CONTROL OF MUSCLE FORCE DEVELOPMENT IN ARM EXTENSORS DURING ISOMETRIC TENSION

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Abstract

The aim of this study is to determine the patterns of force development regulation in arm extensors during isometric tension using the standardized Bench Press test. An evaluation of control for each subject has been made based on the level of force achieved (30%, 50%, 70% and 90%), the rate of force development (RFD), the speed of inclusion of motor units (k), the time necessary to achieve the given level (t) and the differences recorded in the first (initial) and repeated measurements. The experiment was carried out on a sample of 130 respondents. Descriptive and comparative statistics was used along with nonlinear mathematical modeling methods for the analysis of experimental results and for establishing the patterns of control. The results of the analysis indicate that there are statistically significant differences (p <0.01) between the mean values of generated force, generating time, the rate of force development, the speed of inclusion of motor units in a given unit of time and the mean values of the same parameters in repeated measurement at all levels except at the levels of force $F_{70\%}$ (p = 0.02), and $F_{90\%}$ (p = 0.52). The models of force control have a high predictive value, ranging from 90% to 99.88% and a small prediction error, which is in the range from 0.12% to 10%. All analyses indicate high reliability of the results of this research and are therefore recommended for use in research and educational practice.

Key words*: rate of force development, speed of motor unit inclusion, motor control, nonlinear mathematical modeling*

Introduction

The level of generation of muscular force during isometric tension can willingly be controlled by regulating the work of motor units (activation velocity ratio between the number of motor units engaged, synchronization and optimization of their work), the rate of force development and time of muscle engagement (Amanovic & Dopsaj, 2006a,b; Amanovic, Milosevic, Mudric, Dopsaj, & Peric, 2006; Latash, 2012; Latash & Zatsiorsky, 2015; Milosevic, Gavrilovic, & Ivancevic, 1988; Milosevic, Mudric, Dopsaj, Blagojevic, & Papadimitriou 2004; Milosevic, Nemec, Životić, Milosevic, & Rajovic, 2014b; Milosevic & Milosevic, 2014; Schmidt & Lee, 2011). In experimenting, it can additionally be controlled through the length of the muscle (the angle at which the muscle works) and mode (evenly or flicking) of the creation of forces for each level and time. The development of diagnostic equipment made it possible to record the change of force for every 1% up to the maximum level, along with the corresponding time of reaching a certain level by frequency of over 1000 Hz/s (Hakkinen & Komi, 1986; MacDougall, Wenger, & Green, 1991; Pryor, Wilson, & Murphy, 1994; Milosevic, Laparidis, Dopsaj, Arlov, & Blagojevic, 1997; Müller, Benko, Raschner, & Schwameder, 2000; Dopsaj, Miloševic, & Blagojevic, 2000; Milosevic & Milosevic, 2013; Amanovic, Milosevic, & Mudric, 2004; Amanovic & Dopsaj, 2006; Milosevic, Milosevic, Nemec, Zivotic, & Izet, 2014a; Milosevic et al., 2014b). The achieved speed of data acquisition allows us to analyze neuromuscular characteristics of force at any given moment or time range, the percentage of force, rate of force generation, motor unit inclusion, and possibility for designing experiments with different objectives (Dopsaj et al., 2000; Christou, Grossman, & Carlton, 2002; Herzog, 2001; Linnamo, Moritani, Nicol, & Komi, 2002; Amanovic & Dopsaj, 2006a,b; Amanovic, Kostovski, Blazevic, Pavic, & Ljubisavljevic, 2013; Roczniok et al., 2013; Milosevic, Nemec, Jourkesh, et al., 2016; Amanović, Ljubisavljević, Jovanov, 2017). The data acquired by means of modern equipment are very significant from the aspect of research and understanding of control of force generation in sport and other human actvities, particularly understanding mechanisms of neuromuscular adaptation during force training (Nemec, Milošević, Nemec & Milošević, 2016; Amanović, Ljubisavljevic, Blažević, Kostovski & Bunčić, 2016; Amanovic, Baic, Nikac, & Ljubisavljevic, 2015; Zatsiorsky, & Kramer, 2006; Milosevic et al., 1988; Milosevic et al., 2004; Wilson & Murphy, 1996). The problem which this study aims to resolve is to estimate control of force generation in elbow extensors during isometric tension - using the standardized Bench Press test - through the levels of achieved force (F = 30%, 50%, 70% and 90%), time of generating specific levels (t), rate of force development (RFD), the speed of inclusion of motor units (k) and differences between the preset and achieved levels of generated force. The aim of this study is therefore to establish patterns of controlling force of arm extensors in isometric tension using the standardized Bench Press test. We expect that the results obtained in this study will allow more reliable detection of control of muscular force generation, the development of new methods for education and training, as well as better management of educational and training effects and changes.

