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Age-related differences in the symmetry of electromyographic activity and muscle force in lower limbs

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Purpose: Increased reaction time and asymmetrical force generation in muscles may elevate the risk of falling among seniors. Therefore, it seems useful to analyze the symmetry of strength and amplitude parameters that evaluate neuromuscular control. The aim of the study was to evaluate force parameters for the quadriceps and biceps femoris muscles in young and older women performing maximal voluntary contraction. *Methods:* Fifty women (1 group in their twenties and the other in their sixties) participated in the study. The study used surface electromyography methodology and measured peak torque under static conditions. Electromyographic signals and peak torque were recorded separately in knee extensors and flexors of the right and left lower limbs after a visual signal. The following parameters were selected for analysis: 1) maximum the electromyographic amplitude signal; 2) peak torque; 3) rate of torque development; 4) relative force; and 5) "flexor–extensor" ratio. *Results:* The analysis demonstrated a decrease in the values of all parameters in the elderly group and symmetry in EMG amplitude in both the younger and older women. Asymmetry was found in the group of elderly women for peak torque and the relative force for knee flexors and "flexor–extensor" ratio. *Conclusions:* The decline in values of force parameters in knee flexors and their asymmetry (not extensors) revealed in the elderly group might prove an important factor in the assessment of risk factors for falling among the elderly.

Key words: *electromyography, quadriceps femoris, biceps femoris, female*

1. Introduction

Changes in the human nervous and muscular systems observed with age may involve a significant decrease in muscle tension and strength. This may result in an increased number of falls, leading to serious injuries and the premature death of elderly people, especially women.

Muscle tension and strength can be evaluated with biomechanical methods, such as surface electromyography (EMG) and the measurement of peak torque under static conditions. Previous studies based on the EMG method have shown a decrease with age in the number of activated motor units, motor units which become larger in size with age [8]. Also, the number of active neurons decreases in the spinal cord. The constant slowing of motor-neuron stimulation in the central nervous system observed in the elderly occurs with decreased nerve conduction and synaptic transmission. These factors influence the control processes in the nervous and muscular systems, which results in a decrease in the amount of muscle activity and force parameters, such as peak torque or lower dynamics of peak-torque increase [1]. Changes in neuromuscular control can also result from the continual loss of nerve supply (denervation) and supply of new nerves to an organ or body (innervation). This leads to grouping of muscle fibres of one type. Previous studies have shown a decline in all muscle fiber types, and most importantly the atrophication of fast-twitch fibers [7]. The effects of aging on the nervous system disturb, among other things, its regulatory mechanism, which is manifested in the decrease in conduction in nerve fibers.

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This extends the duration of a simple and also complex (alternative) response to a selected stimulus, which, in turn, decreases stability and increases the risk of falling [20]. In addition, researchers have recognized that in older adults, longer response times are due to a decline in skeletal-muscle strength, increased joint stiffness, a weakening of brain function due to progressive neuronal atrophy, loss of connection between dendrites, a decrease in cerebral blood flow and changes in enzyme and receptor function [5].

Changes in the nervous system are accompanied by changes in the muscular system. The Hill-based musculotendon model represents viscoelastic properties, hence it is prone to age-related deformation [10]. Changes are observed in the decrease of muscle strength, which significantly reduces physical fitness and increases the number of falls. This can cause serious injuries and premature deaths in elderly people, especially women [2]. Women exhibit a slightly greater and quicker decline in muscle strength than men, which is explained by the physiology of the female body. The muscle-tendon elasticity specific to women's muscles is related to the effect of estrogen on collagen synthesis [22]. Estrogen affects the structure of tendons causing a drop in the values of stiffness and Young's modulus of synthesized collagen in women in comparison to men [22]. This phenomenon has negative effects in an increased number of injuries, not only in women doing professional sport, but also in everyday activities. The deeper the deficits in muscle strength and body balance, the greater the risk of falling [11], [21]. Borges [3] observed a decrease in muscle strength, especially in lower limbs, in women between the age of 40 and 50. Risk of falling increases with the decline in strength of the quadriceps femoris and biceps femoris muscles, muscles responsible for knee joint stability. The risk is also greater due to the disproportion of strength generated by the left and right limbs. Longer response times and the asymmetry in strength generated by the muscles of the right and left side of the body increase the risk of injuries and falls among the elderly [13]. The risk can be assessed based on EMG signal values and force parameters, such as: peak torque (PT), relative force (RF), "flexor–extensor" ratio or the rate of force/torque development (RFD/RTD). RTD reflects the ability to quickly increase muscle strength and is considered to be an important biomechanical index in the evaluation of athletes and risk-of-falling assessment in the elderly. The RTD value is strictly related to the time a muscle needs to trigger peak torque. Thus, some authors indicate RTD is a parameter more important than PT in assessing the risk-of-falling among the elderly [15]. RTD may be more functionally relevant, especially for older adults, compared to maximal force capacities because many functional movement activities involve durations of less than 250 ms, whereas PT requires greater than 300 ms (approx. 400–600 ms) to achieve. A decline in RTD across a lifespan may therefore lead to large decrements in functional and independent living ability, and increased injury risk associated with performing common, daily activities [18].

