



Polish Society of Biomechanics Morecki&Fidelus Award Winner

Influence of force-time parameters of hip abductors on maintaining balance in frontal plane in young healthy females

ANETA BUGALSKA*, ANNA HADAMUS, SEBASTIAN WÓJTOWICZ,
ANNA DANILUK, KAROLINA WIADERNA, MARTA GRABOWICZ

Department of Rehabilitation, Faculty of Medical Sciences, Medical University of Warsaw, Poland.

Purpose: The aim of this study was to determine the impact of isometric and isokinetic hip abductor muscle strength on the quality of maintaining static balance in healthy subjects. *Methods:* The study enrolled 51 healthy women aged 18–25. Balance assessment was carried out according to the M-CTSIB protocol and Single Leg Stance Test (with eyes open and closed) using the Biodex Balance System. An isokinetic evaluation conducted at 30 °/s and an isometric evaluation of the hip abductors were performed with the Humac Norm system. *Results:* Regression analysis for Sway Index (SW) and Stability Index (ST) in bipedal standing showed a significant importance of the presence of visual feedback ($R_{SW\ EO} = -0.922$; $p < 0.0001$; $R_{ST\ EO} = -0.613$; $p = 0.0493$), and unstable surface ($R_{SW\ US} = 1.253$; $p < 0.0001$; $R_{SW\ US} = 2.547$; $p < 0.0001$). Regression analysis for single-leg stance showed correlations between the following indices: overall sway index (OR) in single-leg stance, the antero-posterior (AP) sway index and the medio-lateral (ML) sway index on the one hand and isometric abduction time to peak torque ($R_{OR\ TPT} = 0.769$; $p = 0.0005$; $R_{AP\ TPT} = 0.565$; $p = 0.008$; $R_{ML\ TPT} = -1.74$; $p < 0.05$, respectively) as well as the test conditions on the other. *Conclusions:* Physiological activation of the hip abductors may be important for physiological maintenance of postural balance in young people, in both leg standing as well as in single-leg stance. The present results warrant prospective, randomized studies of larger groups that are diversified with regard to age and gender of the participants.

Key words: postural balance, isokinetics, isometrics, hip abductor muscles

1. Introduction

Postural balance is a basic skill of motor coordination. It allows to maintain the projection of the body's center of mass within the base of support in both static and dynamic conditions [10]. It enables normal functioning of the human body using its motor ability, which enforces cooperation between the musculoskeletal system and the nervous system. To maintain proper postural balance, it is necessary for information to flow freely from the peripheral systems responsible for assessing the relationship between body and space (the visual system, the vestibular system, the proprioceptive and haptic somatosensory system) to the cen-

tral nervous system (CNS). The proprioceptive system provides information on changes in the position of individual body parts, the velocity of movement, the angular position of the joints, and muscle contraction strength and force using mechanoreceptors located within the joints, ligaments, muscles and fascia [3], [31]. Muscles are the effectors of the balance system. Damage at any stage of stimulus transmission (receptors, spinal tracts, brain areas or effectors) results in balance disorders [6], [28], [32]. The gluteus medius is one of the strongest pelvic stabilizers next to the gluteus minimus and the tensor fasciae latae. It indicates that the muscles that abduct the hip joint and stabilize the pelvis can significantly influence the maintenance of postural balance. At the same time, scientific re-

* Corresponding author: Aneta Bugalska, Department of Rehabilitation, Faculty of Medical Sciences, Medical University of Warsaw, ul. Żwirki i Wigury 61, 02-091, Warsaw, Poland, e-mail: abugalska@wum.edu.pl

Received: October 1st, 2021

Accepted for publication: November 17th, 2021

search shows that muscle weakness is the most common risk factor for falling in old adults [6], [16], [28], [32]. However, the literature does not determine how important in maintaining postural balance are the individual muscles responsible for pelvic stabilization and biomechanical function of the lower limb in the frontal plane. A review of the available literature did not identify any studies that pointed explicitly to the function of the hip abductors in the process of maintaining balance in the frontal plane or referred to the role of muscle strengthening exercises of these muscles in improving balance.

The aim of this study was to determine the influence of isometric and isokinetic hip abductor muscle strength in healthy subjects on the quality of maintaining static postural balance.