Methods

The survey was conducted as an experimental and empirical study aimed at discovering and describing the patterns of control of muscle force generation during isometric tension. Findings from previous studies in physiology, anothropomotorics, biomechanics, training technology, motor control, and motor learning have been used (Latash & Zatsiorsky, 2015; Milosevic & Milosevic, 2014; Latash, 2012; Schmidt & Lee, 2011; Peric, 2003; Bernstein,1966; Milosevic et al., 1988).

The sample

The survey was conducted on a sample of 130 male subjects, students of the College of Internal Affairs in Zemun – Belgrade. Their average age was 21.9 ± 1.5 years. Before testing, all subjects were measured for body height (1820.46 ± 58.61 mm) and weight (83.89 ± 10.21 kg). The testing was preceded by medical and psychological examinations which confirmed the ability of the respondents to work in the Ministry of the Interior of the Republic of Serbia and their suitability for participation in the study. All respondents willingly agreed to take part in the experiment. The experiment was approved by the Dean of the College of Internal Affairs and it was carried out in accordance with the Code of Professional Ethics of the University of Belgrade and the Ethical Principles and Code prescribed by the APA.

The methodology of the force

The force of arms extensors in isometric mode was measured by a specially designed and certified system of hardware and software (Program Engineering, Belgrade) developed for the need of testing the College students (Milosevic et al., 1997) using a standardized Bench Press test (Amanovic, et al., 2004, 2006, 2013; Amanovic & Dopsaj 2006a,b). Peripheral equipment for measuring isometric force included tensiometric probes with the measurement range from 0 to 15000 daN, measurement accuracy of 0.0002 daN and a sampling frequency of 1000 Hz. The force was measured using the dynamometric Belt method (Milosevic et al., 1997, 2004). In doing so, the force $F_m(t)$ was measured for levels of 1%, 2%,....,99% up to the maximum force expressed in dekanewtons (daN) and the time when they were reached (s). Then the maximum force F_{max} was measured in daN[1] along with the moment when it was reached (Milosevic, et al., 1988, 1997, 2004). The maximum level of force is generated by the exponential function which takes the following form:

$$F_m(t) = F_{\max} \cdot \left(1 - e^{-k \cdot \Delta t}\right) \qquad [1]$$

wherein F_m is a level of 1%, 2% .... 99% of the maximum force expressed in daN; F_{max} - maximum force generated by arm extensors expressed in dekanewtons (daN); k – a constant that characterizes the speed of motor unit inclusion expressed in index units (IU); t – time in which a given level of maximum force is reached expressed in seconds (s) (Milosevic, et al., 1997, 2004). Solving the equation number [1] leads to the equation number [2] which calculates the speed of inclusion of extensor motor units:

$$k = -(1/t) \cdot \ln((1 - F_t/Fmax)) \qquad [2]$$

wherein F_t stand for the level of 1%, 2% .... 99% of the maximum force expressed in dekanewtons (daN); F_{max} – the maximum force generated by engaged muscles expressed in dekanewtons (daN); *In* – the natural logarithm; k – a constant of time which characterizes the speed of inclusion of motor units expressed in index units (IU); t – the time in which the appropriate level of maximal force is achieved expressed in seconds (s) (Milosevic, et al., 1997, 2004). On the whole range of generating force, the rate of force development is calculated for very percent (1%) according to the following formula:

$$RFD = F/t \qquad [3]$$

wherein *RFD* stands for the rate of force development expressed in dekanewtons per second ($daN \cdot s^{-1}$), F – the corresponding level of force expressed in dekanewton (daN), and t – the time of force observation expressed in seconds (s) (Milosevic et al., 1997, 2004).

