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The foot deformity versus postural control in females aged over 65 years

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Purpose: Correct foot structure is important due to locomotion and postural stability. The aim of this study was to determine the relationships between morphological foot structure and balance indices in a quiet standing position in women over 65 years of age.

Methods: The study included 116 women aged 65–90 years. The mean age was 70.6 ± 8.4 years and BMI 29.1 ± 3.4 m/kg^2. The measured indices included postural control while standing on both feet and photogrammetric foot evaluation. An analysis was performed of the selected foot and balance indices.

Results: There were no significant differences observed in the feet structure. Certain correlations between some foot indices and the indices of postural control were noted. The increased differences in the width indices between the right and the left foot lead to balance deterioration. Larger angles of valgity and varus deformity of toes and indices describing the longitudinal arch and transverse front arch of the foot have the greatest impact on the deterioration of balance in the medio-lateral axis.

Conclusions: The differences between the indices and morphological indices for the right and the left foot are not significant, which indicates the proportionate formation of feet in the individual life. The increased differences in the width indices between the right and the left foot lead to balance deterioration. Larger angles of valgity and varus deformity of toes and indices describing the longitudinal arch and transverse front arch of the foot have the greatest impact on the deterioration of balance in the medio-lateral axis.

Key words: *postural stability, aging, foot deformity, females, monitoring*

1. Introduction

Taking into account the biomechanical characteristics, a human foot can be considered as a functional unit, which serves two main purposes: to keep up the body weight and to transport, in relation to the ground, the forces propelling the body in gait and running. The maintenance of the body weight in a standing position is not only counteracting the force of gravity, but also keeping up the balance, which is a dynamic process [25]. In the process of maintaining balance, complex functions of the foot and the talo-tibial joint should not be reduced to the mechanics of simple hinge-type joint operation since the foot is an active and flexible element extremely sensitive to deformation, especially in the toe and metatarsal area, even if there is no change within the aforementioned joint [25]. The structure of the foot, and especially its setting in pronation or supination, has an impact on the lengthening of muscle response time of the talo-tibial joint, which may increase the risk of spraining it [8].

The aging process reduces the mechanical properties of the ligamentous-muscular apparatus of human

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foot, including those related to the dynamic and static arches. Control of the balance in the standing position is largely performed by afferent and efferent neurons in the talo-tibial joint, whose movement strategy is described by the inverted pendulum model, taking into account the action of the gastrocnemius muscle and the tibialis anterior muscle [5]. The foot structure is of great importance in the locomotion efficiency and maintaining balance by older people, especially considering the fact that aging is accompanied by an increase in loading the passive part of the motion apparatus [7], [22].

The most important role in keeping up balance in the standing position is played by a vertical component of the ground reaction forces and the path of the point of application of its resultant, described as the center of pressure of the feet on the ground (COP), is the main measure of the performance efficiency of the balance system, [11], [13]. Under static conditions, the COP path is equivalent to the path of COM. It is assumed that COP is a COM signal plus the noise of the balance reaction [5], [15] and that between these signals there is a strong relationship [20]. Syczewska and Zielińska [22] used the analysis of the power spectral density (PSD) of COP and COM signals to evaluate the corrective movements needed to maintain postural stability. Shorter COP path, usually defined as the trace length, means a more efficient system of maintaining balance.

Postural instability has been identified as a major intrinsic risk factor of falling and it is well documented that even healthy older adults show a marked decline of postural control compared with young adults. Several studies have reported the reliability of COP parameters during quiet standing in the elderly [17].

The aim of the study was to determine the relationship between foot morphology and balance indices in quiet standing in women over 65 years of age.

2. Materials and methods

The study included 116 women aged 65–90 years. The mean age was 70.6 ± 8.4 years, body height 161 ± 3.6 cm, body weight 75.3 ± 5.7 kg, and BMI 29.1 ± 3.4 m/kg^2.

