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Force Distribution Model of Motor Units of Leg Extensor Muscles

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Abstract: The paper aims to define the lawfulness (model), by which one can reliably estimate the distribution of motor units' force from the moment when leg extensor muscles start to generate the force until the moment when the maximal level is achieved. The study included 110 participants. To assess the contractile characteristics of leg extensors, standardized equipment and standardized isometric test in sitting position with the angle of the knee joint of 125° were used. The participants were instructed to exert their maximal force as quickly as possible. Using descriptive statistics, cluster analysis and fitting the exponential model of the distribution of force of leg extensor motor units in the whole range of force generation is defined. The model has the following form: $y = 0.2051e^{3.3855x}$, where y is the motor units force expressed in daN (decanewtons), x is the time expressed in s (seconds). It provides an understanding of the control of multivariate motor unit recruitment and distribution of their force during sports movements as well as training programming for the adoption of forms for controlling force distribution of motor units, the development of their maximum force and their involvement speed.

Key words: Motor units force, rate of force development, speed of recruitment for motor units, the exponential model.

1. Introduction[1]

Sport has numerous movements with varying and changing dynamics which allows the possibility of a large number of combinations of speed of recruitment for motor units and the distribution of force in their realization [1-5]. It was found that the patterns of the recruitment of motor units and the distribution of force vary (not always holding to the size principle) in relation to the dynamic and kinematic motion requirements [1, 4, 6-8]. On the other hand, forces generated by individual motor units vary up to 200 times [4, 9, 10]. Therefore, we made our hypothesis of exponential distributions of force level generated by different motor units of leg extensor muscles, becaues it enables maintaining the quality of modulation of muscle contraction, and thus the fine motor control of the entire range of forces that a muscle can use [1, 7, 9, 11]. As the leg extensors are often used in most sport branches, they were the best choice for determination of the distribution of the motor units force model, which would be the aim of this paper.

2. Methods

2.1 Participants

The sample consists from 110 athletes in good shape volunteered to participate in the study (of average body high: 1.819 ± 0.05 m; of average body weight: 78.66 ± 4.38 kg). They were randomly chosen from the athletes in good shape population. All participants gave their informed consent to the procedures of the study. The conditions of the study were approved by the ethics committee.

2.2 Testing Procedure

The velocity of force generating of the leg extensor muscles was measured by Belt method in isometric

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conditions of muscle strain, using a specially developed hardware-software system (program engineering, Belgrade). The results corresponding to the maximal force and also to the levels of 1%, 2%, ..., 99% of the maximal force were sampled as well as the moments when each was reached. The force sampling was performed in each millisecond. Based on the data obtained (for each individual examinee, at each 1% within the whole diapason of the force generating) the following calculations were conducted: the RFD (rate of force development) by using the formula F/t in which F is the appropriate force level (%) in daN (decanewtons), t is the force observing time in s (seconds) and the speeds of recruitment for motor units (C) which follows the equation: $F(t) = F_{max}(1 - e^{-ct})$ in which $F(t)$ is the 1%, 2%, ...,99% of maximal force level in daN; F_{max} is the maximal force (in daN) generated by the active muscle group in the isometric condition; e is the natural logarithm base (2.71); C is the constant which characterizes the motor units inclusion rapidity; t is the time (in seconds) required for achieving the appropriate level of maximal force.

2.3 Data Analysis

The RFD depends directly on the certain groups of motor units force and the rate of their involvement (C) [4, 9-11]. From this relationship, it follows that the value of the certain groups of motor units force, for each of the 100 surveyed points, for each participants, represents quotient of the rate of force development and the speeds of recruitment for motor units (RFD/C), expressed in daN [4, 9-11]. These data are submitted to the descriptive statistics, cluster analysis and data-fitting employing the least squares method.