2. Materials and methods

Characteristics of the study group

The study was conducted at the Movement Analysis Laboratory at the Medical University of Warsaw. It enrolled 51 women aged 20–23 years and practicing recreational sports. Initially, the study also enrolled 4 men, but due to the significant difference in the number of women and men, which could affect the results of the study, men have been excluded from the analysis. All participants were healthy, with no leg injuries within the preceding 2 years. The participants undertook physical activity a mean of 3 times per week, and about 90% of them only undertook one type of activity.

The characteristics of the study group are presented in Table 1.

Table 1. Characteristics of the study group ($N = 51$)

Variable	Characteristic			
	Mean \pm SD	Median (IQR)	Min	Max
Age [years]	20.41 \pm 0.85	20 (20–23)	20	23
Height [cm]	166.9 \pm 6.39	167 (163–173)	152	178
BMI [kg/m ²]	21.38 \pm 2.92	21.23 (19.04–23.14)	15.22	30.74
Frequency of physical activity [times per week]	3.19 \pm 1.26	3 (2–4)	1	7
Variety of physical activity	1.6275 \pm 0.74	1	1	4

SD – standard deviation, IQR – interquartile range.

Ethics Commission approval

The study protocol was approved by the Bioethics Committee of the Medical University of Warsaw (no. KB/217/2020). The study was conducted according to the ethical guidelines and principles of the Declaration of Helsinki.

Examination procedure

At the beginning, all participants were informed about the potential dangers of the study and agreed to participate in it by providing their written consent. Then, a questionnaire designed by the authors was administered to the participants, which, in addition to requests for demographic data, contained questions regarding physical activity (PA), with particular emphasis on previous leg injury, and the exclusion criteria for the study. The detailed exclusion criteria included: pain in the lumbar region, sacroiliac joints, hip and knee; severe muscle soreness, regardless of its cause; previous injury to the hip, knee or ankle joint within the preceding 2 years; neurological or vestibular balance disorders; other neurological disorders; no informed consent provided for participation in the study.

Following the initial qualification, balance assessment was carried out according to the Modified Clinical Test of Sensory Interaction on Balance (M-CTSIB) protocol using the BIODEX Balance System (Biodex Medical Systems, Inc., Shirley, NY, USA). This protocol covers standing on both legs in 4 conditions: eyes open with stable (firm) surface (EOSS); eyes closed with stable surface (ECSS); eyes open with unstable (foam) surface (EOUS); eyes closed with unstable surface (ECUS). The following parameters were assessed: stability index (ST) and sway index (SW) were calculated for each test. Stability index is the average position from center. Sway index represented the standard deviation of the SI; therefore, the higher the SI, the more unsteady or unbalanced a person was during the test. Balance assessment was subsequently performed in single-leg stance on a stable surface with eyes open and closed. This test was performed for each leg separately. The following parameters from single-leg standing were assessed: overall sway index, anteroposterior sway index (AP), and mediolateral sway index (ML). Sway index was calculated in the same way as for M-CTSIB protocol.

Before the muscle strength measurements, all participants performed a 10-minute warm-up consisting of a 5-minute cycle ergometer ride and a 5-minute jog. This was followed by an isokinetic test using the Humac Norm system (CSMi, Inc., Natick, MA, USA). The range of motion was customized for each participant

before the test by performing one active movement in full range of motion without resistance. The isokinetic measurement consisted of 3 trial and 5 test repetitions of hip abduction and adduction at the speed of 30 °/s, with an interval of 30 seconds between sets. All work was performed in the concentric condition. The following parameters were calculated from all repetitions: peak torque (PT; the highest torque noticed during the movement [Nm]), work per repetition (WR; torque times angle, where the torque is in Newton-meters and the angle is in radians [Nm]), average power per repetition (APR; work per unit time [W]), time to peak torque (TPT; the time from the beginning of torque development until the point where peak torque is first developed [s]), time peak torque held (TPTH; the time, during which the peak torque is maintained [s]), force decay time (FDT; the time from the end of peak torque production to the end of the motion [s]), delay time (DT; the time from the beginning of a motion until the beginning of torque development [s]), reciprocal delay (RD; the time required to reverse the direction of limb movement [s]). The strength, work and power parameters were normalized to the subject's body mass.

