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The influence of isometric rotation of the lower limb on the functioning of the knee joint stabilizers and rotator muscles

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Purpose: This paper presents an assessment of the influence of isometric rotation of the lower limb in a standing position on the functioning of the muscles stabilizing the knee joint in the frontal plane with the use of modeling the loads on the musculoskeletal system. *Methods*: The research was carried out in the AnyBody Modeling System software, performing multi-variant simulations of the musculoskeletal system during isometric rotation of the lower limbs. The simulations were carried out using as input data the values of rotating moments and the ground reaction forces acting on foot segments, which were measured using the proprietary Rotenso device and the position of the body segments. *Results*: The result is the muscular activity of the lower limbs of the selected muscle groups during isometric rotation. Muscle activity was recorded for Sartorius, Tensor fasciae latae, Iliopsoas, Gluteus minimus, Gluteus medius, Gluteus maximus, Piriformis, Quadratus femoris, Obturator internus, Obturator externus, Gemellus inferior, Gemellus superior. *Conclusions*: Performing isometric rotation allowed for the activation of most of the knee joint stabilizing muscles and rotators of the lower limb. The results indicate that lower limb rotation exercises can be used in physiotherapy in patients with valgus knee.

Key words: *musculoskeletal system, lower limb isometric rotation, mathematical modeling, AnyBody Modeling System*

1. Introduction

In children and adolescents aged 3–18, varus of the knees is the fourth most common defect, while valgus is seventh. Among postural defects occurring only in the lower limb, they are the most common. Knee varus occurs in 8.5%, knee valgus occurs in 7% of people in a given age group [20].

The human lower limbs are responsible for carrying loads related to the weight of the torso, upper limbs and head, both when standing and performing dynamic activities such as walking or running [9]. Reduced physical activity and a sedentary lifestyle have a negative impact on the functioning of the musculoskeletal system, including the lower limbs [21]. Functional disorders soon lead to overloads, which, in turn, affect the formation of degenerative changes. This also applies to improperly performed physical exercises, which over time can become the cause of pain [8], [10]. Factors that disturb the proper functioning of the musculoskeletal system include morphological, environmental and physiological factors. In this paper, it was decided to focus on the latter, which are based on biomechanical analysis associating the formation of defects within the lower limbs with disturbances in the forces of the carrier (mechanical) axis.

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Due to the frequency of defects within the knee joint, it was decided to focus mainly on it. The function of the muscles in the sagittal plane for the knee joint is well known and described [1]. However, attention should also be paid to motor control and stabilization of the joint in the frontal and horizontal planes, because only balancing each of them is a factor limiting the formation of injuries and overloads [18]. There are publications in the literature on the improvement of the condition of the knee joint through the hip abduction strengthening exercises. Such studies were conducted by Lubahn A. et al. where-weight bearing therapeutic exercises were tested [17]. On the basis of medical imaging, it was also found that setting the limb in a rotated position allows for the correction of knee valgus and varus [12].

The following muscle groups are responsible for the proper knee joint stabilization: Popliteus, Tensor fascie late, Gracilis, Sartorius. Especially the Sartorius, responsible for the spiral stabilization mechanism, has a significant impact on the valgus correction and, consequently, the course of the kinematic chain, also on the quality of the foot arch [7], [16]. The muscles shown are involved in the rotation of the lower limbs. Therefore, it was decided to check whether the lower limbs rotation physiotherapeutic exercises can positively affect the correction of the above posture defects. Research with the use of appropriate measuring devices and computer modeling can significantly contribute to obtaining knowledge about the impact of physiotherapeutic exercises on the improvement of the functioning of the musculoskeletal system. This was confirmed by the research using the above techniques conducted by Nowakowska-Lipiec et al. [24]. This research confirmed the influence of exercises on the loads on the lumbar spine.

The lack of dedicated research tools for isometric rotation measurements affects the number of studies in this field. Additionally direct and non-invasive measurements of internal forces due to the level of technology are impossible and it is likely that they will remain so in the near future [11]. For this reason, it was necessary to use computer modeling techniques to determine the loads on the skeletal–muscular system. An example of such studies are those conducted by Błażkiewicz M. [3], where the loads on the musculoskeletal system were analyzed during classical and jazz pirouettes. In the study, data were collected using a 9-camera system (Vicon, Oxford Metrics, Ltd., UK) and two force plates (Kistler Holding AG, Switzerland). Other examples are the studies of Michnik R. et al. and Joszko K. et al. where musculoskeletal loads related to the spine and pelvis were determined using the AnyBody and Madymo software [14], [22], [25]. The Anybody system is also successfully used to model the loads on the upper limbs in people with impaired motor functions [4] or during ordinary activities of everyday life [2]. In own study, it was also decided to use this system due to the thoroughly tested and validated model of the human body. Taking into account the literature review and the needs indicated by the physiotherapeutic community, this work was aimed to assess the influence of isometric rotation of the lower limb in a standing position on the functioning of the muscles stabilizing the knee joint with the use of modeling the loads on the musculoskeletal system.