Analysis of the symmetry of physiological and biomechanical parameters is important because as a person ages, symmetries occur not only in the ability to generate force but also in the level of bioelectrical tension in the muscles of the right and left sides of the body. Increased reaction time and asymmetrical force generation in the muscles may elevate the risk of falling among seniors. Therefore, it seems useful to analyze the symmetry of strength and amplitude parameters that evaluate neuromuscular control. The aim of the present study was therefore to evaluate the amount of muscle tension and values of force parameters for the quadriceps and biceps femoris in younger and older women performing maximal voluntary isometric contraction (MVIC), as well as to analyze the symmetry of the parameters measured. Based on a review of literature, the following hypothesis was developed: the value of EMG amplitude of the muscles studied and all analyzed force parameters will be significantly lower and asymmetrical in the group of elderly women.

2. Materials and methods

2.1. Material

The research group was comprised of fifty adult women divided into two age groups. The first group (females in their twenties: Young group) included thirty one women between the ages of 20 and 25. The second group (females in their sixties: Elderly group) included nineteen women between the ages of 60 and 69. The participants were different in terms of age, height, body mass and body mass index (BMI) (Table 1).

All women in their twenties were recruited from among physical education students, while the women in their sixties were students of the University of the Third Age. None of the subjects practiced competitive sports. In the Young group, 26 women reported having a regular menstrual cycle, and 5 irregular. All Elderly women did not menstruate. 6 months prior to

Table 1. Participant details

	Young group $N = 31$	Elderly group $N = 19$	*t*-test	*df*	*p*
Age [years]	21.20 ± 1.09	63.23 ± 2.46	–81.51	48	0.0000
Body height [cm]	167.53 ± 4.95	161.11 ± 5.23	4.12	48	0.0000
Body mass [kg]	59.06 ± 6.13	69.32 ± 10.97	–3.75	48	0.0000
BMI [kgm^{-2}]	21.05 ± 2.09	26.74 ± 4.32	–6.18	48	0.0000

the study, none of the participants had taken muscle relaxants having influence on the response time or had suffered a major injury to the right or left lower limb. The measurements were taken at approximately the same time of day to ensure that all subjects had similar muscle activity during the day [22]. All the participants were informed about the aim and methodology, and expressed informed consent to participate in the experiment. The experiment was approved by the local ethics committee.

2.2. Methods

The study used the EMG methodology and a method of measuring of peak torque under static conditions.

2.2.1. EMG measurements

EMG signals were recorded from the knee flexors and extensors of the right and left lower limb. The group of extensors included the three heads of the quadricep femoris muscle: the rectus femoris (m.RF), the vastus lateralis (m.VL) and the vastus medialis (m.VM) (Fig. 1). The group of flexors included the bicep femoris muscle (m.BF) (Fig. 2). The choice of the three quadriceps muscles was caused by their varied architecture. The differences between theses muscles involve their physiological and anatomical cross-sectional areas, length of muscle fiber and muscle fiber bundles and geometry of the transfer of muscle strength to bone lever. Taking the different structure of the quadricep femoris muscle into account, researchers expected a different strategy of motor unit activation within its heads, and thus different values of muscle tension.

