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Research Article

Model of Force Calculation of Fast and Slow Motor Units of Knee Extensor Muscles in Isometric Mode

Andrey Voronov[1, 2, *], Alexey Shpakov[1, 2], Elena Tomilovskaya[2], Anastasia Voronova[1], Nikolay Sokolov[1, 2]

[1]Laboratory of Sports Training Problems, Federal Science Center of Physical Culture and Sport (VNIIFK), Moscow, Russia

[2]Russian Federation State Scientific Center, Institute of Biomedical Problems of the Russian Academy of Sciences, Moscow, Russia

Abstract

Knee extensors are mixed muscles containing both fast (FMU) and slow motor units (SMU). It has been hypothesized that, at high angular velocities (150-360 deg/s), FMU contributes primarily to knee joint moment development, while at low angular velocities (30-120 deg/s), both FMU and SMU contribute to force generation. It was hypothesized that the maximum isometric moment in m. quadriceps, registered on the isokinetic dynamometer “BIODEX System 4Pro”at speeds of 30-150 deg/s, represents the sum of the moments from SMU and FMU, while in the range of 150-360 deg/s, it is primarily generated by FMU. The maximum isometric moment created by the FMU was calculated using a linear equation, as the force-velocity relationship becomes linear at high velocities. During knee extension at a constant angular velocity, the maximum number of RMUs, according to the model, is activated up to an angular velocity of 240 deg/s: (knee amplitude motion 90 deg) / (time developing maximum force 0.37s) = 240 deg/s. The maximum number of MMUs is recruited 1.09 s after the onset of knee extension, which corresponds to an angular velocity of 90 deg/based on the results of isokinetic dynamometry and a mathematical model, FMU and SMU forces were calculated for highly skilled athletes of different sports. For athletes of various specializations, the SMU force does not exceed 24 N/kg, while the FMU force ranges from 52-83 N/kg. The main result of this study demonstrates an acceptable level of agreement between the model and experimental calculations of the SMU and FMU contributions to knee extension force. Based on the obtained model characteristics, individual "boundaries" of SMU and FMU involvement can be determined.

Keywords

Modeling, Isometric Force, Modeling, Motor Units Force, Muscle, Fibers Cross-sectional Areas

1. Introduction

The level of special strength training athletes receive is the limiting factor in achieving high athletic performance. Special performance is determined by the integration of the neuro-muscular system’s properties, which generate strength, power,

*Corresponding author: voronov3057@gmail.com (Andrey Voronov)

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and speed during competitive exercises [1]. According to Ju. V. Verhoshansky, the main characteristic of a sports movement's effectiveness (regardless of the type of activity) is the speed of the athlete's movement. In sports where athletes must overcome significant external resistance to reach high speeds, developing muscle strength and increasing metabolic efficiency are necessary to enhance their performance [2].

Muscles' ability to generate force depends on factors such as muscle mass, muscle fiber type, pennation angle, and muscle activation characteristics. Previous studies have shown that men have a significantly higher ability than women [3, 4], which is believed to be due to greater muscle mass, a higher percentage of fast-twitch muscle fibers [5, 6], and gender-specific muscle activation patterns [7]. Even when normalized for body mass, gender differences in maximum torque persist.

For example, speed skating is a cyclic sport that demands great strength and aerobic capacity from athletes. Highly skilled speed skaters can cover 1,500 and 5,000 meters in approximately two and seven minutes, respectively. Studies show that performance in short distances (500 meters) depends on the maximum strength of the lower limb extensor muscles [8, 9].

Knee extensor muscles are mixed muscles containing both fast (FMU, Type II) and slow motor units (SMU, Type I) [10-13]. The primary function of Type I fibers is to maintain an upright posture, support walking, and enable prolonged, low-intensity exercise, such as long-distance running. Type II fibers facilitate high-intensity exercises, including jumping or sprinting. Laboratory experiments on different fiber types (mainly in animals) in vitro revealed that their force and power properties differ significantly [14]. Studies on the force-velocity relationship in knee extensors have shown that athletes with a higher percentage of Type II fibers generate greater total force at high velocities [11]. The contribution of each fiber type to total force was not considered. In this study, using m. quadriceps as an example, maximum forces for different fiber types were calculated using a mathematical model based on experimental data. The objective of this study was to determine the maximum isometric strength of FMU and SMU in relation to sports specialization.

