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Symmetry of electromechanical delay, peak torque and rate of force development in knee flexors and extensors in female and male subjects

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Purpose: The aim of the study was to evaluate electromechanical delay (EMD), peak torque (PT) and rate of force development (RFD) in selected muscles of right and left lower extremities in groups of female and male subjects. Methods: The study evaluated 9 volunteer female subjects (mean ± SD: age: 21.67 ± 0.87 years; height: 168 ± 7 cm; body mass: 59.44 ± 4.8 kg) and 10 male university students (mean ± SD: age 22 ± 1.25 years; height: 179 ± 6 cm; body mass: 74.3 ± 5.1 kg) from the Faculty of Physical Education. Muscle torques and electromyographic activity were measured for knee flexors and extensors in static conditions, separately for the right and the left lower extremities. During the measurements, the subjects generated the maximum torque as fast as possible. Surface electrodes were placed on the right and left lower extremities on the following muscles: rectus femoris, vastus lateralis (m.VL), vastus medialis and biceps femoris. Results: Symmetry of EMD, RFD and "flexors-extensors" ratio was found in the muscles of the right and left lower extremities (with an exception of m.VL) in the group of male and female subjects. Statistical analysis demonstrated the presence of asymmetry in PT (297.66 vs. 272.05 N·m) and relative force in knee extensors in the group of men (3.90 vs. 3.54 $N\cdot m\cdot kg^{-1}$). Conclusions: Symmetry of EMD and asymmetry of PT might suggest that the cause of asymmetry of the muscular force is mainly morphological characteristics of the muscle rather than the process of controlling its activity.

Key words: *electromyography, gender, lower extremity*

1. Introduction

The problem of upper extremity movement symmetry has been the focus of numerous research studies, whereas the methodology of the research stems from Berstein theory [13]. Humans are asymmetric by their nature. One of the manifestations of the asymmetry is the presence of dynamic and functional asymmetries. Functional asymmetry is understood as preference for using upper and lower extremities as well as sensory organs located at one side of the body. This is caused by a dominance of motor centres in the cerebral cortex of the opposite brain hemisphere. The dynamic asymmetry manifests itself in different possibilities of generating the force and muscular contraction by, e.g., right and left lower or upper extremities [19]. Another manifestation of this type of asymmetry is differentiation of kinematic and kinetic parameters of the right and left extremities during walking [24], strength abilities of the muscles present on the right and left sides of the body [14], [16] as well as precision of movement of right and left upper extremities [11]. There are professional sports with symmetrical and asymmetrical movement techniques [23]. One consequence of asymmetric technique in sports is asymmetric development of strength abilities in the muscles of right and left body sides. With the lack of compensation training, this might lead to a variety of injuries.

Muscular strength depends on the type of muscle tissues as well as control of tissue excitation. Quality

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of control can be evaluated based on EMG signal, with one of the essential parameters being electromechanical delay (EMD). EMD has been defined as a time between electrical excitation of the muscle and the onset of force generation. Cavanagh and Komi [5] demonstrated that EMD for skeletal muscles ranges from 30 to 60 ms. EMD is also affected by such factors as the type and structure of skeletal muscles and fatigue [12], [20], initial muscle length [22] or the type of muscular activity [5]. EMD might also change for various types of physical efforts and age [26]. There have also been studies that pointed to the relationship between EMD and musculotendinous stiffness [7] and even lifestyles [9]. There is also no unequivocal explanation among the researchers about the causes of EMD. One of the causes of EMD is elasticity of the contractile components, which causes that elasticity of the muscular tendon determines EMD levels [26].

EMD values are substantially important during practical evaluation of muscular function, especially during evaluation of the strength and endurance of muscles in professional sports. Numerous studies have demonstrated the essential correlation of EMD with peak torque (PT) and rate of force development (RFD) [3], [20], [22].