Disposable surface electrodes were located on the skin in bipolar configuration above the muscle belly and along muscle fibers (Figs. 1 and 2). Sixteen rectangular, active electrodes (46 × 22.5 mm) with solid gel (Ag-AgCl, No. R-LFR-310, Bio-Lead-Lok, Józefów, Poland) were placed on the muscles and one electrode

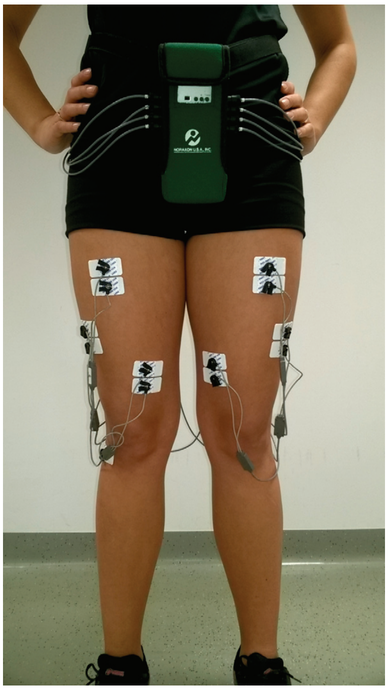

Fig. 1. Position of the surface electrodes on three heads of the quadriceps femoris muscle

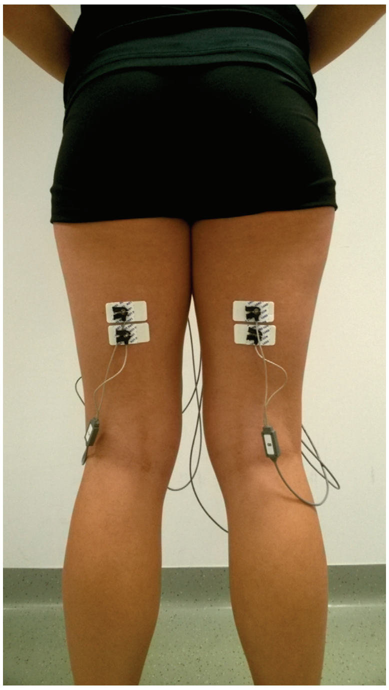

Fig. 2. Position of the surface electrodes on m.BF

on the head of the fibula on the right lower limb. The electrodes were spaced at 20 mm intervals. The participants' skin was prepared in accordance with the SENIAM recommendations (Surface Electromyography for the Non-Invasive Assessment of Muscles) [9] through cleaning and degreasing. 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.

2.2.2. Peak torque measurements

Simultaneous measurement of peak torque and EMG signals were taken in a sitting position in a multi-function armchair (UPR – 01 A/S, SUMMER, Opole, Poland). The technical characteristics of the measuring device were as follows: the measuring range of the tensometric head was 0–500 Nm, the relative error of the tensometric bridge was equal to 0.5%, the direct current amplifier was calibrated at amplification k = 470, bandwidth was 0–1 kHz, and temperature drift was zero 0.6 $\mu V \cdot {}^{\circ}C^{-1}$.

The angle at the hip joints was 90° and 75° at the knee joint (for peak torque of knee extensors) (Fig. 3) and 30° knee joint (for peak torque of knee flexors) (Fig. 4). Full knee extension was 0°. Following the measurement rules, the knee joint axis aligned with the axis of the dynamometer. Subjects crossed their arms over the chest. Belts were placed across the trunk and thighs to stabilize the body and eliminate the influence of other muscle groups on the measurements. During the measurement of EMG amplitude and peak torque, the resistance part of the device was placed at the ankle joint, front (Fig. 3) and back (Fig. 4) of the shank. The length of the external force arm for each person was selected individually, in accordance with generally accepted principles of measuring peak torque under static conditions [4].

2.2.3. Experimental procedure

The testing commenced after each subject performed a 5-min walking-in-place warm-up. Upon a signal, the subject performed peak torque by knee flexors and then extensors. A specially designed light signal was placed in front of the subject. The light was at eye level of the subject and about 150 cm away. The measurements were taken separately for the right and left limb, and randomly to eliminate the effect of fatigue on the results. During measurement, the subjects were verbally encouraged to produce maximum peak torques as quickly as possible. The choice of the position taken during the research and the course of the experiment were carried out in accordance with the principles of measuring peak torque under static conditions [17].