The last part of the examination served to assess isometric strength parameters of the hip abductors. It consisted of 2 trials and 3 test repetitions to measure abduction strength performed under isometric contraction. Duration of the measurement was 5 seconds. The interval between each repetition was 30 seconds. The following parameters were assessed: peak torque (PT [Nm]), average torque (AT; the average torque calculated from 5-seconds isometric contraction [Nm]), peak torque slope (PTS; slope of torque rise curve [Nm/s]), time to half peak torque (THPT; the time from the beginning of torque development until the point where the torque is ½ of the peak torque [s]), time to peak torque (TPT; the time from the beginning of torque development until the peak torque [s]). All strength, work and power parameters were normalized to the subject's body mass.

Statistical analysis

The results were statistically analyzed using Stata 13.1 PL (TIBCO Software, Inc., Palo Alto, CA, USA) and GNU Regression, Econometric and Time-series Library version 2019a (GRET, Free Software Foundation, Boston, MA, USA). A linear least squares regression analysis was performed for following variables: ST and SW for both leg standing, as well as OR, AP, ML for one leg standing. Regression coefficient (R) and p -value were reported for each regression analysis. Akaike's information criterion was used

to select the best prediction model. Values at $p < 0.05$ were assumed to be statistically significant.

3. Results

Both leg standing

SW was shown to depend on the following factors: reciprocal delay of the right hip abductors ($R_{SW\ RD} = -0.833$; $p = 0.0139$), delay time of right hip abductor ($R_{SW\ DT} = -3.486$; $p = 0.0003$), unstable surface ($R_{SW\ US} = 1.253$; $p < 0.0001$) and the presence of visual biofeedback – eyes open ($R_{SW\ EO} = -0.922$; $p < 0.0001$). There was no evidence of any correlation between SW and the anthropometric measurements (age, weight, height, BMI), frequency or variety of physical activity, presence of pain, sit and reach test results, isokinetic strength, power and work parameters, or any isometric parameters obtained in the test.

ST was shown to be influenced by on the following factors: the frequency of physical activity ($R_{ST\ PA} = -0.461$; $p = 0.0005$), presence of pain ($R_{ST\ PP} = -0.693$; $p = 0.0425$), presence of visual biofeedback ($R_{ST\ EO} = -0.613$; $p = 0.0493$), unstable surface ($R_{ST\ US} = 2.547$; $p < 0.0001$), time to peak torque of the right hip abductors ($R_{ST\ PT} = 4.865$; $p = 0.0019$), delay time of the right hip abductors ($R_{ST\ DT} = 9.608$; $p = 0.0319$), force decay time of the left hip abductors ($R_{ST\ FDT} = -2.80728$; $p = 0.0105$), work per repetition of the right hip abductors ($R_{ST\ WPR} = 0.156$; $p = 0.0010$) and the average power per repetition of the left hip abductors ($R_{ST\ APR} = -0.171485$; $p = 0.0083$). There was no evidence of correlation between ST and the anthropometric measurements (age, weight, height, BMI), the variety of physical activity, sit and reach test results, isokinetic strength parameters, and or isometric parameters obtained in the study.

Single-leg stance

The regression analysis for single-leg stance demonstrated a relationship between the overall sway index in single-leg stance and time to peak torque in isometric contraction in the direction of abduction ($R_{OR\ TPT} = 0.769$; $p = 0.0005$) and the test conditions (eyes open/closed; $R_{OR\ TC} = 1.798$; $p < 0.0050$) as well as the diversity of physical activity ($R_{OR\ PA} = 0.38$, $p = 0.0400$). The anteroposterior sway index also depended on the time to peak torque in isometric contraction in the direction of abduction ($R_{AP\ TPT} = 0.565$; $p = 0.0080$) and on the test conditions ($R_{AP\ TC} = -1.38$; $p < 0.0001$). The mediolateral sway index also de-

pended on time to peak torque in isometric contraction in the direction of abduction ($R_{ML\ TPT} = -1.74$; $p < 0.0500$), and the test conditions ($R_{ML\ TC} = -0.97$; $p < 0.0001$). Additionally, ML showed a relationship with time to half peak torque ($R_{ML\ THPT} = -2.4191$; $p = 0.0238$). There was no evidence of dependence on the isokinetic parameters.