The force generated by muscles depends on a variety of factors: structure and length of the muscle, length of the lever arm of force, number of contracting muscle tissues (excited motor units) and pulse frequency for excited motor units. Control of muscular excitation is evaluated based on the electromyographic signal (EMG), which allows, among other parameters, EMD values to be determined. The aim of the study was to answer to the question whether asymmetry of the parameters studied results from morphological characteristics of the muscle or the method of controlling the activity. In order to answer the above questions, the authors evaluated symmetry of EMD, PT and RFD in selected muscles in both right and left limbs, separately in the groups of women and men. Based on the data available in the literature, a hypothesis can be proposed that the above parameters should point to the asymmetry in both male and female groups.

2. Material and methods

2.1. Subjects

Nine women participated in the study (age: 21.67 ± 0.87 years; height: 168 ± 7 cm; body mass: 59.44 ± 4.8 kg) and 10 men (age: 22 ± 1.25 years; height: 179 ± 6 cm; body mass: 74.3 ± 5.1 kg), who were university students from the Faculty of Physical Education. The subjects were informed about the aim and procedure of the study and gave written consent to participate in the experiment. The subjects were involved in physical activity at a high level that resulted from the character of the university course. However, none of them practised sports at professional level. Furthermore, none of the students had been injured for 6 months before the study and had not undergone any surgical intervention in the area of right or left lower extremities. All the women studied pointed to the right lower extremity as the preferred one, whereas in the group of men, eight subjects pointed to the right and two pointed to the left extremity as a preferred one.

2.2. Experimental procedure

The study used the surface electromyography method and the method of measurement of muscle torques under static conditions. The measurements of static muscle torque and EMG activity were performed on a multifunctional chair. The measurement system included torque meter with strain gauge head (measurement range: 0 to 500 Nm, relative error of the strain gauge bridge: 0.5%), direct current amplifier (calibrated amplification k = 470; bandwidth 0 to 1 kHz; zero drift: 0.6 μV/°C).

The subjects were examined in the sitting position. The angle in the hip joints was set at 90°, whereas the angle in the knee joints was 75° (for the measurement of PT in extensors) and 30° (for the measurement of PT in flexors). 0° was adopted as an angle of full extension in the knee joint. According to the principles of measurement, the axis of the knee joint coincides with the axis of the dynamometer. In order to eliminate the effect on the measurement of other muscle groups through muscular transfer, upper extremities were crossed on the chest while the body trunk and thighs were immobilized with stabilizing belts (Figs. 1 and 2). Resistance of the measurement equipment was located:

- at the anterior part of the calf near the ankle joint – for the measurement of EMG and PT in calf extensors (Fig. 1),
- at the posterior part of the calf near the ankle joint – for the measurement of EMG and PT in calf flexors (Fig. 2).

Length of the lever arm of the external force for each subject was chosen according to the generally adopted principles of measurements of muscle torques in statics. The subjects were asked to respond to a cue by producing a maximum torque of flexors and extensors of the knee in the sagittal plane, separately for the right and left lower limb. During the measurements, the subjects were encouraged by the investigators to produce the maximum torque as fast as possible.

Fig. 1. Measurement of PT and EMG signal in extensors of the calf in the knee joint

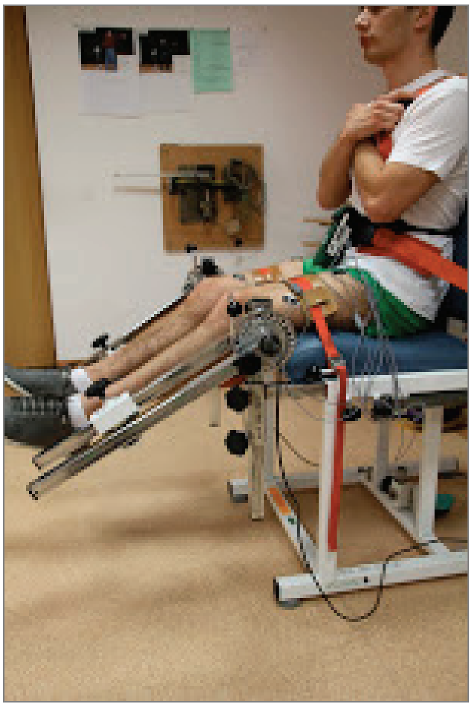

Fig. 2. Measurement of PT and EMG signal in flexors of the calf in the knee joint