2. Materials and Methods

2.1. Design and Participants

Highly skilled athletes of different specializations participated in this study: figure skating (females, n=4), rowing (females, n=7), cyclists in BMX (Bicycle Motocross) discipline (males, n=5; females, n=6), cyclists in track discipline (males, n=6), cross-country skiing (males, n=8), rock climbing in speed discipline (males, n=8), and soccer (n=42, U18). Male volunteers (n=10) al so participated in an experimental study with a 21-day head-down bedrest (HDBR) conducted by the Institute of Biomedical Problems of the Russian Academy of Sciences. All studies were conducted in accordance with the principles of biomedical ethics outlined in the Declaration of Helsinki (1964) and its subsequent updates.

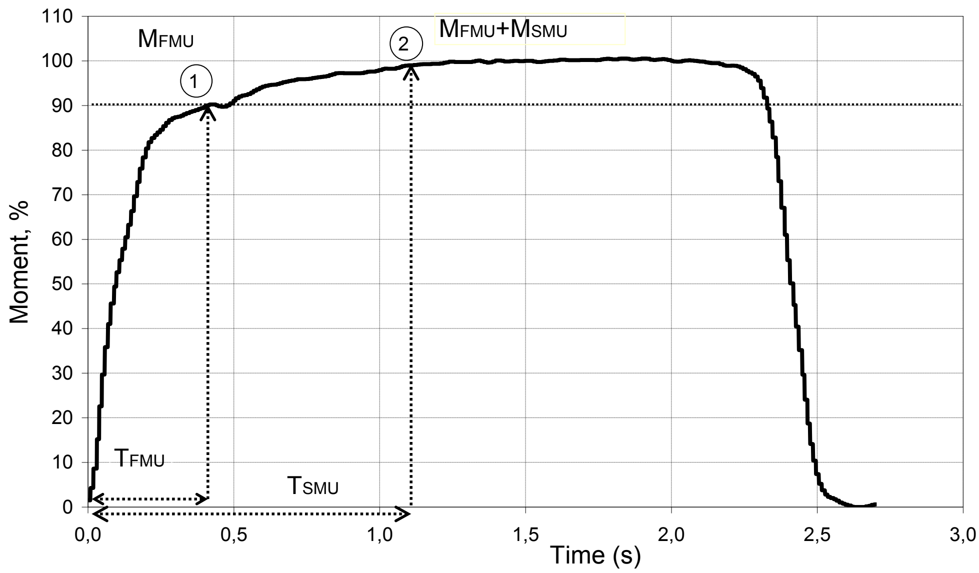

Figure 1. *Profile of maximum isometric force of knee extensor muscles at the knee joint angles of 90 degrees. 1- maximum FMU force. 2 – maximum FMU+SMU force.* T_{FMU} *- time to reach the maximum FMU force 90% of the maximum torque.* T_{SMU} *- time to reach maximum SMU force.*

2.2. Experimental Protocol

All participants of the study performed knee joint extension in the sitting position on the isokinetic dynamometer “BIODEX System 4Pro”. Maximum moments of m. quadriceps were recorded at angular velocities in the range of 30-360 deg/s. During the test, athletes and volunteers performed knee extension at a signal according to the instruction: to perform extension “as quickly and strongly as possible.” The rest period between the “extension-flexion” cycle was 5–7 seconds, and the rest period between angular velocities was 1 minute. The transition from high angular velocities to low ones and sufficient rest intervals between testing at different angular velocities prevented the development of muscle fatigue. At each angular velocity, the volunteers performed no more than three extensions in the knee joint. The maximum isometric force was evaluated at knee joint angle of 90 deg.

2.3. Research Hypothesis

The maximum voluntary isometric force profile is shown in Figure 1. It was hypothesized that the "fast part" (0.37±0.16 s, n=38) of the isometric force profile mainly depends on the force-velocity properties of FMU, while the "slow part, "with a duration of 0.75±0.29 s (n=38), depends on the combined force of SMU and FMU (profile portion from 0.37<t≤1.12 s, Figure 1). SMU "reaches" maximum force on average in 1.09±0.31s from the onset of force development; hence, the knee extension angular velocity should not exceed 90 deg/s (Table 1). When the angular velocity surpasses 150 deg/s, the knee extension duration decreases from 0.6 s to 0.25 s, reducing the maximum possible force developed by SMU from 55% to 23% (Table 1).