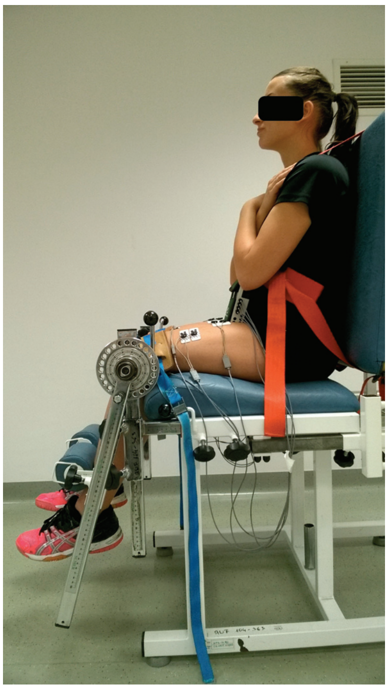

Fig. 3. Measurement of PT and EMG signal in the knee extensors

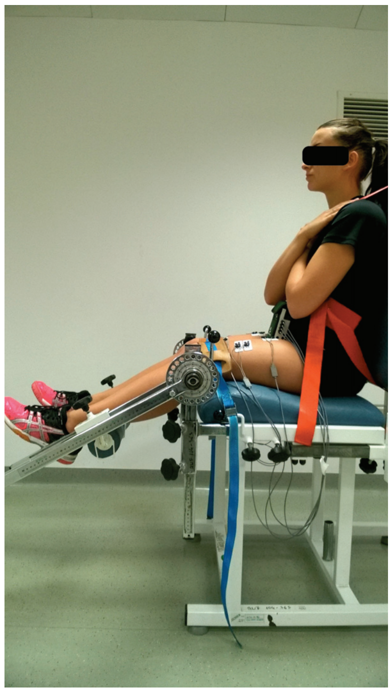

Fig. 4. Measurement of PT and EMG signal in knee flexors

Raw EMG signals and muscle torque were recorded simultaneously on a PC with MyoResearch XP software (Master Edition 1.07.05, Noraxon, USA). The EMG and torque signals were sampled at 3 kHz using an analogue-to-digital converter based on a 16-bit analogue-to-digital board. The signals were filtered with a bandwidth from 10 to 500 Hz and smoothed with a 100-ms RMS (root-mean-square) algorithm. The beginning of the analyzed signal was determined automatically by the software. The EMG onset was defined as the mean resting value (200-ms window) plus 3 SDs from the mean resting value. Torque onset was determined following the same procedures [16].

Based on the EMG signal and torque recorded in the muscles, the following parameters were selected for analysis: 1) maximum EMG amplitude [μV]; 2) PT – the maximal value of the muscle torque on the group of the extensors (m.RF, m.VL, m.VM) and flexors (m.BF) during generation of MVIC [Nm]; 3) RTD – calculated as a quotient of PT and time to reach PT [Nm/s]; 4) RF – calculated as a quotient of PT and body mass of the subject [Nm/kg]; 5) "Flexor–extensor" ratio, calculated as a quotient of the PT of the flexor muscles to extensor [17]. For the purpose of this study, the common names of force parameters were used: PT, RF, RTD and "flexor–extensor" ratio.

2.2.4. Statistical analysis

Statistica 13 software (StatSoft, Inc., Tulusa, Oklahoma) was used for statistical data analysis. Comparison of the means of the variables between the two age groups used the Student's unpaired *t*-test, whereas symmetry was verified with the Student's paired *t*-test. The results of the statistical analysis include: N – the number of subjects, and p – the probability level, df – degrees of freedom. Tables present mean values and standard deviation (SD), [a] denotes statistically significant differences between the older and younger women, [b] denotes statistically significant differences between the right and left limbs. Pearson's correlation coefficient (r) was used to assess correlations between the parameters studied. The level of significance was set at $\alpha < 0.05$.

3. Results

Comparative analysis of examined parameters between the right and left limb of Young and Elderly group is presented in Tables 2 and 3.

3.1. EMG amplitude versus age and symmetry

Analysis of the EMG amplitude of the examined muscles showed significantly lower values of muscle activity in all tested muscles in the Elderly group ($p = 0.001$). There were no statistically significant differences between the EMG signals of the right and left limb. This points to the symmetry of muscle activity in the both groups (Table 2).