2.3. EMG data processing

Double disposable surface electrodes were glued to the skin over the muscle belly and along the direction of muscle tissues. Sixteen active electrodes were glued (Noraxon Inc., No 272, Scottsdale, USA; Spacing = 20 mm) on the muscles studied and 1 reference electrode on the head of the right fibula. Active electrodes (self-adhesive, silver–silver chloride) were glued using a bipolar configuration on the muscles that represent a group of flexors and extensors of the calf in the knee joint in right and left leg as follows:

- muscle rectus femoris (m.RF) – on the line from the anterior spina iliaca superior to the superior part of the patella,
- muscle vastus lateralis (m.VL) – approximately at 2/3 on the line from the anterior spina iliaca superior to the lateral side of the patella,
- muscle vastus medialis (m.VM) – approximately at 80% on the line between the anterior spina iliaca superior and the joint space in front of the anterior border of the medial ligament,
- muscle biceps femoris (m.BF) – approximately at 50% on the line between the ischial tuberosity and the lateral epicondyle of the tibia.

The skin was prepared for the experiment according to the recommendations of SENIAM project [8]. A 16-channel electromyographic device TeleMyo 2400T G2 (Noraxon Inc., USA) was used to acquire EMG signals. The amplifier bandwidth ranged from 10 to 1,500 Hz and the common-mode rejection ratio was 100 dB. The EMG signals were sampled at 1,000 Hz by using an analog-to-digital converter based on a 16-bit analog-to-digital board.

2.4. Data collection

Based on the EMG signal and muscle torque recorded in the muscles studied, the following parameters were selected for the analysis (Fig. 3):

- electromechanical delay (EMD), defined as the time between the onset of EMG activity and the onset of torque generation [s],
- peak torque (PT), the resultant value of maximum torque in groups of flexors (m.BF) and extensors (m.RF, m.VL, m.VM) of the knee joint [N·m],
- rate of force development (RFD), calculated as a quotient of the peak torque and time to reach the peak torque [$N \cdot m \cdot s^{-1}$],
- relative force, calculated as a quotient of peak torque and body mass of a subject [$N \cdot m \cdot kg^{-1}$],

- "flexors-extensors" ratio, calculated as a quotient of the PT of the flexor muscles to the extensor.

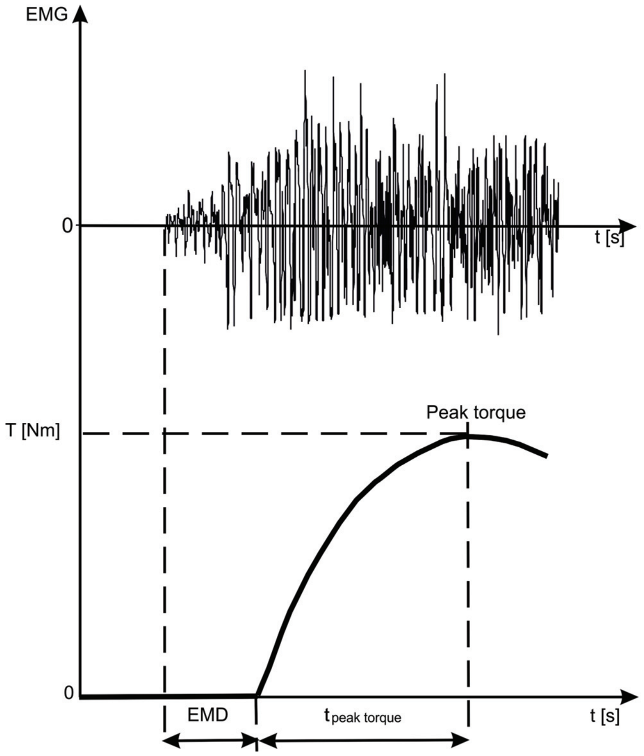

Fig. 3. Parameters analysed in the study (description in the text)