2. Materials and methods

2.1. Description of the measuring device

There are no devices on the market that allows for the measurement of moments of force (*MoF*) rotating the limb in the appropriate position of the body. Therefore, it was necessary to design and manufacture a device that allows for the measurement of *MoF* rotating the lower limb with simultaneous measurement of the distribution of ground reaction forces (*GRF*). The study was carried out using the Rotenso platform (Fig. 1) and 9 degrees of freedom (*DoF*) inertial measurement unit (*IMU*) sensors (Yost Labs, Portsmouth, Ohio – orientation accuracy of ±1° for dynamic conditions, 360° orientation range for each axis). The Roensto platform is a device for conducting tests of the distribution of *GRF* of the foot for 4 anatomical support zones with simultaneous measurement of *MoF* rotating the lower limbs. Measurement sensors with a maximum load of 200 [N], accuracy of ±0.03% were used for the measurement of *MoF*. Measurement sensors with a maximum load of 500 [N], accuracy of ±0.4% were used for the measurement of *GRF*. Data was recorded at a frequency of 10 [Hz]. The Rotenso was equipped with 16 *GRF* sensors for each foot and two *MoF* sensors. The device was designed on the basis of pilot studies [5]. A patent application was filed for the device at the Patent Office of the Republic of Poland (Application number: P.434688).

The operation of the Rotenso measuring system has been verified using a reference device: AXIS FA500. The verification was carried out by combining the measurement data with the reference data in the functional range of the device, and then the linear regression coefficient was calculated to obtain a regression accuracy of R^2 equal to 0.9947.

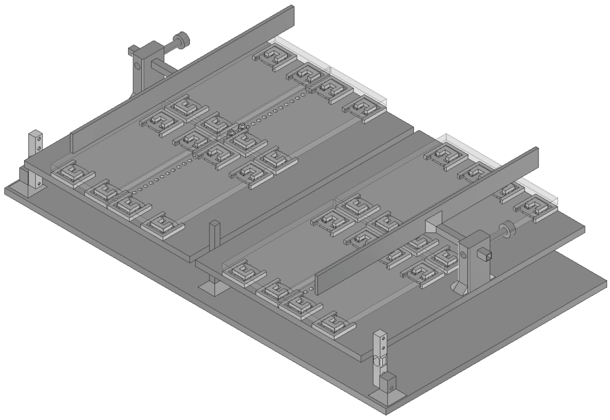


Fig. 1. Rotenso measuring device design

2.2. Characteristics of the group of examined persons

The experimental tests were attended by 33 individuals (having an average mass of 71 ± 18.5 [kg], an average heigh of 166 ± 17.7 [cm]). The studied group consisted of people who did not complain about any ailments or injuries.

2.3. Description of the test carried out

Using IMU 9DoF sensors, kinematic parameters such as inclination of the pelvis (*IoP*) in the sagittal plane of the body and the angle of rotation of the lower limbs were recorded. The Rotenso platform determined the values of the *GRF* resulting from standing and the values of *MoF* rotating the lower limbs during isometric rotation – food movement was blocked by part of the Rotenso platform. The above parameters were recorded during the tests.

Two 9DoF IMU sensors were placed on the collateral ligaments of the knee joint. The third sensor was placed on the sacrum of the pelvis in order to record the *IoP* (Fig. 2).

The foot has been divided by Rotenso platform into four parts so that each of these parts has contact with one separated measuring part. The division into forefoot and hindfoot was determined by the Chopart's joint. The external and internal parts of the foot were determined by the center of the ankle joint in the frontal plane.

During the study, 3 trials were recorded successively:

- maximum external isometric rotation of right lower limb and left lower limb simultaneously (*RLLS, LLLS*) for 10 seconds;
- maximum external isometric rotation of the right lower limb (*RLL*) for 10 seconds;
- maximum external isometric rotation of the left lower limb (*LLL*) for 10 seconds.

