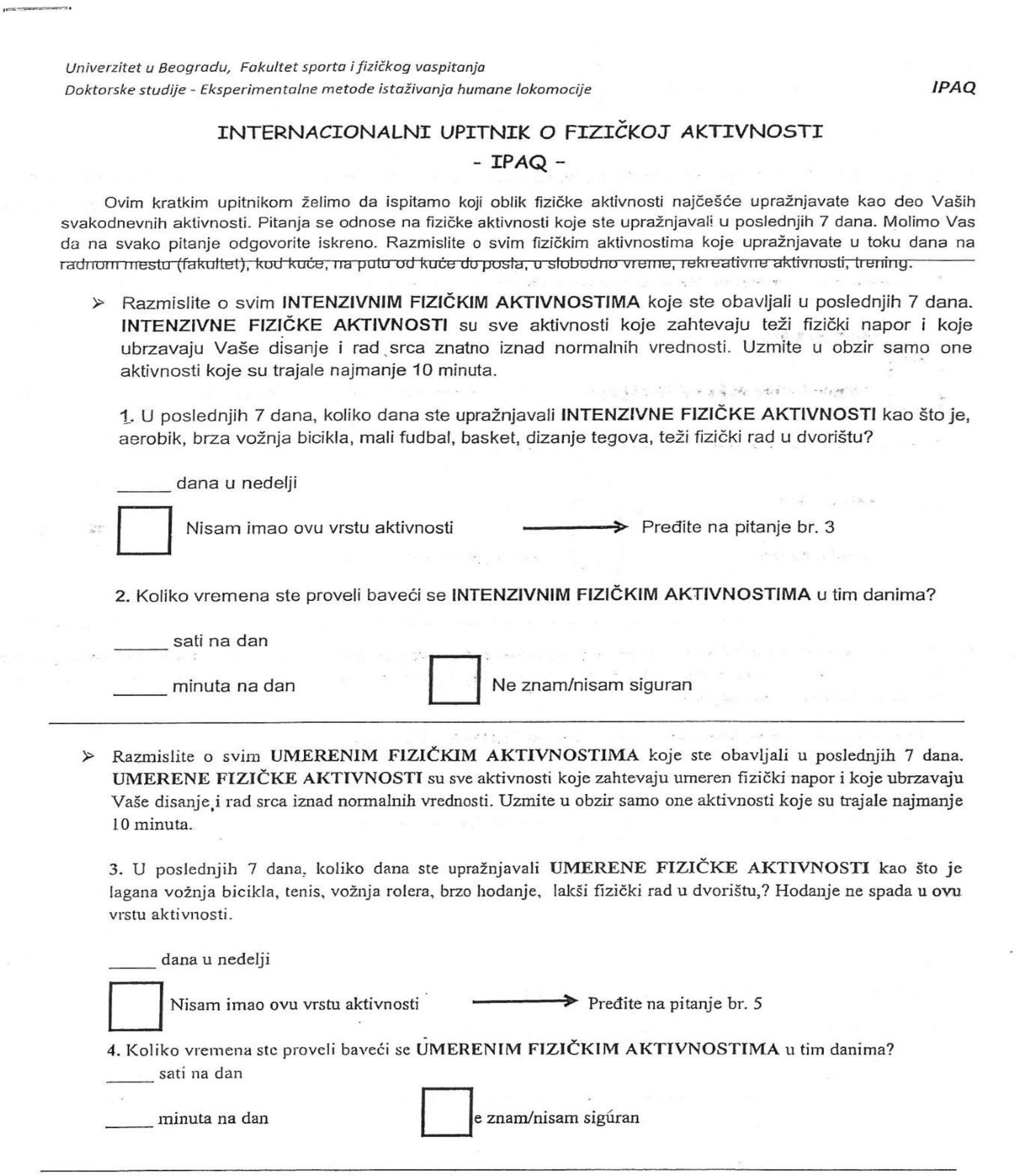
7. ПОТПИСИ

Потпис испитаника: ______________________ Датум: _________

Страна 2 од 2

Иницијали испитаника

Supplementary document 3. International physical activity questionnaire (IPAQ)



Univerzitet u Beogradu, Fakultet sporta i fizičkog vaspitanja
Doktorske studije - Eksperimentalne metode istaživanja humane lokomocije *IPAQ*

INTERNACIONALNI UPITNIK O FIZIČKOJ AKTIVNOSTI
- IPAQ -

Ovim kratkim upitnikom želimo da ispitamo koji oblik fizičke aktivnosti najčešće upražnjavate kao deo Vaših svakodnevnih aktivnosti. Pitanja se odnose na fizičke aktivnosti koje ste upražnjavali u poslednjih 7 dana. Molimo Vas da na svako pitanje odgovorite iskreno. Razmislite o svim fizičkim aktivnostima koje upražnjavate u toku dana na radnom mestu (fakultet), kod kuće, na putu od kuće do posla, u slobodno vreme, rekreativne aktivnosti, trening.

➢ Razmislite o svim **INTENZIVNIM FIZIČKIM AKTIVNOSTIMA** koje ste obavljali u poslednjih 7 dana. **INTENZIVNE FIZIČKE AKTIVNOSTI** su sve aktivnosti koje zahtevaju teži fizički napor i koje ubrzavaju Vaše disanje i rad srca znatno iznad normalnih vrednosti. Uzmite u obzir samo one aktivnosti koje su trajale najmanje 10 minuta.

1. U poslednjih 7 dana, koliko dana ste upražnjavali **INTENZIVNE FIZIČKE AKTIVNOSTI** kao što je, aerobik, brza vožnja bicikla, mali fudbal, basket, dizanje tegova, teži fizički rad u dvorištu?