2.5. Torque and EMG signal processing

The raw EMG signal and torque were both recorded on a PC computer with BioWare® (V.3.2.6) software. The data collected were exported to files with *.tbd format and then Analizator software dedicated for numerical analysis of continuous signals sampled by BioWare was used. Analizator software allowed the module of muscle torque and electrical signal of the muscles to be determined as well as the moving average to be computed with the step 101. Moving average can be considered as an outcome of low-pass filtration. This method allowed phase lags to be avoided, which are typical of one-way filtering [6], [14], [15]. Results of calculations from Analizator software were moved to a spreadsheet where the data for statistical analysis were prepared.

2.6. Statistical analysis

The Wilcoxon signed-rank test was used to assess the effect of symmetry and gender on EMD, PT, RFD, relative force and "flexors-extensors" ratio. The results of the statistical analysis included: N (the number of subjects), and p (the probability level for the Wilcoxon test). Tables contain the median (Me – middle value) and quartile deviation (Qc). The level of significance (α) was set at 0.05. In the correlation analysis, the authors used Spearman's rank correlation coefficient.

3. Analysis of the results

3.1. Electromechanical delay

Comparative analysis for EMD between the muscles of right and left lower extremities is presented in Table 1. Statistical analysis revealed the presence of EMD asymmetry only for the VL muscle, both in the female group (0.035 vs. 0.06 ms, p = 0.0381), and the male group (0.048 vs. 0.012 ms, p = 0.005). Furthermore, medians for EMD of the muscles of the right lower extremity were longer in each case in men compared to women (differences were not statistically significant). The same analysis performed for the muscles of lower extremity showed longer EMD in the muscles in women compared to men, with significant differences between women and men recorded only for m. VL (0.06 vs. 0.012 ms, p = 0.0208).

3.2. Peak torque, rate of force development, relative force and "flexors-extensors" ratio

Statistical analysis with Wilcoxon test did not reveal statistically significant differences between the value of PT measured for the right and left extremities in the female group (Table 2). Differences in PT recorded between the right and left extremities in the group of men were statistically significant only for the extensors of the knee joint.

Comparative analysis of PT in the muscles in female and male subjects revealed significant differences between the groups in all muscle groups analysed. The PT values achieved by men were higher in all the cases compared to the group of women. Since the level of muscular PT is significantly correlated to body mass, in order to eliminate its effect (comparing the group of women and men), the relative force was calculated. The analysis revealed statistically significant differences between women and men only for one muscular group, i.e., flexors of the knee joint in the right extremity (1.57 vs. 2.17 N·m·kg^{-1}, at

Table 1. Medians (Me) and quartile deviations (QC) of the EMD values between muscles of the right and left extremities in female ($N = 9$) and male ($N = 10$) subjects

	EMD [s]							
	Right lower extremity				Left lower extremity			
	m.VL	m.VM	m.RF	m.BF	m.VL	m.VM	m.RF	m.BF
Females	0.035 ±0.011	0.029 ± 0.010	0.036 ± 0.008	0.044 ± 0.016	0.060 ± 0.026*	0.055 ± 0.020	0.050 ± 0.020	0.046 ± 0.010
Males	0.048 ± 0.016	0.047 ± 0.025	0.051 ± 0.023	0.045 ± 0.016	0.012 ± 0.013*#	0.041 ± 0.018	0.037 ± 0.012	0.040 ± 0.013

Note: * Indicates significant differences between the right and left lower extremity;
# Indicates significant differences between females and males.