People were instructed to stay in an upright position without changing the kinematics of the upper limbs, trunk and head.

2.4. Description of model studies

The work uses an appropriate prepared model available in the AMMR repository of the AnyBody envi-

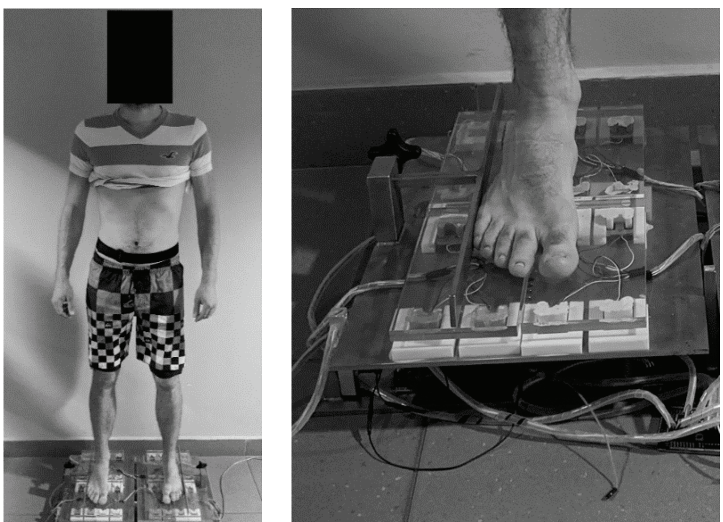


Fig. 2. Study of isometric rotation of the lower limb on the Rotenso platform

ronment (AnyBody Modeling System 5.2.0, AnyBody Technology A/S, Niels Jernes Vej 10, DK-9220 Aalborg Ø, Denmark). The FreePostureStatic model is characterized by 69 rigid bodies, about 1000 muscle actons, simple muscle model, the ScalingLengthMassFat linear scaling method – based on the entered body mass and height values, optimization criterion – minimization of the sum of the cubes of the ratio of muscle strengths to their maximum values.

The FreePostureStatic model is a static model that does not move. Joint angles are entered before simulation and are checked in the "mannequin.any" file. The model was prepared for each of 33 people in terms of scaling in relation to body mass and height. The method of implementation of input data resulting from research for a model is presented in Fig. 3. The *GRF* were applied in the direction of the vertical axis of the human body, at points according to the data recorded during the pilot studies [5] and literature. The force resulting from *GRF* on the hindfoot was applied to the center of the calcaneus (F_1). The force resulting from *GRF* on the external part of the forefoot was applied to the center of the bone of the fifth phalange (F_2). The force resulting from *GRF* on the internal part of the forefoot was applied to the center of the bone of the first phalange (F_3). The *MoF* (F_4) of the limb was applied to the fifth phalange and is directed in accordance with the direction of the frontal axis of the human body.

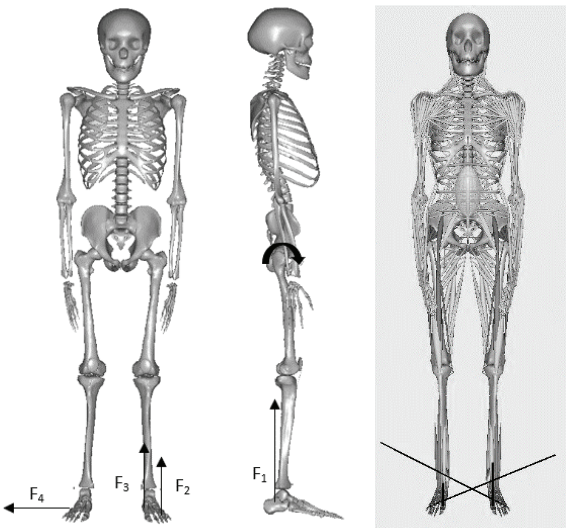


Fig. 3. Illustration of input implemented in the FreePosture model and model during simulation – AnyBody Modeling System software

The simulations allow for the determination of muscle strength, muscle activity and joint reactions forces. Based on the simulation, the muscles responsible for the stabilization of the knee joint and the rotators of the lower limb were analyzed. The results of muscle activity were presented for such muscles as: Sartorius, Tensor fasciae latae (knee joint stabilizers) and Iliopsoas, Gluteus minimus, Gluteus medius, Gluteus maximus, Piriformis, Quadratus femoris, Obturator internus, Obturator externus, Gemellus inferior, Gemellus superior (lower limb rotators).