The testing of all respondents comprised two tasks. The first task (Test 1) required the subjects to generate the maximum force of the arm extensors in the standardized Bench Press test as fast as possible (Amanovic, et al., 2004, 2006, 2013; Amanovic & Dopsaj 2006a,b). The force, the maximum rate of force development, maximum rate of motor unit inclusion and the time to achieve these at 30%, 50%, 70% and 90% of the maximum force were measured and stored in the database for each respondent for the purpose of this study. The second task (Test 2) involved communicating to the respondents the achieved levels of force and the time it had taken them to achieve it, after which

[1] 1 daN = 10^1N

they were asked to repeat their scores as accurately as possible for the levels of 30%, 50%, 70% and 90% of the maximum force. The values of force, the rate of force development, the rate of motor unit inclusion and the time to achieve these at 30%, 50%, 70% and 90% of the maximum force were measured for this task as well.

Methods of data processing

To determine the patterns of the force generation control, all collected data were processed using descriptive and comparative statistics (Peric, 2006) and methods of nonlinear mathematic modeling (Milovanovic & Djordjevic, 2006; Milosevic et al., 1997; Peric, 2006; Watts, Bates, 2007). For testing the significance of differences between mean values obtained in Test 1, we used T-test for paired samples (*T paired test*). All conclusions were realized with the level of significance of 0.01 ($Sig \leq 0.01$). To model the control of arm extensor force generation, we used polynomials of the following general form:

$$y = a_0 + a_1 x + a_2 x^2 + ... + a_n x^n \quad [4]$$

wherein y is the level of generated force of arm extensors at 30%, 50%, 70% and 90% of the maximum force in Tests 1 and 2 expressed in dekanewtons (daN), x – the first denotes the time expressed in milliseconds (ms), the second - the rate of force development expressed in dekanewtons per second (daN/s) and the third - the speed of inclusion of motor units of arm extensors expressed in index units (IU), and a_0, a_1, a_2,............a_n, the coefficients of the polynomial. The processing of raw data was performed using SPSS software, version 22.0.

Results

The values obtained in all types of analyses and modeling (Tables 1-5) indicate high reliability of the research results. A descriptive analysis showed that the value of standard deviation was 10 % smaller that the average value, that the error in estimating average values in the observed population was very low, below 5 % of the mean value in the sample, and the coefficient of variation was relatively low. T-statistics additionally showed that all the differences between the results obtained in Test 1 and Test 2 were significant on the one percent level of risk ($p<0.01$), except in one observation, and that the models of control of force generation were highly reliable and had a very low prediction error.Differences in force, rate of force development, speed of motor unit inclusion and time of reaching the levels of 30%, 50%, 70% and 90% of the maximum force recorded in Test 1 and Test 2 are shown in Tables 1-4 and Figure 1. It has been established (Table 1) that the generated levels of force at 30% and 50% achieved in Test 1 were significantly ($p<0.01$) lower (20.78 daN and 7.47 daN) than the force for the same percentage achieved in Test 2. The force generated at 70% of the maximum force in Test 1 was significantly lower (3.41 daN) but at the two-percent level of risk (*Sig.*=.02) than the force achieved in Test 2. No significant differences were found only at 90% of the maximum force where the significance level was 0.52 (*Sig.*=.52). It was further found (Table 2) that the rate of force development was significantly higher ($p<0.01$) in Test 1 for all levels (30%, 50%, 70% and 90%) than the rate of force development at the same levels in Test 2. We established (Table 3) that the speed of inclusion of the arm extensor motor units achieved in Test 1 was significantly lower ($p<0.01$) at all levels (30%, 50%, 70% and 90%) than the speed of inclusion of arm extensor motor units for the same levels (4.01 IU, 2.29 IU, 1.59 IU and 1.26 IU) in Test 2. Finally, it was established that the time needed to generate the force of arm extensors for all levels (30%, 50%, 70% and 90%) achieved in Test 1 was significantly shorter ($p<0.01$) (689.89ms, 757.79ms, 839.91ms, 750.15ms) that the time required to achieve the same levels in Test 2.