Table 2. Medians (Me) and quartile deviation (QC) of peak torque, rate of force development, relative force and "flexors-extensors" ratio in the muscle groups in male ($N = 10$) and female ($N = 9$) subjects

	Gender	Right lower extremity		Left lower extremity	
		Knee joint extensors	Knee joint flexors	Knee joint extensors	Knee joint flexors
Peak torque [N·m]	Females	201.07 ± 14.01	92.46 ± 9.78	186.35 ± 14.07	92.88 ± 9.45
	Males	297.66 ± 26.91#	157.20±39.15#	272.05±13.79*#	143.24±21.09#
Relative force [N·m·kg^{-1}]	Females	3.21 ± 0.15	1.57±0.52	3.19±0.08	1.61±0.49
	Males	3.90 ± 0.85	2.17±0.91#	3.54±0.57*	1.89±0.52
Rate of force development [N·m·s^{-1}]	Females	122.43 ± 43.41	76.66±23.02	101.34±16.37	67.60±17.99
	Males	137.10 ± 13.15	91.45±26.12	121.75±15.26	75.34±41.40
"Flexors-extensors" ratio	Females	0.485 ± 0.11		0.518±0.09	
	Males	0.551 ±0.26		0.558±0.19	

Note: * Indicates significant differences between the right and left lower extremity;
# Indicates significant differences between females and males.

$p = 0.02$). Analysis of relative force with respect to symmetry showed only one statistically significant difference, i.e., the difference between extensors of the right and left lower extremity in the group of men (3.90 vs. 3.54 N·m·kg^{-1}, at $p = 0.03$). This analysis confirms statistically significant differences in PT in extensors in the group of men (Table 2).

The study also measured "flexors-extensors" ratio (Table 2). The statistical analysis revealed a symmetry in this ratio between the right and left lower extremity in the group of female subjects (0.485 vs. 0.518 at $p = 0.269$) and the group of male subjects (0.551 vs. 0.558 at $p = 0.862$). A symmetry was also found for the ratio between women and men for the right (0.485 vs. 0.551 at $p = 0.268$) and left extremity (0.518 vs. 0.558 at $p = 0.291$).

Statistical analysis of RFD also revealed symmetry of this parameter for all the muscle group studied in men compared to women (right lower extremity: extensors 137.1 vs. 122.43 N·m·s^{-1} at $p = 0.77$; flexors: 91.45 vs. 76.66 N·m·s^{-1} at $p = 0.37$; left lower extremity: extensors 121.75 vs. 101.34 N·m·s^{-1} at $p = 0.31$; flexors: 75.34 vs. 67.6 N·m·s^{-1} at $p = 0.21$), and between right and left muscle groups in lower extremities (women: extensors 122.43 vs.101.34 N·m·s^{-1} at $p = 0.14$, flexors: 76.66 vs. 67.6 N·m·s^{-1} at $p = 0.76$; men: extensors: 137.1 vs.121.75 N·m·s^{-1} at $p = 0.14$, flexors: 91.45 vs. 75.34 N·m·s^{-1} at $p = 0.96$) (Table 2).

3.3. Electromechanical delay vs. peak torque and rate of force development

At another stage of the study, the authors evaluated the strength of correlation between EMD and PT and between EMD and RFD. Analysis of correlation between EMD and PT in the muscles of both lower extremities turned out to be statistically insignificant in the group of men. Furthermore, a statistically significant correlation was found in the female group between EMD and the PT for m.RF in the right lower extremity ($r = -0.78$; $p = 0.012$) and m.VM ($r = 0.73$; $p = 0.024$) and m.BF ($r = -0.76$; $p = 0.016$) of the left lower extremity.

Analysis of correlation between EMD and RFD revealed a significant correlation for two muscles of lower extremity: m.RF ($r = 0.66$; $p = 0.037$) and m.BF ($r = 0.78$; $p = 0.007$). Furthermore, only one correlation was found in the female group betwen EMG and

RFD, for m.VM of the right lower extremity (negative correlation, $r = -0.70$, $p = 0.035$).

4. Discussion

4.1. Symmetry of electromechanical delay, peak torque and rate of force development

Although there have been a number of publications concerning evaluation of the symmetry of strength abilities in different muscle groups, it is difficult to compare our results with the findings obtained by other authors in terms of EMD symmetry since many authors have analysed muscular activity on one side of the body or one lower or upper extremity, choosing usually the preferred one. The analysis of evaluation of symmetry between EMD values revealed statistically significant differences only between the right and left m.VL, both in the group of women and men. The results of our previous studies [16] have demonstrated EMD symmetry in rectus abdominis and erector spinae muscle. In a study by Szpala et al. [17] the EMD value was analysed before and after strength training of abdominal muscles. The results of the study have also shown the symmetry of the EMD values between the right and left side of the rectus abdominis muscle and external abdominal oblique muscle, both before and after the completion of the training program. However, the asymmetry of EMD value for the untrained antagonist muscle group (m. erector spinae) was observed, however, only after the completion of the training program.