3. Results

3.1. Results of experimental studies

For the model, the input data resulting from experimental studies are summarized in Table 1, where the mean values (mean) and standard deviations (std) are presented. The data implemented in the model come from the moment of time when the maximum value of the *MoF* rotating the lower limb was recorded. During the tests, the angular value of the rotation of the lower limbs was recorded too. Due to the values of this rotation, which for each of the subjects were lower than the measurement uncertainty of the device (±1°), they were not included in the simulations – this confirms the fact of isometric rotation. The low rotation values of the lower limbs were due to the fact that the rotation was isometric. The structure of

Table 1. Average values of input data for lower limbs

		LLLS	*RLLS*	*LLL*	*RLL*
MoF [N*m]	mean	14.02	13.74	11.77	11.28
	std	6.34	6.41	5.38	6.28
MoF [*BM*]	mean	0.20	0.20	0.17	0.16
	std	0.07	0.07	0.06	0.06
Hindfoot GRF [N]	mean	221.08	201.01	239.21	218.22
	std	79.02	55.37	90.25	75.32
Hindfoot GRF [BM]	mean	3.31	3.01	3.58	3.27
	std	0.85	0.54	0.83	0.73
Inner part of the forefoot GRF [N]	mean	46.88	43.79	32.09	39.43
	std	39.34	28.47	29.10	33.13
Inner part of the forefoot GRF [BM]	mean	0.70	0.66	0.48	0.59
	std	0.52	0.39	0.41	0.40
Outer part of the forefoot GRF [N]	mean	99.22	70.45	72.65	70.45
	std	41.01	32.81	31.61	32.81
Outer part of the forefoot GRF [BM]	mean	1.43	1.34	1.09	1.05
	std	0.45	0.44	0.41	0.39
IoP [°]	mean	1.83	1.83	1.64	0.77
	std	2.67	2.67	2.78	1.87

the platform did not allow the limb to rotate along the vertical axis of the body, because the foot was blocked during movement. *MoF* were standardized according to the body mass (*BM*). In summary, the model inputs were force vectors resulting from GRF, MoF rotating lower limb and IoP (Table 1). Experimental studies were the source of data.

3.2. Results of simulation studies

Averaged results muscles activity are presented in Table 2. Muscle activity is presented in the range of 0–1, where 0 is the lack of muscle activity and 1 is the maximum activity (strength) that a muscle is able to generate. Of the selected muscle groups during rotation, the highest average value of muscle activity was obtained for the Gluteus maximus for the *RLLS*. The average activity value for this muscle was 0.72 ± 0.25. A completely inactive muscle whose activity value was 0.00 ± 0.00 is the Obturator externus. Apart from this muscle, all others showed activity in at least one test.

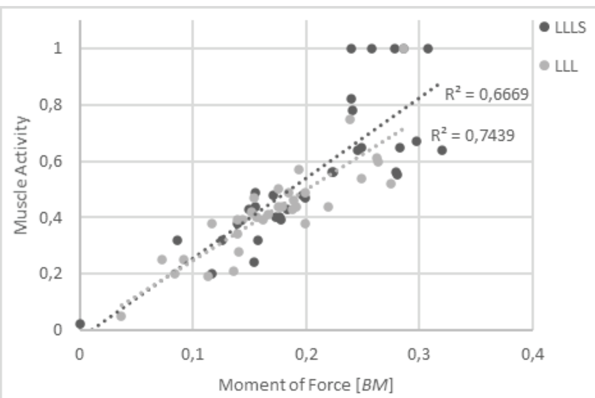
The results of simulation tests for 99 models (33 for *RLLS* and *LLLS*, 33 for *RLL*, 33 for *LLL*) in the form of muscle activity were compared to the value of the limb rotating moment standardized to the *BM*. These results were presented for the Sartorius muscle which is responsible for the spiral stabilization mechanism of the lower limb and Tensor fasciae latae with is knee joint stabilizer (Figs. 4, 5).

Linear regression coefficient was calculated and regression accuracy R^2 was equal to 0.67 for *LLLS*, 0.77 for *RLLS* and 0.74 for *LLL*, 0.79 for *RLL* for Sartorius. For Tensor fasciae latae regression accuracy R^2 is equal 0,66 for *LLLS*, 0.81 for *RLLS* and 0.70 for *LLL*, 0.78 for *RLL*.