4. Discussion

Previous studies showed a significant correlation between postural control and the muscle strength of selected leg muscle groups, but they focused mainly on the muscles working in the sagittal plane, i.e., flexors and extensors of the knee and ankle [9], [15], [22], [25]. In recent years, individual studies have attempted to assess balance with respect to leg muscles that contribute to movement in the frontal plane. Svoboda et al. [29] presented data on the correlation between the muscle strength of muscles responsible for inversion and eversion of the ankle joint and the control of bipedal stance in people of different ages. Their results showed no significant correlation between ankle joint muscle strength and postural balance in young people. At the same time, they showed a significant correlation between the work of the ankle evectors and the sample entropy in the mediolateral direction. The results of the present study also demonstrate that hip abductors have a significant impact on postural control in the mediolateral direction, both ST and SW. Svoboda et al. [29] also showed that although maintaining balance in bipedal stance does not require maximum ankle muscle strength, there is a correlation between maximum muscle strength and sway during postural exercise. They suggest that greater maximum strength is associated with greater capacity of these muscles, even during simple motor tasks, supporting reduction of postural sway. Similarly, our study showed that in order to maintain postural stability (ST), the average power and average work per repetition of hip abductors, per body mass, are important.

Porto et al. [24] and Chang et al. [5] proved that the muscles that abduct the hip and stabilize the pelvis in the frontal plane are crucial in maintaining postural balance. These muscles influence the risk of falls in older adults, especially in such cases as loss of balance or single-leg stance. Porto et al. [24] assessed static and dynamic balance of 81 elderly people (women and men) using tandem gait and single-leg stance. An isokinetic dynamometer was used to analyze muscle function (peak torque and rate of torque development normal-

ized to body mass). They observed a statistically significant association between tandem gait speed and peak torque of abductor in single-leg stance, showing a correlation between hip abductor weakness and increased falling risk. Chang et al. [5], who studied the relationship between the rate of hip abductor force development and the performance of reactive and voluntary balance tasks in older adults, had similar results. They studied 30 people (men and women) over the age of 65, measuring the hip abductor strength and center of pressure displacement during walking, performing single-leg stance tests and tandem gait tests. Significant results were observed for single-leg stance and tandem gait. Similarly to the results of Porto et al. [24], Chang et al. [5] concluded that hip abductor strength is an important aspect of maintaining postural balance. These studies mainly analyzed strength parameters, showing their association with an increased risk of falling. Our study shows that, in the case of young people, strength parameters are significant only for the stability index. Porto et al. [24] and Chang et al. [5] did not answer the question of whether disturbances in the biomechanical parameters (measured in the isokinetic test) of hip abduction muscles have an impact on balance. Our results show that there is such an impact, especially for time parameters.

Lopez-Valenciano et al. [18] investigated football players to assess the impact of isometric strength parameters of the hip muscles measured in the frontal and sagittal planes on postural balance. Their results showed that isometric peak torque of the hip adductors and abductors has no significant impact on dynamic balance in footballers. The present study confirms these results, as it shows no significant impact of the parameters in the isometric measurement on the stability index in both leg standing.

Even though researchers do not agree on the nature of the role that each individual hip abductor plays in maintaining balance in single-leg stance, the literature clearly shows that their contribution is significant [1], [7]. The abduction strength of the hip is important both for the effectiveness of the so-called “hip strategy” [30] in controlling dynamic and static balance while standing on one leg [4], [13], [20], [21], [26]. The strength and activation of the hip abductors is required for balance to keep the center of gravity within the base of support [8], [14]. Regardless of the method of measurement, researchers focus on hip abductor strength, especially among the older adults [17]. However, there is a lack of studies assessing any time parameters for these muscles, i.e., those indicating physiological activation of muscles for various age groups. Ambegaonkar et al. [2] emphasize that, although muscle activation

has not been shown to have a direct impact on muscle strength, these two measurements are related. In their study, the measured isometric flexor, extensor and abductor strength showed a positive correlation with the results of single-leg stance tests, in both a lateral and posterolateral direction.