This study also demonstrated the symmetry of PT values in the muscles of the right and left lower extremities in women, while asymmetry in PT in knee extensors was found in the group of male subjects. Asymmetry also concerned the value of the relative force. Furthermore, the symmetry was observed for RFD in both female and male groups.

The study also calculated "flexors-extensors" ratio for the knee joint. The studies in the literature emphasize that this index has an improved diagnostic value, which is especially useful in prevention of injuries compared to the values of torque [18]. The results of our study showed a symmetry of values of "flexors-extensors" ratio in both men and women and the results might be different than those contained in a study by Trzaskoma and Trzaskoma [18], where statistically significant values were found for "flexors-extensors" ratio in the group of women compared to men (0.47 vs. 0.43). The authors explain this with greater strength of knee flexors compared to extensors in the female group. However, it should be emphasized that the studies of the above authors evaluated professional athletes from different sports.

4.2. Female vs. male subjects

Effect of elasticity of muscular tendon on EMD value might be one of the causes of differences in sports results obtained by women and men. From the standpoint of physiology, the particular type of musculotendinous elasticity, typical of female muscles is connected with the effect of oestrogen hormones on collagen synthesis [26]. Oestrogens affect the structure of the tendon [4], which consequently leads to lower values of stiffness and Young's modulus of the synthesized collagen in women compared to men [10]. One negative effect of this phenomenon is increased number of injuries in women practising professional sports [1], which additionally justifies the research in the groups with division into genders. The results of our study demonstrated that the EMD values in the muscles of right lower extremity are in each case longer in men compared to women. Furthermore, for the left lower extremity, all the EMD values were longer in female subjects. However, only in one case (left m.VL) the differences between women and men turned out to be statistically significant. Studies by other authors have suggested the relationship between genders and EMD times. In a study by Winter and Brooks [25], significantly longer EMD times were found in women compared to men. These authors made their observations by testing the triceps surae muscle (m.TS) in only one lower extremity, termed "dominant extremity". They argued that the different EMD values in women and men might have been caused by differences in neuromotor control which involves the conduction of the action potential along the T tubule system, the release of Ca^{+2} by the sarcoplasmic reticulum, cross bridge formation between actin and myosin filaments, the subsequent tension development in the shortening elements and the series elastic component which in men is more resistant to stretch. Bell and Jacobs [2] found longer EMD in women compared to men in the biceps brachii muscle in the right upper extremity. These authors suggest that the factor that causes differences in EMD is dominant type of muscle tissues. Other authors point to the lack of differences in EMD between males and females. In a study by Blackburn et al. [3], no differences were found in EMD between women and men (127.49 vs. 125.43 ms, at $p = 0.788$) during the examination of the activity of m.BF in the right lower extremity. Similar findings were presented by Yavuz et al. [26], who analysed the activity of m.TS in the left lower extremity. The aim of the study is to determine whether longer EMD might be the cause of a high tendon injury ratio in women. However, no significant differences were demonstrated between EMD value in women and men. Furthermore, More at al. [12] found that the EMD both before and after a research fatigue procedure is shorter in women compared to men. Results suggest that males and females may respond differently to isokinetic fatigue, with males having a greater capacity to compensate for contraction force failure when responding to mechanical perturbations.

This study attempted to evaluate the relationships of EMD with PT and RFD. The results of our study demonstrated significantly higher PT values in males in each muscle group studied. Furthermore, the analysis of the relative force index showed statistically significant differences between men and women in knee flexors of the right extremity.