Models of control of arm extensor force development have been defined based on the interdependence of the achieved percent of the maximum force at 30%, 50%, 70% and 90% levels and the time required to achieve each of these (Table 5), then through dependence of the force achieved at the levels of 30%, 50%, 70% and 90% and the rate of force development, and finally through dependence of the force achieved at the 30%, 50%, 70% and 90% levels and the speed of inclusion of the motor units (Table 5). Analyses showed that the recorded measuring can be approximated by a second degree polynomial using the method of least squares (Milovanovic & Djordjevic, 2006; Milosevic et al., 1997; Peric, 2006; Watts & Bates, 2007) wherein the polynomial coefficients a_0, a_1 and a_2 relate to: (a_0) - the shifts to the left or to the right along the x axis, (a_1) – the rate in which the function increases or declines, and (a_2) - the steepness of the parabola at the intersection with the y axis. The reliability of prediction of output data of in these models is extremely high, ranging from 90% to 99.88% with an exceptionally small prediction error of 0.12% to 10%.

Table 1. Descriptive statistics for the variable **F%** calculated for different levels of force.

Variable	Test	**Mean** (DaN)	Std. Deviation	Std. Error	Minimum	Maximum	t	*Sig.*
30%	1	62.82	10.23	0.89	37.70	78.64	*-11.00*	***.00***
	2	83.6	21.36	1.87	50.52	146.34		
50%	1	104.16	16.95	1.48	62.96	129.29	*-3.69*	***.00***
	2	111.63	25.42	2.22	29.62	173.21		
70%	1	144.18	23.58	2.06	86.73	177.44	*-2.32*	***.02***
	2	147.59	24.68	2.16	80.38	207.93		
90%	1	185.56	30.38	2.66	111.87	228.71	*-.63*	***.52***
	2	184.86	33.36	2.92	117.34	253.1		

Table 2. Descriptive statistics for the variable **RFD** calculated for different levels of force.

Variable	Test	**RFD** (DaN/s)	Std. Deviation	Std. Error	Minimum	Maximum	t	*Sig.*
30%	1	508.4	359.08	34.17	148.44	1761.59	*11.38*	***.00***
	2	108. 9	61.01	5.89	35.78	419.36		
50%	1	511.0	328.05	31.74	147.62	1781.4	*11.34*	***.00***
	2	136.89	76.9	7.43	35.78	522.96		
70%	1	395.19	210.82	20.38	99.36	761.45	*12.24*	***.00***
	2	134.55	74.77	7.22	27.99	360.75		
90%	1	229.39	127.47	12.32	54.97	761.45	*8.11*	***.00***
	2	121.23	67.97	6.57	42.27	373.9		

Table 3. Descriptive statistics for the variable **k** calculated for different levels of force.

Variable	Test	**k** (IU)	Std. Deviation	Std. Error	Minimum	Maximum	t	*Sig.*
30%	1	2.49	1.48	0.13	0.31	6.96	*-15.42*	***.00***
	2	6.5	3.09	0.27	1.31	16.32		
50%	1	3.17	1.82	0.15	0.55	9.77	*-8.59*	***.00***
	2	5.46	2.9	0.25	1.03	19.83		
70%	1	3.16	1.6	0.14	0.85	9.01	*-7.36*	***.00***
	2	4.75	2.38	0.2	1.48	14.31		
90%	1	2.07	1.43	0.12	1.03	7.7	*-3.66*	***.00***
	2	3.33	1.7	0.14	1.19	10.64		

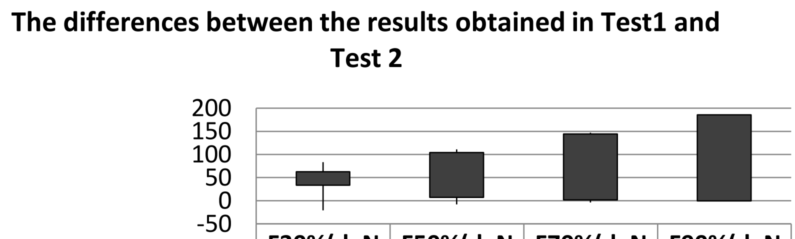
Table 4. Descriptive statistics for the variable **t** calculated for different levels of force.