The results of present study do not point to any isometric strength parameters being significant. However, it was found, that the longer the time needed for isometric peak torque, the greater the balance deficits for all parameters, i.e., overall, AP and ML sway indices. Additionally, ML was shown to have a correlation with the time needed to half peak torque. This demonstrates the importance of time parameters, and thus of normal muscle activation, for maintaining balance in the frontal plane. In addition, our study did not show the significance of any isokinetic force or time parameters in maintaining balance. This may be due to the fact that in static single-leg stance, isometric muscle contraction or, more precisely, physiological hip abductor activation time is used more in isometric work.

Cha et al. [4], Huynh et al. [11] and Muehlbauer et al. [23] noted that single-leg stance is inherently unstable, because visual feedback is the main factor influencing the ability to balance, and the lack of visual feedback can further increase the instability. Ishii et al. [12] also show that for single-leg stance balance tests the results among young people that are not professional athletes are worse for tests with closed eyes than with open eyes. The present study shows that the conditions of the test are extremely important and confirm the results of other researchers. The high importance of visual feedback among young people who participated in this study may indicate that they have a number of deficits, that are compensated for by eyesight. However, the present study did not show that any strength parameters of the hip abductors were responsible for the inferior results in a static isometric or isokinetic single-leg stance test.

A study by Promsri et al. [27] did not show that leg dominance was significant during static balance exercises. This is in line with the results of the present study as we did not observe any significant results due to leg dominance.

In conclusion, the few studies assessing balance and muscle strength in the frontal plane have not found significant correlations between these variables, especially among young people. The present study shows that an evaluation of time parameters is necessary and probably more important, as these parameters may have a significant impact on the possibility of generating a normal motor reaction to maintain stand-

ing balance. The development of indicators of muscle activity in terms of strength and, above all, muscle activation method depending on different time parameters could help in the development of balance training programs suitable for different age groups that meet the different neuromuscular needs of these groups.

This study, although it is very innovative, has some limitations. The sample size was relatively small, the age range was narrow and the sample comprised of women only, limiting the generalizability of the findings to the general population. Nevertheless, this study is the first, to the authors' knowledge, to compare several strength and time parameters of the hip abductors with objective balance measurement for both bipedal and single-leg stance. Moreover, in addition to the hip muscles, there are other lower limb muscles that are also involved in maintaining balance that would require precise measurements. Due to the limited time of the evaluation and the patient's fatigue, it does not seem possible to examine the remaining muscles in a single person. Based on our results, we also see the need to modify the parameters of the isokinetic and isometric tests as well as to increase the number of trials for the balance assessment.

5. Conclusions

Physiological activation of the hip abductors is important for physiological postural control in young people, in both leg standing as well as in single-leg stance.

The present results warrant prospective, randomized studies of larger groups that are diversified with regard to age and gender of the participants.

References

- [1] ADDISON O., INACIO M., BAIR W.N., BEAMER B.A., RYAN A.S., ROGERS M.W., *Role of Hip Abductor Muscle Composition and Torque in Protective Stepping for Lateral Balance Recovery in Older Adults*, Arch. Phys. Med. Rehabil., 2017, 98 (6), 1223–1228, DOI: 10.1016/j.apmr.2016.10.009.
- [2] AMBEGAONKAR J.P., METTINGER L.M., CASWELL S.V., BURTT A., CORTES N., *Relationships between core endurance, hip strength, and balance in collegiate female athletes*, Int. J. Sports Phys. Ther., 2014, 9 (5), 604–616.
- [3] CHA H.G., *Effects of trunk stabilization exercise on the local muscle activity and balance ability of normal subjects*, J. Phys. Ther. Sci., 2018, 30 (6), 813–815, DOI: 10.1589/jpts.30.813.
- [4] CHA J.H., KIM J.J., YE J.G., LEE S.J., HONG J.M., CHOI H.K., CHOI H.S., SHIN W.S., *Static balance according to hip joint angle of unsupported leg during one-leg standing*, J. Phys. Ther. Sci., 2017, 29 (5), 931–935, DOI: 10.1589/jpts.29.931.