_____ dana u nedelji

☐ Nisam imao ovu vrstu aktivnosti → Pređite na pitanje br. 3

2. Koliko vremena ste proveli baveći se **INTENZIVNIM FIZIČKIM AKTIVNOSTIMA** u tim danima?

_____ sati na dan

_____ minuta na dan ☐ Ne znam/nisam siguran

➢ Razmislite o svim **UMERENIM FIZIČKIM AKTIVNOSTIMA** koje ste obavljali u poslednjih 7 dana. **UMERENE FIZIČKE AKTIVNOSTI** su sve aktivnosti koje zahtevaju umeren fizički napor i koje ubrzavaju Vaše disanje i rad srca iznad normalnih vrednosti. Uzmite u obzir samo one aktivnosti koje su trajale najmanje 10 minuta.

3. U poslednjih 7 dana, koliko dana ste upražnjavali **UMERENE FIZIČKE AKTIVNOSTI** kao što je lagana vožnja bicikla, tenis, vožnja rolera, brzo hodanje, lakši fizički rad u dvorištu,? Hodanje ne spada u ovu vrstu aktivnosti.

_____ dana u nedelji

☐ Nisam imao ovu vrstu aktivnosti → Pređite na pitanje br. 5

4. Koliko vremena ste proveli baveći se **UMERENIM FIZIČKIM AKTIVNOSTIMA** u tim danima?

_____ sati na dan

_____ minuta na dan ☐ e znam/nisam siguran

- Razmislite koliko vremena ste proveli **HODAJUĆI** u poslednjih 7 dana. Odnosi se na hodanje na radnom mestu (fakultet), kod kuće, na putu od kuće do posla i nazad, u slobodno vreme, hodanje kao rekreativna aktivnost, kao deo treninga,.....

5. U poslednjih 7 dana, koliko dana ste hodali najmanje 10 minuta u kontinuitetu?

______ dana u nedelji

☐ Nisam hodao duže od 10 minuta → Pređite na pitanje br. 7

6. Koliko vremena ste proveli **HODAJUĆI** u tim danima?

______ sati na dan

______ minuta na dan ☐ Ne znam/nisam siguran

- Poslednje pitanje se odnosi na količinu vremena koje ste proveli sedeći u poslednjih 7 dana. Odnosi se na vreme koje ste sedeli na radnom mestu (fakultetu), kod kuće, sedenje za stolom, u poseti kod prijatelja, čitanje, gledanje Tv-a,.....

7. U poslednjih 7 dana, koliko vremena ste proveli **SEDEĆI** u toku jednog dana?

______ sati na dan

______ minuta na dan ☐ Ne znam/nisam siguran

✓ *Za testiranje je potrebno da budete u sportskoj opremi (šorc, majica, patike)*

<u>Saglasan sam da učestvujem u testiranju</u> *Vaš potpis* ______________________

Telefon ______________________ *e-mail adresa* ______________________

Supplementary document 4. Online accepted version of the paper

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Journal of Sports Sciences

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Feasibility of the two-point method for assessing the force-velocity relationship during lower-body and upper-body isokinetic tests

Danica Janicijevic, Amador García-Ramos, Olivera M. Knezevic & Dragan M. Mirkov

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To link to this article: https://doi.org/10.1080/02640414.2019.1636523

Biography

Born on 29th of October 1991 in Belgrade where she finished elementary school “Dragojlo Dudić” and “VI Grammar school”. After finishing Grammar school, she started studying Bachelor studies on the Faculty of sport and physical education (University of Belgrade) in the school year 2010/2011 and finished it with the highest grades in generation (average grade: 9.39). Afterwards, she finished Master studies in the school year 2015/2016 with the average grade 9.44. In the same school year she enrolled into doctoral programme, where she passed all exams with the average grade 9.92. During her professional career she worked as a volleyball coach, as a coach and co-owner in the sport school “Sportomanija”, and in several elementary schools as a professor of physical education. Currently she is working as a research assistant on the Faculty of sport and physical education in the University of Belgrade 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). She conducted research stay at Catholic University of the Most Holy Concepcion, Faculty of education, Concepcion (2 months) and also at University of Granada, Faculty of Sport Sciences, Department of Physical Education and Sport, Granada, Spain (one month). Besides this she is an author of 10 papers published in international journals (indexed in WOS) and varies publications in national journals and scientific conferences. Additionally, she has been reviewer for International Journal of Sports Physiology and Performance and Peer J.

Образац 5.

Изјава о ауторству

Име и презиме аутора __Даница Јанићијевић________

Број индекса __5007/2016 _________________________

Изјављујем

да је докторска дисертација под насловом

Mechanical capacities of the different muscle groups assessed using "two-velocity" method (Процена механичких својстава различитих мишићних група применом методе „две брзине“)

- резултат сопственог истраживачког рада;
- да дисертација у целини ни у деловима није била предложена за стицање друге дипломе према студијским програмима других високошколских установа;
- да су резултати коректно наведени и
- да нисам кршио/ла ауторска права и користио/ла интелектуалну својину других лица.

Потпис аутора

У Београду, _________________

____

Образац 6.

Изјава о истоветности штампане и електронске верзије докторског рада

Име и презиме аутора: Даница Јанићијевић

Број индекса: 5007/2016

Студијски програм: Експерименталне методе изучавања хумане локомоције

Наслов рада: Mechanical capacities of the different muscle groups assessed using "two-velocity" method (Процена механичких својстава различитих мишићних група применом методе „две брзине“

Ментор: научни сарадник Оливера Кнежевић

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.

Потпис аутора

У Београду, ________________________

____

Образац 7.

Изјава о коришћењу

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

Mechanical capacities of the different muscle groups assessed using ''two-velocity'' method (Процена механичких својстава различитих мишићних група применом методе „две брзине“)

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).

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У Београду, ________________________ ____________________

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