Variable	Test	**t** (ms)	Std. Deviation	Std. Error	Minimum	Maximum	t	*Sig.*
30%	1	219.38	175.49	15.39	51.36	1160.75	*-17.05*	***.00***
	2	909.27	419.44	36.78	287.22	2278.95		
50%	1	307.44	203.72	17.86	71.18	1254.58	*-14.91*	***.00***
	2	1065.23	571.8	50.15	110.15	2573.16		
70%	1	471.31	230.53	20.21	134.46	1382.89	*-13.78*	***.00***
	2	1311.22	674.45	59.15	334.00	3049.67		
90%	1	1028.85	415.3	36.42	293.7	2158.69	*-10.78*	***.00***
	2	1779.0	689.44	60.46	486.72	3987.13		

Table 5. Models of control of arm extensor force development in terms of the time of development, the rate of force development and the speed of inclusion of motor units.

Test	a_0	a_1	a_2	R^2
1	-18.932	0.2632	-0.0002	0.9952
2	-140.77	0.25	-7E-05	0.9988
1	75.976	0.1691	-0.0005	0.8902
2	-3814.9	62.734	-0.2519	0.9875
1	-4236.5	3026.2	-527.24	0.9285
2	102.27	5..196	-2.6657	0.9938

Note: a_0, a_1, a_2 are the coefficients of the polynomial and R^2 a level of significance of prediction.



	F30%(daN)	F50%(daN)	F70%(daN)	F90%(daN)
Mean- Test 1	**62.82**	**104.16**	**144.18**	**185.56**
Mean- Test 2	**83.6**	**111.63**	**147.59**	**184.86**
The difference absolute	**-20.78**	**-7.47**	**-3.41**	**0.7**
The difference relative (%)	**33.08**	**7.17**	**2.37**	**-0.38**

Figure 1. Differences between the given and achieved values for each level of force.