- [5] CHANG S.H., MERCER V.S., GIULIANI C.A., SLOANE P.D., *Relationship between hip abductor rate of force development and mediolateral stability in older adults*, Arch. Phys. Med. Rehabil., 2005, 86 (9), 1843–1850, DOI: 10.1016/j.apmr.2005.03.006.
- [6] CZERWIŃSKI E., BOROWY P., JASIAK B., *Contemporary fall prevention principles with the use of rehabilitation* (in Polish), Ortopedia Traumatologia Rehabilitacja, 2006, 4 (6), 380–387.
- [7] DAVIS L.A., ALLEN S.P., HAMILTON L.D., GRABOWSKI A.M., ENOKA R.M., *Differences in postural sway among healthy adults are associated with the ability to perform steady contractions with leg muscles*, Exp. Brain Res., 2020, 238 (2), 487–497, DOI: 10.1007/s00221-019-05719-4.
- [8] GAO F., REN Y., ROTH E.J., HARVEY R., ZHANG L.Q., *Effects of repeated ankle stretching on calf muscle-tendon and ankle biomechanical properties in stroke survivors*, Clin. Biomech. (Bristol, Avon), 2011, 26 (5), 516–522, DOI: 10.1016/j.clinbiomech.2010.12.003.
- [9] GUIRELLI A.R., CARVALHO C.A., DOS SANTOS J.M., FELICIO L.R., *Relationship between the strength of the hip and knee stabilizer muscles and the Y balance test performance in adolescent volleyball athletes*, J. Sports Med. Phys. Fitness, 2021, DOI: 10.23736/s0022-4707.21.11744-x.
- [10] HONG C.Y., GUO L.Y., SONG R., NAGURKA M.L., SUNG J.L., YEN C.W., *Assessing postural stability via the correlation patterns of vertical ground reaction force components*, Biomed. Eng. Online, 2016, 15 (1), 90, DOI: 10.1186/s12938-016-0212-z.
- [11] HUYNH B., TACKER R., HUNG Y.J., *Active ankle position sense and single-leg balance in runners versus non-runners*, Physiother. Theory Pract., 2019, 1–9, DOI: 10.1080/09593985.2019.1698084.
- [12] ISHII Y., NOGUCHI H., SATO J., ISHII H., ISHII R., TOYABE S.I., *Association of knee osteoarthritis grade with one-leg standing balance and quadriceps strength in male independent ambulators aged ≥ 80 years*, J. Orthop., 2020, 21, 79–83, DOI: 10.1016/j.jor.2020.03.013.
- [13] JONSSON E., SEIGER A., HIRSCHFELD H., *One-leg stance in healthy young and elderly adults: a measure of postural steadiness?*, Clin. Biomech. (Bristol, Avon), 2004, 19 (7), 688–694, DOI: 10.1016/j.clinbiomech.2004.04.002.
- [14] KIM M.K., YOO K.T., *Effect of isotonic and isokinetic exercise on muscle activity and balance of the ankle joint*, J. Phys. Ther. Sci., 2015, 27 (2), 415–420, DOI: 10.1589/jpts.27.415.
- [15] KUSHYAR H., NUSSBAUM M.A., DAVY K.P., MADIGAN M.L., *Relative Strength at the Hip, Knee, and Ankle Is Lower Among Younger and Older Females Who Are Obese*, J. Geriatr. Phys. Ther., 2017, 40 (3), 143–149, DOI: 10.1519/jpt.0000000000000086.
- [16] KOZINC Ž., SMAJLA D., ŠARABON N., *Relationship between hip abductor strength, rate of torque development scaling factor and medio-lateral stability in older adults*, Gait Posture, 2020, DOI: 10.1016/j.gaitpost.2020.11.010.
- [17] LACROIX A., HORTOBÁGYI T., BEURSKENS R.U., GRANACHER R., *Effects of Supervised vs. Unsupervised Training Programs on Balance and Muscle Strength in Older Adults: A Systematic Review and Meta-Analysis*, Sports Med., 2017, 47 (11), 2341–2361, DOI: 10.1007/s40279-017-0747-6.