RFD describes dynamics of releasing muscular force and represents the measure of mean rate of the increase in muscular force. The analysis of RFD revealed higher values in all muscle groups studied in men compared to women. However, none of the differences observed was statistically significant. The studies of other authors pointed to the relationship between EMD and PT and between EMD and RDF. A study by Bell and Jacobs [2] found a weak but significant correlation of EMD with RFD and PT. The study also demonstrated significant differences between women and men in the values of relative force calculated as a product of maximum force and body mass. In a study by van Dieen et al. [20], a reverse proportion was observed for the relationship between EMD and RFD, which was explained by the researchers with time necessary to extend series elastic component. Another explanation may be found in differences in recruitment strategy at different rates of force development or contraction velocities: at a higher rate or speed more type II fibres will be activated, resulting in a shorter EMD. In a study by Viitasalo and Komi [21], a positive correlation between EMD and PT and a negative correlation between EMD and RFD were demonstrated. These researchers made the observations by testing m. VL in the right lower extremity. Similar conclusions were obtained by Vint et al. [22], who found a decline in EMD with the increase in PT and RFD.

5. Conclusions

Among the parameters analysed for the right and left lower extremities, statistically significant symmetry was found for EMD in the muscles studied (with an exception of m. VL) and for RFD in both female and male groups. Furthermore, a statistically significant asymmetry in PT of knee extensors was found in the male group. This might suggest that the asymmetry of muscular force is likely to be caused by morphological characteristics rather than the process of controlling its excitation.

References

[1] ARENDT E.A., AGEL J., DICK R.W., *Anterior cruciate ligament injury patterns among collegiate men and women*, J. Athl. Train., 1999, 34(2), 86–92.

[2] BELL D.G., JACOBS I., *Electromechanical response-times and rate of force development in males and females*, Med. Sci. Sports Exerc., 1986, 18(1), 31–36.

[3] BLACKBURN J.T., BELL D.R., NORCROSS M.F., HUDSON J.D., ENGSTROM L.A., *Comparison of hamstring neuromechanical properties between healthy males and females and the influence of musculotendinous stiffness*, J. Electromyogr. Kinesiol., 2009, 19(5), e362–e369, DOI: 10.1016/j.jelekin.2008.08.005.

[4] BURGESS K.E., PEARSON S.J., BREEN L., ONAMBELE G.N.L., *Tendon structural and mechanical properties do not differ between genders in a healthy community-dwelling elderly population*, J. Orthop. Res., 2009, 27(6), 820–825, DOI: 10.1002/jor.20811.

[5] CAVANAGH P.R., KOMI P.V., *Electromechanical delay in human skeletal muscle under concentric and eccentric contractions*, Eur. J. Appl. Physiol., 1979, 42(3), DOI: 10.1007/BF00431022.

[6] DRAPALA J., BRZOSTOWSKI K., SZPALA A., RUTKOWSKA-KUCHARSKA A., *Two stage EMG onset detection method*, Arch. Control Sci., 2012, 22(4), 371–384.

[7] GROSSET J.F., PISCIONE J., LAMBERTZ D., PEROT C., *Paired changes in electromechanical delay and musculo-tendinous stiffness after endurance or plyometric training*, Eur. J. Appl. Physiol., 2009, 105(1), DOI: 10.1007/s00421-008-0882-8.

[8] HERMENS H.J., FRERIKS B., MERLETTI R., STEGEMAN D., BLOK J., RAU G., DISSELHORST-KLUG C., HÄGG G., *European Recommendations for Surface Electromyography. Results of SENIAM project*, 2nd ed. Enschede, Netherlands: Roessingh Research and Development, 1999.

[9] KUBO K., AKIMA H., KOUZAKI M., ITO M., KAWAKAMI Y., KENEHISA H., FUKUNAGA T., *Changes in the elastic properties of tendom structures following 20 days bed-rest in humans*, Eur. J. Appl. Physiol., 2000, 83(6), 463–468.

[10] KUBO K., KANEHISA H., FUKUNAGA T., *Gender difference in the viscoelastic properties of tendon structures*, Eur. J. Appl. Physiol., 2003, 88(6), 520–526.