Discussion

The obtained results for all of the observed levels indicated that at all the subjects generated, at a statistically significant level (*Sig.*>.01), more force than required, in a longer time of generation, at a higher speed of motor unit inclusion and a lower rate of force development. What regularities influenced the outcome of our experimental measurements? What caused this to happen? In our experiment focusing on achieving the set values of force, 30 points of force-time were observed for the level of 30%, and for all other levels 20 points were observed. The brain regulates the achievement of the set level of force in the experiment by producing the force of motor units (Aagaard et. al., 2002; Amanovic et al., 2006c; Andersen & Aagaard, 2006; Andersen, Andersen, Zebis & Aagaard, 2010; Hodson-Tole & Wakeling, 2009; Milosevic et al., 1997, 2004, 2014b; Milosevic, Blagojevic, Pilipovic, & Tosic, 2000). For this purpose, it applies different patterns of their involvement (Aagaard et. al., 2002; Amanović et al. 2006c; Andersen & Aagaard 2006; Andersen et. al., 2010; Hodson-Tole & Wakeling, 2009; Milosevic et al., 2000, 2004, 2014b). In the pattern that is frequently used for controlling force generation at lower levels, up to the maximum of 50% of the force, the values of speed of inclusion of motor units and rates of force development increase from the onset of contraction to 100 ms when they reach the maximum, and then gradually decline to 200 ms, dropping far more rapidly thereafter (Aagaard et al., 2002; Amanovic et al., 2006c; Andersen & Aagaard, 2006; Andersen et al., 2010; Hodson-Tole & Wakeling, 2009; Milosevic et al., 1997, 2000, 2004, 2014b). This level of force generation is characterized by involving mostly those motor units that individually generate the minimum (1 daN to 2 daN) or small (2 to 21 daN) amounts of force and have the lowest initiation thresholds (5 Hz to 20 Hz and 20 Hz to 30 Hz) (Grimby, 1984; Milosevic & Milosevic, 2013, 2014; Milosevic et al., 2000, 2004, 2014b; Peric, 2003; Stein, 1974). In this model, force development is regulated by successive recruitment of new or exclusion of the already involved motor units of the same ignition threshold but different levels of maximum force as well as by modulation (increase or decrease) in the frequency of impulses coming into the muscle (Aagaard et. al., 2002; Amanovic et al. 2006c; Andersen & Aagaard, 2006; Andersen et al., 2010; Duntsh & Stoboy, 1996; Grimby, 1984; Hodson-Tole & Wakeling, 2009; Milosevic et al., 1997, 2000, 2004, 2014b; Stein, 1974). A different pattern applies to the levels between 50% and 70%. This pattern typically involves recruiting additional motor units of higher ignition thresholds (from 30 Hz to 65 Hz) and higher levels of force (from 22 daN to 65 daN) to generate the set level of force (Grimby, 1984; Milosevic & Milosevic, 2013, 2014; Milosevic et al., 2004, 2014b; Stein, 1974). In this pattern the values of speed of motor unit inclusion and the rate of force development increase from the onset of contraction to 100 ms when they reach the maximum, gradually decline to 200 ms, and then begin to decline much faster (Aagaard et. al., 2002; Amanovic et al., 2006c; Andersen & Aagaard 2006; Andersen et. al., 2010; Hodson-Tole & Wakeling, 2009; Milosevic et al., 2000; 2004, 2014b). Control of force level is achieved by recruiting new and excluding the already engaged motor units of the same ignition threshold but different levels of the maximum force as well as by modulation of frequency of the impulses coming into the muscles (Aagaard et. al., 2002; Amanovic et al., 2006c; Andersen & Aagaard 2006; Andersen et. al., 2010; Duntsh & Stoboy 1996; Grimby, 1984; Hodson-Tole & Wakeling, 2009; Milosevic et. al., 2004, 2014b; Stein, 1974). For achieving the levels of 70% to 90% or more of the maximum force a pattern of motor unit inclusion that is used involves synchronous recruitment of only those motor units that ignite at 80 or more Hz and that generate force ranging from 65 daN to 110 daN (Grimby, 1984; Duntsh & Stoboy, 1996; Milosevic & Milosevic, 2013, 2014; Milosevic et al., 2004, 2014b; Stein, 1974). The speed of motor unit inclusion and the rate of force development follow the same scheme as in the previous two patterns.