The primary study group included 465 women over 65 years of age living in Rzeszów district that responded to the invitation and agreed to perform the proposed research (1st rule of randomization). Then we excluded from the study women: with locomotor system or neurological disorders, those that could not maintain balance when standing, or were moving using orthopedic equipment (crutches, walker, wheelchair), which prevents the execution of reliable measurement. Exclusions were made only at the stage of measurements, because the information was verified on the basis of an interview with the test person and observations. In case of doubt, the results also excluded from the analysis. From the analysis we also removed measurements containing technical errors. After exclusion of those not meeting the inclusion criteria, with the remaining 409 women the Statistica program was used to draw without repetitions 116 people whose results were analyzed (2nd rule of randomization).

The criteria for participation in the measurements were: the ability to assume vertical posture and the lack of neurological, orthopedic and other disorders, which could significantly impair balance. Due to the pending feet measurements, the participants could not have open wounds, ulcers, or fresh injuries of the lower limbs. Each of the women examined consented to have the measurements taken and also agreed to the use of the results for scientific purposes. The study design was approved by the Bioethics Committee at the Medical Faculty of the University of Rzeszów.

The examination consisted of performing measurements of postural control and podoscopic feet evaluation. The most common method of assessing the efficiency of the human balance system is registering changes of ground reaction forces using dynamometric platforms referred to as stabilography. Stabilographic tests can be carried out both in static and dynamic conditions [20], and each test lasts preferably 30 seconds [9], or – less frequently – 20 [11], or 45 seconds [23]. Balance was measured on a two-plate stabilometric platform (CQstab), whose three sensors enable the COP shift analysis. The CQstab platform makes it possible to carry out the analysis of the measured indices for each leg separately. COP shift is recorded in the x-axis (medio-lateral) and y-axis (antero-posterior) in the form of a statokinesiogram as well as a stabilogram where kinematic values are presented as a function of time. During the test, the platform was set parallel to the ground at a distance of 2 m from the wall on which a marker was placed for the study subjects to focus their sight on it during the measurements. Such arrangement of the marker allowed the position of the head of the subject to be controlled. In front of the platform, a rectangle was set from which the persons tested stepped on the platform and then assumed a natural standing position with the upper limbs hanging along the body. The measurement time was 30 seconds. The tests were conducted in accordance with the applicable standards. Before each measurement, calibration of the equipment was performed according to the manufacturer's instructions. The tests were conducted in the afternoon. All women rested for a few minutes in a sitting position before the measurements. The indices were assessed with eyes open simultaneously for the left and the right leg and for both feet together: the COP sway path (SP), the sway path along the *y*-axis (SPAP), the sway path along the *x*-axis (SPML), the mean amplitude of COP (MA), the mean velocity of the COP (MV), the field of COP during the test (SA), the mean frequency of COP (MF), the number of antero-posterior COP amplitudes (LWAP) and the number of medio-lateral COP amplitudes (LWML).

The examination of the plantar feet surfaces was performed with the photogrammetric method using an apparatus for computer foot evaluation (CQ-ST). The computer examination of the plantar side of the foot is the development and improvement of the well-known podoscopic examination. In addition to an exact foot print, we obtained information about the spatial shape of the foot arch. This allows for a reliable evaluation of the longitudinal arch, the angle of valgity of the hallux, and the angle of the varus deformity of toe V as well as the observation of the bearing spheres, which is helpful in evaluating the distribution of the pressure forces in the foot. The elaboration of the images involves marking specific points on the foot, based on which there are determined lines and angles defining the longitudinal and transverse arch of the foot. The following indices were evaluated: Clarke's angle (Cl), the hallux valgus angle (ALPHA), the angle of varus deformity of toe V (BETA), the heel angle (GAMMA), the Wejsflog index (WI) which defines the proportions of the foot (foot length to foot width ratio) (DL/W), the Sztriter–Godunov index (the index of the depth of the longitudinal arch of the foot – KY), forefoot width (SZ), heel width (ST), and foot length (DL). We analyzed the differences between the left and the right foot.