[11] MILEWSKA J., RUTKOWSKA-KUCHARSKA A., JAROSZCZUK S., *Step aerobics and rhythm of movement of the upper and lower limbs*, Hum. Mov., 2013, 14(1), 70–75, DOI: 10.2478/humo-2013-0006.

[12] MOORE B.D., DROUIN J., GANSNEDER B.M., SHULTZ S.J., *The differential effects of fatigue on reflex response timing and*

amplitude in males and females, J. Electromyogr. Kinesiol., 2002, 12(5), 351–360.

[13] PETRYŃSKI W., *Bernstein's construction of movement model and contemporary motor control and motor learning theories*, Hum. Mov., 2007, 8(2), 136–146.

[14] RUTKOWSKA-KUCHARSKA A., SZPALA A., PIECIUK E., *Symmetry of muscle of activity during abdominal exercises*, Acta Bioeng. Biomech., 2009, 11(1), 25–30.

[15] RUTKOWSKA-KUCHARSKA A., SZPALA A., *Electromyographic muscle activity in curl-up exercises with different positions of upper and lower extremities*, J. Strength Condition Res., 2010, 24(11), DOI: 10.1519/JSC.0b013e3181ddb308.

[16] SZPALA A., RUTKOWSKA-KUCHARSKA A., DRAPALA J., BRZOSTOWSKI K., ZAWADZKI J., *Asymmetry of electromechanical delay (EMD) and torque in the muscles stabilizing spinal column*, Acta Bioeng. Biomech., 2010, 12(4), 11–18.

[17] SZPALA A., RUTKOWSKA-KUCHARSKA A., DRAPAŁA J., *Electromechanical delay of abdominal muscles is modified by low back pain prevention exercise*, Acta Bioeng. Biomech., 2014, 16(3), DOI: 10.277/abb140311.

[18] TRZASKOMA Z., TRZASKOMA Ł., *The proportion between maximal torque of core muscles in male and female athletes*, Acta Bioeng. Biomech., 2001, 3, suppl. 2, 601–606.

[19] VAGENAS G., HOSHIZAKI B., *Functional asymmetries and lateral dominance in the lower limbs of distance runners*, Int. J. Sport Biomech., 1991, 7, 311–329.

[20] Van DIEEN J.H., THISSEN C.E.A.M., Van de VEN A.J.G.M., TOUSSAINT H.M., *The electro-mechanical delay of the erector spinae muscle: influence of rate of force development, fatigue and electrode location*, Eur. J. Appl. Physiol. Occup. Physiol., 1991, 63(3–4), 216–222.

[21] VIITASALO J.T., KOMI P.V., *Interrelationships between electromyographic, mechanical, muscle structure and reflex time measurements in man*, Acta Physiol. Scand., 1981, 111(1), DOI: 10.1111/j.1748-1716.1981.tb06710.x.

[22] VINT P.F., MCLEAN S.P., HARRON G.M., *Electromechanical delay in isometric actions initiated from nonresting levels*, Med. Sci. Sports Exerc., 2001, 33(6), 978–983.

[23] WINIARSKI S., DUBIEL-WUCHOWICZ K., RUTKOWSKA-KUCHARSKA A., *Symmetry of suport scull and vertical position stability in synchronized swimming*, Acta Bioeng. Biomech., 2013, 15(1), 113–122, DOI: 10.5277/abb130114

[24] WINIARSKI S., RUTKOWSKA-KUCHARSKA A., *Estimated ground reaction force in normal and pathological gait*, Acta Bioeng. Biomech., 2009, 11(1), 53–60.

[25] WINTER E.M., BROOKES F.B.C., *Electromechanical response times and muscle elasticity in men and women*, Eur. J. Appl. Physiol. Occup. Physiol., 1991, 63(2), 124–128.

[26] YAVUZ S.U., SENDEMIR-URKMEZ A., TURKER K.S., *Effect of gender, age, fatigue and contraction level on electromechanical delay*, Clin. Neurophysiol., 2010, 121(10), DOI: 10.1016/j.clinph.2009.10.039.