3. Results

Fig. 1 shows the model of the leg extensor motor units force distribution in the whole range of force generation. Table 1 shows the descriptive characteristics of the leg extensors force generated in the isometric mode in the model developed in this paper, and Table 2 shows the average value of certain

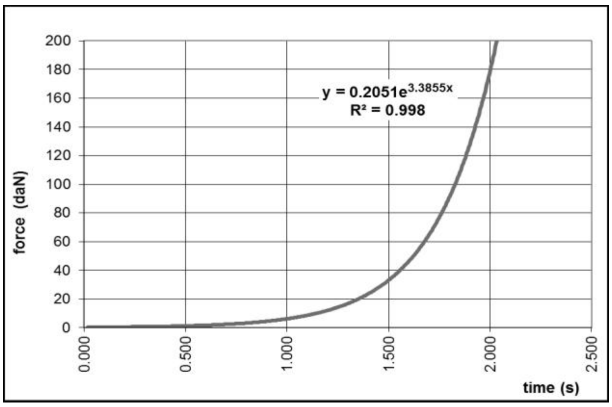

Fig. 1 Model of force distribution of motor units of leg extensor muscles.
Force distribution of motor units of leg extensor muscles is realised by model: $y = 0.2051e^{3.3855x}$ where y is motor units force expressed in daN; x is the time expressed in seconds.

Table 1 Descriptive characteristics force in leg extensors.

Force characteristics	Mean	SD
Max force in leg extensors (daN)	651.95	32.59
Time necessary to generate maximal force (s)	1.91	0.17
Max rate of force development for leg extensors (daN/s)	2296.29	282.43
In time (s)	0.097	0.008
Level of force (daN)	222.74	15.59
Max speed of recruitment for motor units of leg extensor motor units (IU)	4.35	0.36
In time (s)	0.106	0.012
Level of force (daN)	248.87	23.89

Table 2 Force developed by motor units in knee extensors.

Group of motor units	Mean	SD
Force for the 1st group of leg extensor motor units (daN)	3.22	0.35
Force for the 2nd group of leg extensor motor units (daN)	36.49	5.67
Force for the 3rd group of leg extensor motor units (daN)	58.71	8.22
Force for the 4th group of leg extensor motor units (daN)	176.14	18.26

groups of motor units force.