The collected data were analyzed statistically using Statistica 10.0 PL. We considered the mean and median values, the dominant, the standard deviation, and the range of the first and third quartile of the feet indices. The assessment of the conformity of statistical distributions of the variables studied with the normal distribution was performed with the use of the Shapiro–Wilk test. On this basis, the tests to evaluate the differences were selected, namely Student's *t*-test for the normal distribution and the Wilcoxon test for the cases in which the hypothesis of the normal distribution was rejected. The differences at the level $p \leq 0.05$ were assumed to be statistically significant. The degree of the correlation between the analyzed indices was assessed with the application of Pearson's correlation coefficient.

3. Results

Table 1 lists the mean values (±SD) of the analyzed indices and the feet indices.

In order to determine the relationships among the values of the analyzed and the feet indices for the left

Table 1. Mean values (±SD) of the analyzed indices and the feet indices

Indice/Index	Mean	SD
DLp – right foot length [mm]	221.9	13.21
DLl – left foot length [mm]	222.9	12.68
SZp – right forefoot width [mm]	87.5	9.86
SZl – left forefoot width [mm]	88.4	17.21
DL/SZp – Wejsflog index – right foot [–]	2.57	0.255
DL/SZl – Wejsflog index – left foot [–]	2.59	0.317
ALPHAp – hallux valgus angle in the right foot [°]	9.6	9.54
ALPHAl – hallux valgus angle in the left foot [°]	10.7	10.48
BETAp – angle of varus deformity of toe V – right foot [°]	15.8	9.54
BETAl – angle of varus deformity of toe V – left foot [°]	16.6	8.96
GAMMAp – heel angle – right foot [°]	16.00	4.02
GAMMAl – heel angle - left foot [°]	15.90	3.59
CLp – Clarke's angle – right foot [°]	40.5	19.23
CLl – Clarke's angle – left foot [°]	38.7	15.15
STp – heel width in the right foot [mm]	51.4	6.52
STl – heel width in the left foot [mm]	51.0	5.52

and right foot, Pearson's correlation coefficient was analyzed (Table 2).

Table 2. Pearson's correlation coefficient values for the variables tested

Variables		Correlation coefficient
Pair 1	DLp vs. DLl	0.864*
Pair 2	SZp vs. SZl	0.746*
Pair 3	DL/SZp vs. DL/SZl	0.708*
Pair 4	ALPHAp vs. ALPHAl	0.383*
Pair 5	BETAp vs. BETAl	0.233*
Pair 6	GAMMAp vs. GAMMAl	0.539*
Pair 7	CLp vs. CLl	0.290*
Pair 8	STp vs. STl	0.733*

Explanations: see Table 1, *significant relationship ($p \leq 0.05$).

The values of the correlation coefficient for all analyzed variables are positive and significant, which means that along with an increase in the value of the indice for the right foot, its value for the left foot also increases. The lowest values of the correlation coefficient were obtained for the angle of varus deformity of toe V (BETA), Clarke's angle (CL) and the hallux valgus angle (ALPHA).

In order to determine the differences in the values of the indices for the left and the right foot, Student's *t*-test was used (for dependent samples). In the case of Clarke's angle (CL), the forefoot width (SZ) and the Wajsflog index (DL/SZ), whose values were not normally distributed, the non-parametric Wilcoxon test was used (Table 3).

Table 3. Results concerning the significance of the differences between the mean values of the analyzed indices and the indices for the right and left foot

Variables	Statistical test	Test statistics
DLp vs. DLl	Student's *t*-test	–1.577
SZp vs. SZl	Student's *t*-test	–0.776
DL/SZp vs. DL/SZl	Wilcoxon test	–1.323
ALPHAp vs. ALPHAl	Student's *t*-test	–1.063
BETAp vs. BETAl	Student's *t*-test	–0.748
GAMMAp vs. GAMMAl	Student's *t*-test	0.243
CLp vs. CLl	Wilcoxon test	–0.541
STp vs. STl	Wilcoxon test	–1.050

Explanations: see Table 1.

In all the cases analyzed, the differences between the means of the indices considered and the indices for the right and the left foot were not statistically significant (Table 3).

Table 4 demonstrates the mean values (±SD) of the analyzed stabilometric indices.

The next stage of the statistical analysis was the assessment of the relationship between the foot indices and the stabilometric indices.