3.2. Force parameters versus age and symmetry

There was a statistically significant decrease in all mean values of PT and RF in the Elderly group in comparison to the Young group ($p = 0.0001$). The Elderly group showed one asymmetry of PT (*t*-test = 4.14, $p = 0.0001$) and RF for knee flexors (*t*-test = 4.27, $p = 0.0001$) (Table 3).

Statistical analysis revealed only one significant difference in RTD values between the Young and Elderly group for the flexors of the left lower limb

Table 2. Mean values and standard deviation of EMG amplitude in Young and Elderly group for right and left lower limb

Examined group	Examined muscles	Right limb [μV]	Left limb [μV]	*t*-test	*p*
Young $N = 31$	VL	190.61 ± 107.11	209.28 ± 106.24	–1.04	0.308
	VM	268.25 ± 206.61	249.39 ± 137.84	0.52	0.606
	RF	215.82 ± 148.07	191.73 ± 90.52	0.99	0.328
	BF	198.62 ± 116.88	178.70 ± 78.05	1.04	0.308
Elderly $N = 19$	VL	115.08 ± 102.34[a]	108.62± 98.62[a]	0.47	0.634
	VM	105.43 ± 69.26[a]	101.42 ± 60.00[a]	0.44	0.662
	RF	81.46 ± 41.32[a]	74.95 ± 47.13[a]	0.96	0.340
	BF	112.86 ± 75.93[a]	107.16 ± 66.10[a]	0.66	0.509

[a] denotes statistically significant differences between Elderly and Young group at $p = 0.001$.

Table 3. Mean values and standard deviation of examined force parameters in Young and Elderly group for the right and left lower limb

Examined parameters	Examined groups	Right limb Extensors	Right limb Flexors	Left limb Extensors	Left limb Flexors
PT [Nm]	Young	165.37 ± 48.94	75.84 ± 23.79	160.89 ± 41.49	77.05 ± 21.72
	Elderly	119.55 ± 30.24 [a]	46.24 ± 13.28 [a]	115.63 ± 27.57 [a]	40.25 ± 11.97 [a,b]
RTD [Nm/s]	Young	130.26 ± 97.31	65.51 ± 35.03	140.06 ±108.69	67.01 ± 29.65
	Elderly	102.11 ± 68.74	41.41 ± 28.85	120.72 ± 80.55	38.55 ± 29.45 [a]
RF [Nm/kg]	Young	2.79 ± 0.73	1.28 ± 0.37	2.71 ± 0.56	1.30 ± 0.34
	Elderly	1.77 ± 0.53 [a]	0.68 ± 0.19 [a]	1.72 ± 0.53 [a]	0.59 ± 0.17 [a, b]
"Flexors–extensors" ratio	Young	0.4842 ± 0.17		0.4895 ± 0.12	
	Elderly	0.3928 ± 0.12[a]		0.3569 ± 0.11 [a, b]	

[a] denotes statistically significant differences between Elderly and Young group, [b] denotes statistically significant differences between the right and left limbs.

(*t*-test = 3.78, *p* = 0.0003). There were no statistically significant differences between groups in RTD values for the right and left limb. This indicated a symmetry of RTD in both groups.

The proportion of peak torque of flexors to extensors was determined using the "flexor–extensor" ratio. The analysis revealed significant differences between the Young and Elderly group for both limbs and showed an asymmetry in the Elderly group.

3.3. EMG amplitude versus force parameters

Next, the assessment involved analyzing the strength of correlation between the EMG signal of the examined muscles and force parameters. The analysis of EMG amplitude correlation in young women showed the following dependencies for: a) the right lower limb between the m.VL and PT (*r* = 0.49) and RF (*r* = 0.49), m.VM and PT (*r* = 0.41) and RF (0.54), m.RF and RF (*r* = 0.41) and "flexor–extensor" ratio (*r* = –0.44), m.BF and PT (*r* = 0.4), RTD (*r* = 0.38) and RF (*r* = 0.47); b) the left lower limb between m.VL and PT (*r* = 0.57) and RF (*r* = 0.58), m.VM and PT (*r* = 0.41) and RF (*r* = 0.51), m.RF and RF (*r* = 0.49) and "flexor–extensor" ratio (*r* = –0.38), m.BF and RF (*r* = 0.52). Contrary to the Young group, analysis of the EMG signal correlation in the Elderly group showed only a) three correlations for the right lower limb – between m.VL and RF (*r* = 0.52); m.VM and RF (*r* = 0.61), and m.BF and RF (*r* = 0.47); b) the left lower limb between m.VL and PT (*r* = 0.47) and RF (*r* = 0.62), m.VM and PT (*r* = 0.6) and RF (*r* = 0.72), m.RF and PT (*r* = 0.55) and RF (*r* = 0.7), m.BF and PT (*r* = 0.42) and RF (*r* = 0.53).