The dominant mechanism of force level control in the pattern is the mechanism that ensures modulation of impulse frequency (Grimby, 1984; Duntsh & Stoboy 1996; Milosevic & Milosevic, 2013, 2014; Milosevic et al., 2000; 2004, 2014b; Stein, 1974). The obtained results indicate that the respondents used all of the three above mentioned patterns. In all of the patterns, the level of force is regulated by recruiting new and excluding the already engaged motor units of the same ignition thresholds and different maximum force levels, as well as modulation of impulse frequency. The results of the experiment showed that pattern three was slightly modified. When the required level of force for each of the tasks was communicated to the respondents, they made an ideal program for the development of the set level of force which they controlled by means of speed of motor unit inclusion, rate of force development and time. For all the given levels of force, the values of speed of motor unit inclusion and the rate of force development increase from the onset of contraction to 100 ms when they reach the maximum, then gradually decline to 200 ms, and begin to drop much faster. This suggests that the respondents initially used significantly higher values of speed of motor unit inclusion and rate of force development to achieve the set force levels, which required making corrections or else it would result in the levels of force much higher than the required ones if it continued in time. Tendon receptors send information about muscle tension on the basis of which the respondents make decisions whether or not they have achieved the required levels of force (Bernstein, 1966; Latash & Zatsiorsky, 2015; Milosevic et al., 1988; Milosevic & Milosevic, 2014). If they have achieved it, they finish the test and if they have not, they continue tension and make corrections in order to achieve it. Based on the information on the force, the respondents can make corrections at 180 millisecond intervals (Bernstein, 1966; Latash & Zatsiorsky, 2015; Milosevic et al., 1988; Milosevic, Milosevic, 2014; Peric, 2003; Schmidt & Lee, 2011). The length of time to achieve the required level of force was extremely high in all tasks due to corrections that were made. Given the duration of time for achieving the specified levels of force and changes in the rates of force development and motor unit inclusion in that time it can be concluded that the respondents made corrections on multiple occasions during the experimental task (Milosevic et al., 1988; 2004, 2014b; Milosevic, Milosevic, 2013, 2014). The rate and level of force depends on the speed (the number) of recruited motor units and the levels of force they produce (Aagaard et. al., 2002; Amanovic et al. 2006c; Andersen & Aagaard, 2006; Andersen et. al., 2010; Duntsch & Stoboy, 1996; Grimby, 1984; Hodson-Tole & Wakeling, 2009; Milosevic et al., 2000; 2004, 2014b; Stein, 1974). Changes in the value of speed of motor unit inclusion and rate of force development in achieving the set values of force, particularly at the level of 30%, indicate that corrections were made by excluding the groups of motor units which generate higher levels of force and by changing the initiation frequency. The corrections resulted in reductions in the speed of inclusion of motor units, the rate of force development and lower levels of generated force, which remained above the set point throughout the testing, except at the 90% level. Repeated corrections contributed to reducing the error in achieving the set level over time. Errors that the respondents made were greater in attaining lower levels of force, speed of inclusion, and rate of force development than in the higher levels. This was also confirmed by research in the variability of force during isometric contraction of leg extensors (Christou et al., 2002; Milosevic et al., 1997, 2000; 2004, 2014b). Making corrections influenced the rate of force development to be smaller at almost all levels than the set one, which indicates that control by reduction in the number of involved motor units was dominant. Based on the obtained data for each level of force, the models of generating the set level of force were fitted using the least square approach (Table 5) (Milovanovic & Djordjevic, 2006; Milosevic et al., 1997; Peric, 2006; Watts & Bates, 2007). The square shape of the model was the best to describe the variability of experimental data. The models have a high predictive value, ranging from 89.02% to 99.88%, and a small prediction error, ranging from 0.12% to 10%. All analyses largely confirmed the principles of force generation control and produced new knowledge in the field of motor control (Amanovic et al. 2006c; Bernstein, 1966; Christou et al., 2002; Gipson, StClair, Lambert, & Noakes, 2001; Latash, 2012; Latash & Zatsiorsky, 2015; Linnamo et al., 2002; Milosevic et al., 1988, 1997, 2000, 2004, 2014b; Milosevic & Milosevic, 2014; Schmidt & Lee, 2011). The results of this study provide an understanding of the mechanisms of control of multivariate motor unit recruitment, the distribution of force, the rate of force development in order to achieve the set levels of force in time and give an opportunity to develop new methods of training and education (Amanovic et al. 2004; Schmidt & Lee, 2011; Milosevic & Milosevic, 2014; Amanovic et al., 2015). In addition to this, they allow the mechanism of adaptation which induces changes in the neuromuscular apparatus to be located in terms of the level and method of motor unit activation (synchronous or successive), regulation (decrease or increase) of the number of active motor units and (or) increased frequency of impulses coming into the muscle. Since the obtained results and models are characterized by high reliability, they can be used for programming and managing training effects and changes in the sphere of adopting patterns of control and the distribution of force of motor units, the development of their maximum force, the speed of their inclusion and the rate of force development (Andersen et. al., 2010; Hakkinen & Komi, 1986; Milosevic et al., 1988, 2014; Milosevic & Milosevic, 2013, 2014; Müller et al., 2000; Roczniok, et al., 2013; Zatsiorsky & Kramer, 2006; Wilson & Murphy, 1996).