Next, the Pearson correlation coefficient was calculated to determine the strength of the relationship between the value of the *MoF* and muscle activity. Pearson correlation coefficient was considered statistically significant at $p < 0.05$ and only these were presented in Table 3. The lack of statistical significance of the Pearson correlation coefficient ($p > 0.05$) occurred for the Quadratus femoris, Obturator externus, Gemellus inferior for both limbs. For each simulation a high correlation ($r > 0.5$) was found between the value of the *MoF* and the activity of the Sartorius muscle which is responsible for the spiral stabilization mechanism of the lower limb.

Table 2. Muscle activity during isometric rotation

		Sartorius	Iliopsoas	Gluteus minimus	Gluteus medius	Gluteus maximus	Piriformis	Quadratus femoris	Obturator internus	Obturator externus	Gemellus inferior	Gemellus superior	Tensor fasciae latae
RLLS	mean	0.52	0.53	0.62	0.67	0.72	0.66	0.02	0.1	0.00	0.06	0.14	0.56
	std	0.23	0.19	0.25	0.25	0.25	0.27	0.07	0.14	0.00	0.09	0.24	0.22
LLLS	mean	0.55	0.60	0.62	0.65	0.71	0.66	0.02	0.17	0.00	0.07	0.19	0.57
	std	0.25	0.21	0.25	0.25	0.25	0.25	0.08	0.23	0.00	0.12	0.31	0.24
RLL	mean	0.38	0.48	0.46	0.50	0.57	0.49	0.00	0.02	0.00	0.01	0.03	0.42
	std	0.18	0.16	0.20	0.20	0.22	0.21	0.00	0.06	0.00	0.04	0.04	0.17
LLL	mean	0.43	0.59	0.47	0.50	0.56	0.51	0.01	0.09	0.00	0.05	0.06	0.43
	std	0.17	0.18	0.17	0.17	0.18	0.18	0.05	0.16	0.00	0.11	0.08	0.15



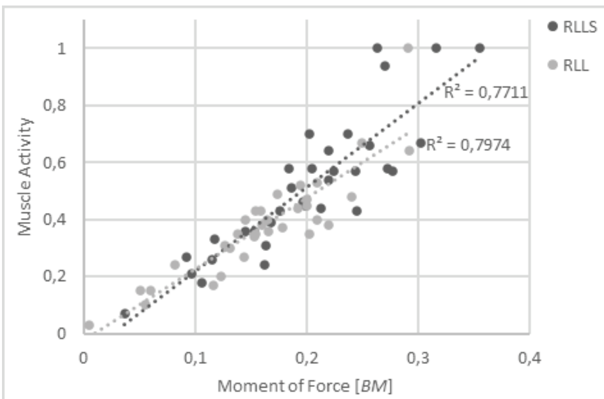
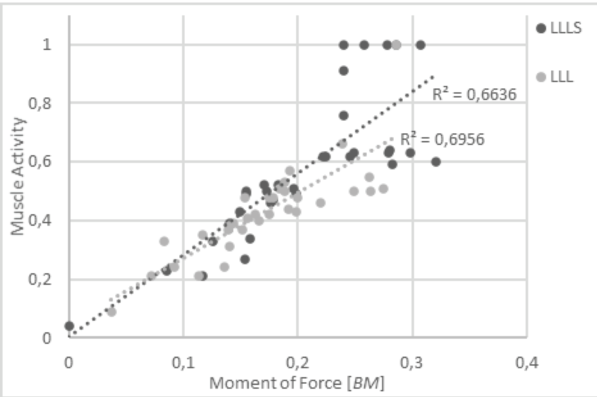


Fig. 4. Graph of the dependence of muscle activity on MoF [BM] for Satorius muscle



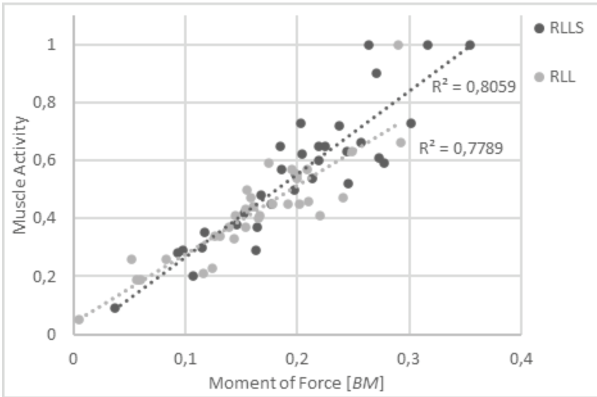


Fig. 5. Graph of the dependence of muscle activity on MoF [BM] for Tensor fasciae latae muscle