Table 1. *MDE force in% of maximum as a function of knee extension time and velocity.*

Angular velocity deg/s	Time of knee extension (s)	Strength in% maximum
30	3,0	100
60	1,5	100
90	1,0	92
120	0,75	69
150	0,60	55
180	0,50	46
240	0,375	34
300	0,30	28
360	0,25	23

2.4. Calculation Model for FMU and SMU Force

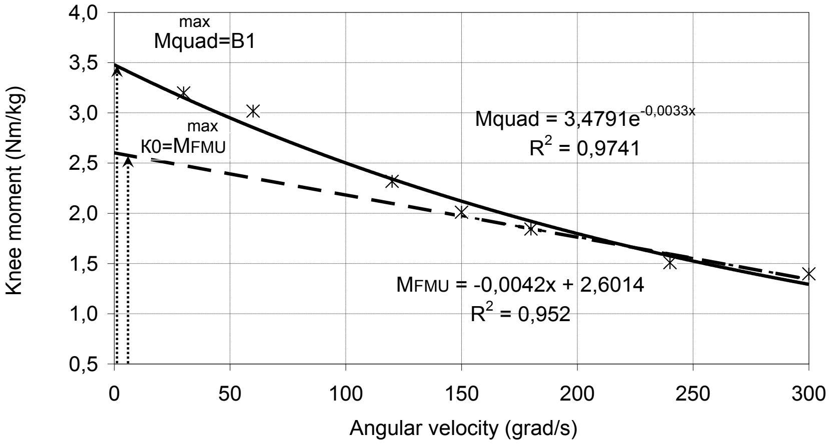

Figure 2. *FMU and SMU Maximum Isometric Force Model Based on «BIODEX System 4Pro» Testing Results. Solid line-regression equation for all fiber types in the range of 0-300deg/s. Dashed line-regression equation for FMU in the range of 150-300 deg/s.*

It was hypothesized that the maximum isometric moment in m. quadriceps, registered on the isokinetic dynamometer "BIODEX System 4Pro"at speeds of 30-150 deg/s, represents the sum of the moments from SMU and FMU, while in the range of 150-360 deg/s, it is primarily generated by FMU [15].

The maximum isometric moment created by the FMU was calculated using a linear equation, as the force-velocity relationship becomes linear at high velocities [16, 17]. By extrapolating equation (1) to the y-axis (dashed line in Figure 2), the maximum isometric force predominantly of Type II fibers was determined (coefficient K0). By extrapolating the regression equation (2) for SMU and FMU to the y-axis, the maximum total isometric force of all fiber types was calculated (solid line in Figure 2, coefficient B1, equation (2). By subtracting the moment value for FMU from the total moment, the moment generated by SMU was estimated (Figure 2). Normalizing for the knee joint moment arm, maximum FMU and SMU forces were evaluated.

$$M_{\mathrm{FMU}}^{\max} = K_1 * V - K_0\,; \quad F_{\mathrm{FMU}}^{\max} = \frac{K_0}{d} \tag{1}$$

$$F_{\mathrm{SMU}}^{\max} = \frac{M_{qud}^{\max} - M_{FMU}^{\max}}{d} = \frac{(M_{quad}^{\max} - K_0)}{d}$$

$$M_{quad}^{\max} = \mathrm{B}_1 * \exp(-0{,}0033 * \mathrm{V}) \tag{2}$$

where

$M_{quad}^{\max}$ - maximum isometric moment of m. quadriceps (Nm);

M_{FMU}, $M_{\mathrm{FMU}}^{\max}$ -isometric moment and maximum isometric moment of FMU (Nm);

$F_{\mathrm{FMU}}^{\max}$, $F_{\mathrm{SMU}}^{\max}$ - maximum forces of FMU and SMU, respectively (N);

K1, K0, and B1- coefficients of regression equations. Last two coefficients correspond to the maximum isometric moment of FMU and SMU+FMU, respectively (Nm);

V – angular velocity in the knee joint (deg/s);

d- m. quadriceps arm in the knee joint, d=0,045-0,05 (m).