As for the right leg, the analysis showed a positive correlation only between the values of the angle of varus deformity of toe V (BETAp) and the maximum distance between two furthest points of the statokinesiogram in the antero-posterior axis (MaxAP-P), and between the BETAp values and the field of COP during the test (SA-EO-P). The values of the correlation coefficient were 0.215 and 0.211, respectively, and were significant at $p \leq 0.05$.

As for the left leg, the analysis showed a positive relationship only between the values of the angle of varus deformity of toe V (BETAl) and the number of medio-lateral COP amplitudes (LWML-L), and between the values of the difference in the width of the forefoot (SZp-SZl) and the sway path in the medio-lateral axis (SPML-L). The values of the correlation coefficient were 0.218 and 0.193, respectively, and were significant at $p \leq 0.05$.

Significant positive correlations were noted between the values of the difference in the width of the forefoot (SZp-SZl) and the COP sway path (SP), sway path in the medio-lateral direction (SPML), mean amplitude of COP from the point O (MA), mean medio-lateral COP amplitude (MAML), mean velocity of the COP (MV), mean velocity of the COP in the medio-lateral direction (MVML) and the field of COP during the test (SA). A significant positive relationship was demonstrated ($r = 0.235$) between the values of the hallux valgus angle in the right foot (ALPHAp) and the number of antero-posterior COP amplitudes (LWAP). Clearly more relationships were observed between the angle of varus deformity of toe V (BETAp) and the global stabilometric indices. A significant positive association was noted ($p \leq 0.05$) between BETAp and the sway path in the medio-lateral direction (SPML, $r = 0.197$), the mean medio-lateral COP amplitude (MAML, $r = 0.185$), the mean velocity of the COP in the medio-lateral direction (MVML, $r = 0.196$) and the field of COP during the test (SA, $r = 0.218$).

Table 6 shows the correlation coefficients between the global stabilometric indices (SPML and MVML) and the indices of the right and left foot.

Table 4. Mean values (±SD) of stabilometric indices

Indice	Mean	SD
SP – COP sway path [mm]	283.2	142.2
SP-P – COP sway path – right [mm]	300.5	155.6
SP-L – COP sway path – left [mm]	290.6	160.8
SPAP – sway path in the antero-posterior direction [mm]	225.9	112.3
SPAP-P – sway path in the antero-posterior direction – right [mm]	259.5	142.8
SPAP-L – sway path in the antero-posterior direction – left [mm]	250.5	147.6
SPML – sway path in the medio-lateral direction [mm]	124.2	74.2
SPML-P – sway path in the medio-lateral direction – right [mm]	121.9	63.5
SPML-L – sway path in the medio-lateral direction – left [mm]	112.9	58.5
MA – mean amplitude of COP COP [mm]	4.2	2.1
MA-P – mean amplitude of COP – right [mm]	4.1	2.1
MA-L – mean amplitude of COP – left [mm]	3.8	2.1
MAAP – mean amplitude of COP in the antero-posterior direction [mm]	3.2	1.4
MAML – mean amplitude of COP in the medio-lateral direction [mm]	2.0	1.7
MV – mean velocity of the COP [mm/s]	9.4	4.7
MV-P – mean velocity of the COP – right [mm/s]	10.0	5.2
MV-L – mean velocity of the COP – left [mm/s]	9.7	5.4
MVAP – mean velocity of the COP w osi OY [mm/s]	7.5	3.7
MVML – mean velocity of the COP in the medio-lateral direction [mm/s]	4.1	2.5
SA – field of COP during the test [mm^2]	545.0	735.3
SA-P – field of COP during the test – right [mm^2]	309.3	470.1
SA-L – field of COP during the test – left [mm^2]	398.0	713.3
MF – mean frequency of COP [Hz]	0.38	0.14
MF-P – mean frequency of COP – right [Hz]	0.42	0.16
MF-L – mean frequency of COP – left [Hz]	0.43	0.15
LWAP – antero-posterior COP amplitudes [number]	17.2	9.0
LWAP-P – antero-posterior COP amplitudes – right [number]	17.1	8.5
LWAP-L – antero-posterior COP amplitudes – left [number]	15.6	8.6
LWML – medio-lateral COP amplitudes [number]	10.7	7.1
LWML-P – medio-lateral COP amplitudes – right [number]	12.8	7.7
LWML-L – medio-lateral COP amplitudes – left [number]	11.1	6.8