Table 3. Pearson correlation coefficient between limb rotational moment value and muscular activity

	Sartorius	Iliopsoas	Gluteus minimus	Gluteus medius	Gluteus maximus	Piriformis	Obturator internus	Gemellus superior	Tensor fasciae latae
MoF RLLS [N*m]	0.71	–	0.74	0.75	0.76	0.71	–	0.69	0.75
MoF LLLS [N*m]	0.59	0.56	0.69	0.72	0.76	0.71	0.40	0.39	0.62
MoF RLL [N*m]	0.84	0.63	0.87	0.87	0.84	0.84	0.38	0.51	0.85
MoF LLL [N*m]	0.88	0.98	0.95	0.93	0.99	0.64	–	0.97	–

4. Discussion

It is difficult to find studies on isometric rotation of the lower limb in the standing position in the literature. However, there are studies examining this type of exercise in other body positions. An example of such research is that conducted by Mendonça L.D.M. et al. [19]. The tests were carried out in the prone position. The average values of the recorded *MoF* for isometric rotation of the lower limb ranged from 0.29 to 0.46 [*BM*], depending on gender and the sport practiced. In tests on the Rotenso platform in the standing position, these values were in the range of 0.16–0.20 [*BM*]. The results of the Rotenso platform were compared to those of Urinati et al. [26], too. The article checks the value of the *MoF* rotating the lower limb for recumbent, semi-recumbent and sitting positions. The study was carried out using the Biodex System 3 (Biodex Medical Systems, Shirley, NY). In this publication, the mean value of the *MoF* for the recumbent position was 36.5 ± 14.7 [Nm]. For own research on the Rotenso device for the *RLL*, the value of the *MoF* was 11.28 ± 6.28 [Nm]. As can be seen in the studies of Uritani D. [26], the change from recumbent position to sitting possition significantly affected the results. The value of the *MoF* rotating the lower limb was also studied by Johnson S. and Hoffman M. [13]. The study was carried out using the Biodex System 3 (Biodex Medical Systems, Shirley, NY). The tests were carried out in a sitting position, for three different angles of flexion in the hip joint (10°, 40°, 90°). The values of the *MoF* rotating the lower limb for different positions were in the range of 20.52–48.75 [Nm]. The values recorded during the research on the Rotenso device were in range 11.28–14.04 [Nm] for different rotations type. For each of the above-mentioned works, the differences in the recorded values may result mainly from the position in which the exercise is performed.

The next results analyzed in the study were muscle activity during the rotation of the lower limb. According to research by Letafatkar A. et al., the muscles that are significantly activated during lower limb isometric rotation are the Gluteus Medius and the Tensor fasciae latae [15]. The rotation was performed by pressing the lower limb against the wall and muscles activity was recorded using electromyography (*EMG*). Another studies confirming the activation of specific muscle groups during lower limb rotation exercises are those conducted by Moore D. et al. [23]. The work is aimed to check isotonic rotation of the lower limb as a therapeutic exercise allowing for the activation of the Gluteus medius and the Gluteus minimus. The research was carried out using *EMG* in the supine and squat position. This studies confirmed the activation of these muscles. In addition, literature reports indicate a significant impact of the pelvic position on the ability to generate MoF rotating lower limb. This is confirmed by research conducted by Cibulka M. et al. [6].

5. Conclusions

Experimental and model studies made it possible to analyze the effect of lower limbs rotation physiotherapeutic exercises on the muscular activity of the lower limb. In particular stabilizers of the knee joint and rotators of the lower limb were analyzed.

Based on the obtained results, the following conclusions were formulated:

- position of the body, in which rotation is performed, is very important for the value of the *MoF* rotating the lower limb. The value of *MoF* in sitting position in literature studies was more than 4 times greater than rotation while standing in own research;
- the value of the *MoF* rotating the lower limbs during simultaneous rotation is by 19% greater for left limb and by 21% for right limb than when rotating the limbs separately;
- performing isometric rotation allowed for the activation of most of the knee joint stabilizers and the rotators of the lower limb;
- the high correlation ($r > 0.5$) occurs between the activity of a significant number of muscle that are lower limb rotators, knee stabilizers and the value of the *MoF* rotating the lower limb;
- there is a greater correlation between muscle activity and limb rotation separately than simultaneously.

The above conclusions show that the lower limb rotating exercises by strengthening the muscles stabilizing the knee in the frontal plane can be used in physiotherapy in patients with valgus knee.

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Conflicts of interest

The authors declare no conflict of interest.

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