2.5. Model Validity Assessment

To verify the assumptions for assessing maximum SMU and FMU force, m. quadriceps moments before and after extended exposure to simulated microgravity effect sin the 21-day HDBR study were compared. Studies by Institute of Biomedical Problems of the Russian Academy of Sciences have shown that maximum isometric force of ankle and knee extensors decreases by 15-21% under natural (space flight) and simulated microgravity conditions [18, 19]. The cross-section al area (CSA) of SMU fibers decreases by 15-20% [20, 21]. Figure 3 shows SMU and FMU force calculations for knee extensors before and after HDBR (n=10), calculated according to equations (1) and (2). FMU force decreases by 4%, while SMU force decreases by 22%, corresponding to a 15-21% reduction in SMU CSA.

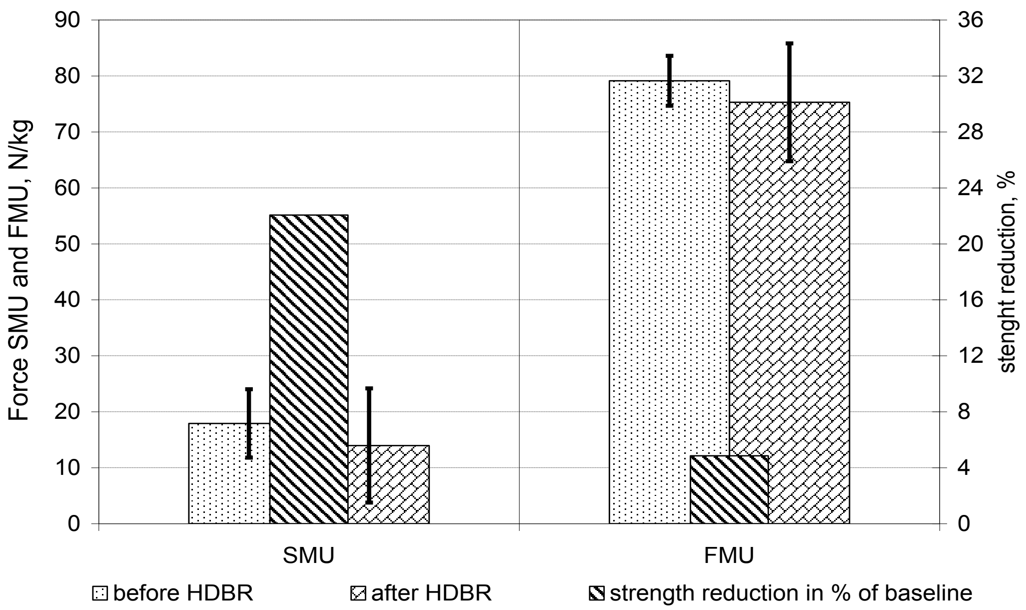

Figure 3. *FMU and SMU maximum forces Before and after HDBR 2021-2022, averaged data (n=10).*

3. Results

Having confirmed the validity of the hypotheses made using the 21-day ANOG as an example, the MMU and RMU forces were calculated in the isometric mode in athletes in various sports. During knee extension at a constant angular velocity, the maximum number of RMUs, according to the model, is activated up to an angular velocity of 240 deg/s: (knee amplitude motion ≈90 deg)/(time developing maximum force 0.37 s) = 240 deg/s, Figure 1). The maximum number of MMUs is recruited 1.09 s after the onset of knee extension, which corresponds to an angular velocity of 90 deg/s. With an increase in knee extension velocity to 360 deg/s, type I fibers "do not have time" to develop force; their contribution to the total moment is less than 30% (Table 1).

The maximum force of the quadriceps muscle in cross-country skiers is 65.6 N/kg, while that of cyclists and climbers is >81 N/kg (Figure 4). The strength of the MMU is influenced by sport specialization: the shorter the distance, the weaker the type I fibers. In male climbers (speed discipline), the MMU strength is the lowest of all - 10.1 N/kg, and, conversely, in rowing and cross-country skiing, the MMU strength is 23.6 and 19.8 N/kg, respectively.