- [18] LÓPEZ-VALENCIANO A., AYALA F., DE STE CROIX M., BARBADO D., VERA-GARCIA F.J., *Different neuromuscular parameters influence dynamic balance in male and female football players*, Knee Surg. Sports Traumatol. Arthrosc., 2019, 27 (3), 962–970, DOI: 10.1007/s00167-018-5088-y.
- [20] MCLEISH R.D., CHARNLEY J., *Abduction forces in the one-legged stance*, J. Biomech., 1970, 3 (2), 191–209, DOI: 10.1016/0021-9290(70)90006-0.
- [21] MIRSHAMS SHAHSHAHANI P., ASHTON-MILLER J.A., *On the importance of the hip abductors during a clinical one legged balance test: A theoretical study*, PLoS One, 2020, 15 (11), e0242454, DOI: 10.1371/journal.pone.0242454.
- [22] MORELAND J.D., RICHARDSON J.A., GOLDSMITH C.H., CLASE C.M., *Muscle weakness and falls in older adults: a systematic review and meta-analysis*, J. Am. Geriatr. Soc., 2004, 52 (7), 1121–1129, DOI: 10.1111/j.1532-5415.2004.52310.x.
- [23] MUEHLBAUER T., METTLER C., ROTH R., GRANACHER U., *One-leg standing performance and muscle activity: are there limb differences?*, J. Appl. Biomech., 2014, 30 (3), 407–414, DOI: 10.1123/jab.2013-0230.
- [24] PORTO J.M., FREIRE JÚNIOR R.C., BOCARDE L., FERNANDES J.A., MARQUES N.R., RODRIGUES N.C., DE ABREU D.C.C., *Contribution of hip abductor-adductor muscles on static and dynamic balance of community-dwelling older adults*, Aging Clin. Exp. Res., 2019, 31 (5), 621–627, DOI: 10.1007/s40520-018-1025-7.
- [25] POTVIN-DESROCHERS A., RICHER N., LAJOIE Y., *Cognitive tasks promote automatization of postural control in young and older adults*, Gait Posture, 2017, 57, 40–45, DOI: 10.1016/j.gaitpost.2017.05.019.
- [26] PRIOR S., MITCHELL T., WHITELEY R., O’SULLIVAN P., WILLIAMS B.K., RACINAIS S., FAROOQ A., *The influence of changes in trunk and pelvic posture during single leg standing on hip and thigh muscle activation in a pain free population*, BMC Sports Sci. Med. Rehabil., 2014, 6 (1), 13, DOI: 10.1186/2052-1847-6-13.
- [27] PROMSRI A., HAID T., WERNER I., FEDEROLF P., *Leg Dominance Effects on Postural Control When Performing Challenging Balance Exercises*, Brain Sci., 2020, 10 (3), DOI: 10.3390/brainsci10030128.
- [28] RIMLAND M., ABRAHA I., DELL’AQUILA G., CRUZ-JENTOFT A., SOIZA R., GUDMUSON A., PETROVIC M., O’MAHONY D., TODD C., CHERUBINI A., *Effectiveness of non-pharmacological interventions to prevent falls in older people: a systematic overview*, The SENATOR Project ONTOP Series, PLoS One, 2016, 11 (8), e0161579.
- [29] SVOBODA Z., BIZOVSKA L., GONOSOVA Z., LINDUSKA P., KOVACIKOVA Z., VUILLERME N., *Effect of aging on the association between ankle muscle strength and the control of bipedal stance*, PLoS One, 2019, 14 (10), e0223434, DOI: 10.1371/journal.pone.0223434.
- [30] VAN DIEËN J.H., VAN LEEUWEN M., FABER G.S., *Learning to balance on one leg: motor strategy and sensory weighting*, J. Neurophysiol., 2015, 114 (5), 2967–2982, DOI: 10.1152/jn.00434.2015.
- [31] WALASZEK R., RIDAN T., WALASZEK K., BURDACKI M., *Assessment of postural stability in women with hallux valgus deformity of the foot*, Medical Review T., 2016, 14, DOI: 10.15584/medrev.2016.1.4 (in Polish).
- [32] ZAK M., SWINE C., GRODZICKI T., *Combined effects of functionally-oriented exercise regimens and nutritional supplementation on both the institutionalised and free-living frail elderly (double-blind, randomised clinical trial)*, BMC Public Health, 2009, 9, 39, DOI: 10.1186/1471-2458-9-39.