Conclusion

Based on the obtained results, it can be concluded that the research problem has been successfully resolved and that the objective of the study has been achieved. In their attempts to achieve the values of force set in Test 1 the respondents generated statistically significant excess (p=0.00 and p=0.02 in the level of force in Test 2. For the level of 30%, the excess amounted to 20.78 daN, for the 50% level it was 7.47 daN, and for the 70% level it was 3.41 daN. Only at the level of 90% there was no statistically significant difference (p = 0.52) between the set level of force and the achieved one. The level of error was the highest for 30% and then steadily declined with higher levels of force (50%, 70%, 90%). Achieving higher levels of force than required was caused by statistically significant (p<0.01) attainment of higher values of the speed of inclusion of arm extensor motor units then the set ones at all the observed levels (30%, 50%, 70%, 90%). For the level of 30% the speed of motor unit inclusion was higher by 4.01 IU, for the level of 50% it was higher by 2.29 IU, for the level of 70% it was hihger by 1.59 IU, and for the level of 90% by 1.26 IU. The pattern here resembles the previous one: the higher the level of generated force (30%, 50%, 70%, 90%), the smaller the error in the speed of motor unit inclusion. Given the fact that it was the first time the respondents encountered the type of test that eliminates the possibility of education, they used longer periods of time than the default time to achieve the set values of force at a statistically significant level (p<0.01). For the level of 30% they used 689.89ms more, for the level of 50% they used 757.79ms more, for the level of 70% they used 839.91ms more and for the level of 90% they used 750.15ms more time. One of the reasons for longer time of force development lies in fact that in the course of first 100 ms the respondents have extremely high levels of motor unit inclusion and rate of force development, which causes exceeding the preset force values at all of the the observed levels. The respondents solve this problem by changes in the recruitment of motor units and the frequency of impulses coming to the muscles, reducing the speed of motor unit inclusion and the levels of force, as well as the rate of force development, thereby reducing errors that might occur. The processes of error reduction and achieving the set values of force consumes significantly more time than in Test 1. The obtained results indicated that three patterns of motor unit inclusion were used, one for the levels from 30% to 50%, another for the levels from 50% to 70%, and the third from 70% to 90% and more. The patterns of force development prediction have a high predictive value, which ranges between 89.02% and 99.88% and a small prediction error, ranging from 0.12% to 10.98%. All analyses indicate high reliability of the results of this study and are therefore recommended for use in research and educational practice.

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KONTROLA RAZVOJA SILE MIŠIĆA EKSTENZORA RUKU TIJEKOM IZOMETRIČKE NAPETOSTI

Sažetak

Cilj ovog istraživanja je utvrditi obrasce regulacije razvoja sile ekstenzora ruku tijekom izometričke napetosti primjenom standardiziranog testa Bench Press. Evaluacija kontrole za svaku razinu napravljena je na temelju postignute sile (30%, 50%, 70% i 90%), brzine razvoja sile (RFD), brzine uključivanja motornih jedinica (k) , vrijeme potrebno za postizanje zadane razine (t) i razlike zabilježene u prvom (inicijalnom) i ponovljenom mjerenju. Eksperiment je proveden na uzorku od 130 ispitanika. Za analizu eksperimentalnih rezultata i utvrđivanje obrazaca kontrole koristi se deskriptivna i komparativna statistika uz nelinearne matematičke metode modeliranja. Rezultati analize pokazuju da postoje statistički značajne razlike ($p < 0.01$) između srednjih vrijednosti generirane sile, vremena stvaranja, brzine razvoja sile, brzine uključivanja motornih jedinica u određenoj jedinici vremena i srednje vrijednosti istih parametara u ponovljenom mjerenju na svim razinama osim na razinama sile F70% ($p = 0.02$) i F90% ($p = 0.52$). Modeli kontrole sile imaju visoku prediktivnu vrijednost, u rasponu od 89.02% do 99.88% i malu pogrešku predviđanja koja je u rasponu od 0.12% do 10.98%. Sve analize ukazuju na visoku pouzdanost rezultata ovog istraživanja i stoga se preporučuju za korištenje u istraživačkoj i obrazovnoj praksi.

Ključne riječi: *brzina razvoja sile, brzina uključivanja motora, kontrola motora, nelinearno matematičko modeliranje*

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