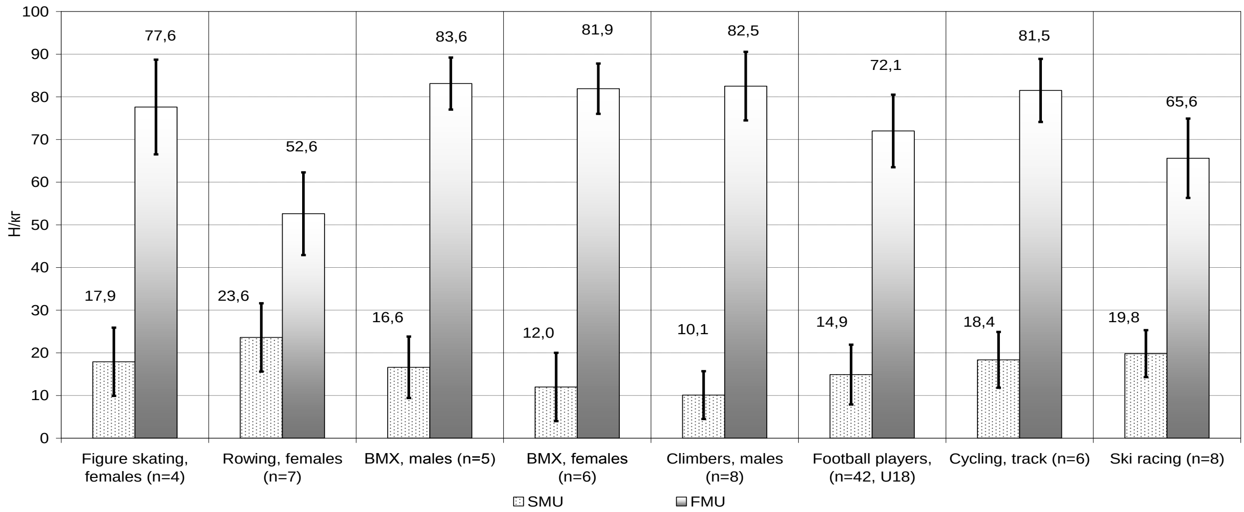

Figure 4*. Maximum Isometric FMU and SMU forces depending on sport.*

4. Discussion

The main result of this study demonstrates an acceptable level of agreement between the model and experimental calculations of the SMU and FMU contributions to knee extension force. Based on the obtained model characteristics, individual "boundaries" of SMU and FMU involvement can be determined.

The results obtained in this study are fully comparable with the results of testing speed-strength manifestations in an experiment with 21-day hypokinesia [22], which found that after prolonged modeling, the greatest "loss" of force occurred in the low-speed range (120-30 deg/s). Moreover, the decrease in maximum voluntary force was independent of changes in the force gradient [22]. At angular velocities from 120 to 30 deg/s, the time to reach the maximum torque is from 0.6 to 0.8 s; all types of muscle motor units are active, including slow ones (Slow Oxidative), according to the Slow Oxidative + high-threshold motor units (Fast Oxydative and Fast Glycolytic) scheme [23], and the subjects manage to develop a significant torque during knee extension.

A number of studies have shown the effect of weightlessness on the state of the SMU [20, 23-25]. It has been shown that exposure to real and simulated weightlessness does not lead to a significant change in the state of the FMU [26-28]. Thus, we can conclude that the results of the afore mentioned studies can be compared with our calculations, since it was at low angular velocities (range from 30 – 120 degrees/s) that a significant decrease in maximum voluntary force occurred, due to a decrease in the contractility of the SMU knee extensor muscles.

5. Recommendations

Strength training, which calculates load as a percentage of the 1RM, is aimed at developing the strength of the MU muscle fibers and has little effect on the strength of type I fibers. The strength of the MU muscle fibers does not exceed 24 N/kg, which is two or more times less than the strength of the MU muscle fibers for the corresponding sport. Changing strength training regimens to develop the strength of type I fibers will improve the efficiency of performing moderate-intensity competitive exercises, for example, in soccer, where a professional soccer player spends more than 75-80% of their time standing, walking, and running at a speed of 8-12 km/h [29].

Abbreviations

FMU	Fast Motor Units
SMU	Slow Motor Units
HDBR	Head-Down Bed Rest
CSA	Cross-Sectional Area

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Author Contributions

Andrey Voronov: Formal Analysis, Methodology, Resources, Validation, Writing - review & editing.

Alexey Shpakov: Data curation, Investigation, Supervision.

Elena Tomilovskaya: Data curation, Investigation, Supervision.

Anastasia Voronova: Conceptualization, Data curation, Formal analysis.

Nikolay Sokolov: Conceptualization, Data curation, Formal analysis.

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Data Availability Statement

Data are available upon reasonable request from the authors.

Conflicts of Interest

The authors declare no conflicts of interest.

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