4. Discussion

4.1. EMG amplitude versus force parameters versus age

From the results, the key finding was the significant decrease of EMG amplitude in the examined muscles of both lower limbs and a drop of all mean PT and RF values in the Elderly group in comparison to the Young one. The Elderly group also revealed significantly lower values in the "flexor–extensor" ratio. Statistical analysis revealed only one significant difference in RTD values between the Young and Elderly groups for the flexors of the left lower limb.

Prior studies have also shown a relationship between age and force parameters. Borges [3], in his research on groups of men and women, demonstrated the dependency between age and PT values of knee flexors and extensors, with the highest decrease in PT between the ages 60 and 70 in both sexes. On the other hand, Thompson et al. [18] showed that the RTD of lower limb flexors (not extensors) may be particularly important for aging individuals pertaining to functional performance, as this muscle group has been shown to be an effective and sensitive discriminator of athletic-related performances, and an important contributor in many locomotion related movements. The ability to rapidly contract lower limb flexors may be important for the preservation and enhancement of mobility, which, in turn, may lead to the improved independence of older adults. For example, RTD in leg flexors but not extensors was found to be predictive of the risk of fall in elderly women [2], which may have important implications for the assessment of risk of injury and interventions aimed at minimizing fall-related injuries and disabilities in the elderly. Said authors justify the importance of RTD of knee flexors in the risk of injury by presenting a sequence of actions after tripping: "Tripping usually occurs during single support, in the middle of the swing phase, producing a loss of balance. After tripping, the body's center of mass moves forward, passing the base of support, causing the fall. The only way to prevent such fall is through the fast recovery of step in the swing leg by supporting body weight. However, the individual should reduce the moment of inertia of the swinging leg to increase the whole segment's angular acceleration. A high RTD in the knee flexor muscles may produce a fast knee flexion movement, which reduces the radius of gyration and, consequently, the segment's moment of inertia".

4.2. EMG amplitude and force parameters versus symmetry

The results of this experiment found support for the symmetry of EMG amplitude and RTD in both groups. The findings demonstrated an asymmetry of PT and RF of knee flexors in the Elderly group. Asymmetry in the "flexor–extensor" ratio was also observed in the Elderly. This parameter shows a proportion of peak torque of knee flexors to extensors.

The literature emphasizes its greater diagnostic value, especially in injury prevention, compared to the actual values of PT [6], [19]. The asymmetry discovered between PT, RF and "flexor–extensor" ratio in knee flexors in the Elderly group may increase the risk of injury and limit the influence of these muscles on the stability of the knee joint in elderly women. It directly results from the function of the m.BF, which limits anterior tibiofemoral displacement and lateral rotation of the femur to the tibia. In turn, Laroche et al. [12] revealed an asymmetry in the strength of knee extensors in women aged 65–80 while walking. The proven asymmetry effects greater variability of gait parameters, which may influence mobility and risk of falling in older adults. The influence of symmetry of strength and power on the risk of falling has been researched also by Skelton et al. [14], who observed greater asymmetry in the power of lower limb extension in the elderly community-dwelling fallers than in age-matched non-fallers, although strength symmetry was similar.

The limitation of the present study is that the symmetry of the analyzed parameters reported in both groups may be due to the fact that the participants actively participated in physical activates at the university. None of the subjects were involved in competitive sports, however, active participation in many fitness classes is a part of the university curriculum of persons from both groups, which could have a significant impact on the values of the analyzed parameters.

5. Conclusions

This study demonstrated a decrease in the values of all the analyzed parameters in the Elderly group and symmetry in EMG amplitude in both younger and older women. Asymmetry was found in the group of older women for PT ($p = 0.0002$) and RF ($p = 0.0001$) for knee flexors and "flexor–extensor" ratio ($p = 0.02$). The decline in values of the force parameters in knee flexors (not extensors) in the Elderly group might prove an important factor in the assessment of risk factors for falling in the elderly.

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