4. Discussion

This study shows that the distribution model of motor units power is exponential. Its general form is $y = ae^{bx}$. Its explicit form is: $y = 0.2051e^{3.3855x}$. The model was developed in an experiment in which the distribution of leg extensor motor units force lasted for 1.91 ± 0.17 s. During this time, participants have achieved the maximum force (F_{max}) of 651.95 ± 32.59 daN. The maximum force of certain groups of motor units ranged between 3.22 ± 0.35 daN (the 1st group of leg extensor motor units) and 176.14 ± 18.26 daN (the 4th group of leg extensor motor units). Kinematic characteristics of the movement in a large number of sports confine force in athletes at intervals of 0.050-0.250 s or slightly more seconds from the start of muscle contraction [9, 12-14]. Therefore, it is much more important that during this time, athletes have a high RFD_{max} rather than a high F_{max} value for achieving a better sports result, that is to have it in an early stage of the muscle contraction [1, 4, 11-14]. At the same time, for the RFD_{max} values to be high in the early stages of muscle contraction, it is necessary for contraction to have high values of speed of recruitment for motor units, in this stage [2-5, 15]. Further, the speed and the level of force generation depend on the individual motor units groups force level [2-5, 12, 16]. The model developed in this paper whereby the central nervous system according to the space and time requirements of movement in sport regulates the intensity of the motor units force production allowing their involvement patterns to change complying with the specified requirements, is in the end, the most important model for achieving the impressive sports result [1, 4, 7-9, 11]. Based on the model developed in this study participants achieved a maximum rate of force development (RFD_{max}) of 2296.29 ± 344.44 daN/s for a period of 0.097 ± 0.016 s with the force of 222.74 ± 4.92 daN. In the same movement, participants also achieved the maximum speed of recruitment for motor units (C_{max}) of 4.35 ± 0.69 IU (index units) in the period of 0.106 ± 0.02 s with the force of 238.87 ± 21.46 daN and the rate of force development of 2253.49 ± 281.69 daN/s. Experimental data indicate that RFD in participants increases from the beginning of the contraction up to 0.097 ± 0.016 s when RFD_{max} is achieved. At this time, *RFD* drops to 0.2 s when the breakpoint occurs. This segment of the curve is described by a quadratic function: $RFD\ (t < 0.2) = -179437t^2 + 44792t - 428.64$ where t is time in seconds (s). After that time, *RFD* continued to decline but by the following function: $RFD\ (t > 0.2) = 254.52t^4 - 1555.2t^3 + 3484t^2 - 3655.4t + 2045.4$ where t also represents the time in seconds (s). The speed of recruitment for motor units experimental data (C) behavior agrees with the RFD data behavior. The speed of recruitment for motor units first rises up to 0.106 ± 0.02 s when it reaches maximum values (C_{max}) and then decreases. The dynamics changes are described by the following functions: $C\ (t < 0.2) = -220.04t^2 + 58.732t + 0.2286$ where t is time in seconds (s) and $C\ (t > 0.2) = -0.0978t^3 + 1.0727t^2 - 2.5403t + 3.423$ where t is also the time in seconds (s). The resulting model shows which types of motor units are to involve in order to achieve the experimental RFD_{max} and C_{max} scores. In the dynamic generation force regime, much higher RFD_{max} and C_{max} values are achieved in a shorter time than in the isometric regime [5, 10, 15, 16]. In the amortization muscle work regime (eccentric contractions) in the drop jump amortization from the elevation of 110 cm, it was achieved RFD_{max} of 5540.3 daN/s during 0.109 s with the force of 603.89 daN and at the speed of recruitment for motor unit of 50.62 IU [10]. In the reversible muscle work regime in drop jump depth jump from the elevation of 80 cm, it is achieved RFD_{max} of 10479.9 daN/s during the time of 0.077 s at the force of 806.9 daN and the speed of recruitment for motor units from 60.1 IU [10]. An exponential model describes well the motor units force distribution in a dynamic mode of leg extensor, except that the coefficients *a* and *b* is far greater than in case of isometric mode [9]. Muscle groups in humans differ in speed of force, the level of force of certain groups of motor units and the speed of their involvement [10]. From the conditions already presented, it is clear that for every motor task, there are many possible combinations of the motor units recruitment [1, 4, 6-8]. For a movement to achieve the required speed, timing and accuracy, it is necessary that each muscle group participating in the movement develop a required amount of force at a certain creation speed in the required time. Considering the outlined muscle groups differences, CNS (central nervous system) solves this problem by optimizing the motor units operation of the all muscles involved in the movement distributing the force according to the current kinematic motion requirements [1, 4, 6, 8]. CNS controls the force distribution through firing frequency, speed and number of motor units recruitment changes [1, 4, 11-14]. Therefore, the exponential model developed in this paper could help us in the understanding of the control mechanisms of approximately 300,000 motor units in human body (estimated amount of all motor units in human body) [1, 4, 6, 8, 11]. Output of this model allows numerical definition of training objectives, training effects and changes [1, 4, 5, 9, 10, 15]. Additionally, it might be used for the training process programming making the adoption of forms for the control of motor units force distribution, the development of their maximum force and their involvement speed possible [1, 4, 5, 9, 10, 15, 16].

5. Conclusion

The mathematical model that has been developed in this study supports the hypothesis of a possible exponential distributions of force level generated by different motor units with the objective of maintaining the quality of modulation of muscle contraction, that is, the fine control of muscle force throughout the range of its generating. The model has the following form: $y = 0.2051e^{3.3855x}$, where y is the motor units force expressed in decanewtons, x is the time expressed in seconds. It provides an understanding of the control of multivariate motor unit recruitment and distribution of their force during sports movements as well as training programing for the adoption of forms for controlling force distribution of motor units, the development of their maximum force and their involvement speed.

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