Table 5. The values of the correlation coefficients between the values of the difference in the forefoot width of the right and the left foot (SZp – SZl) and the global balance indices

Indices	SP [mm]	SPAP [mm]	SPML [mm]	MA [mm]	MAAP [mm]	MAML [mm]	MV [mm/s]	MVAP [mm/s]	MVML [mm/s]	SA [mm^2]	MF [Hz]	LWAP	LWML
SZp – SZl	0.191*	0.133	0.260**	0.180*	0.090	0.224*	0.199*	0.128	0.250**	0.220*	0.073	0.062	0.004

Explanations: descriptions of global postural control indices are given in Table 4 and the text; the significant relationship $*p \leq 0.05$, $**p \leq 0.01$.

A significant negative correlation was found between the values of the heel angle of the left foot (GAMMAl) and the sway path along the medio-lateral axis (SPML) as well as the mean velocity of the COP in the medio-lateral axis (MVML). The correlations between the values of SPML and MVML and Clarke's angle of the right foot (CLp) are positive. These relationships indicate that in the case of a hollow foot (greater Clarke’s angle) and a flat foot (smaller GAMMA angle) the values of the path length and the mean COP velocity in the medio-lateral axis are higher.

Table 6. Values of the correlation coefficient between the sway path in the medio-lateral direction (SPML), the mean velocity of the COP in the medio-lateral direction (MVML), the heel angle and Clarke’s angle in the right and left foot (GAMMAp, GAMMAl, CLp, CLl, respectively)

Indice	GAMMAp	GAMMAl	CLp	CLl
SPML [mm]	0.021	–0.186*	0.212*	–0.014
MVML [mm/s]	0.001	–0.186*	0.208*	–0.009

Explanations: correlation significance $*p \leq 0.05$.

4. Discussion

In our study, the measurements were conducted on a two-plate stabilometric platform during quiet standing. According to Kilby and Newell [11], the results of measurements obtained from two adjacent plates make it possible to characterize the postural control more fully than with the use of the traditional single-plate platform.

Feet, as a structural element of the executive part of the equilibrium system, are shaped throughout a person’s life. Although the collected data revealed no significant differences between the analyzed indices and indices for the left foot and the right foot ($p < 0.05$), still in the examined population of older women there were certain trends within the shape of the feet. The left foot in the subjects was more often a hollow foot, and the transverse metatarsal arch in most cases was correctly formed. Andrzejewska et al. [2] referred the foot indices analyzed by them to BMI values of the subjects indicating that the structure of the foot is associated with a different typology of the body of athletes. Both our studies and research attempts of other authors, e.g., Puszczałowska-Lizis [20], show also the relationship between the same limbs (right of left) indices (e.g., lowering of the dynamic arch increases the valgity of the hallux). Fan et al. [10] determined the effect of the foot structure on the dynamic and postural control as well as gait, indicating the morphological changeability of the foot structure and its impact on the analyzed indices.

In our study, it was found that a bigger difference in the width of the feet was accompanied by a longer sway path in the *x*-axis (medio-lateral). The same regularity was observed in the case of the relationships between the global assessment balance indices and the disparity in the width of the feet. The observed associations related mainly to the values measured in the transverse axis. Instability in this axis is one of the determinants of the risk of falling, which has been demonstrated by Pavol [19] and Błaszczyk and Michalski [6]. The analysis of the results presented in this work indicates that the increased angle of varus deformity of toe V in the left foot had an effect on the increase in the number of side sways for that limb. For the right foot, it was established that the increased angle of varus deformity of toe V was associated with an increase in the distance between the two furthest points of statokinesiogram in the antero-posterior direction and an increase in the surface area determined by the COP shift of that limb. The interdependences between the morphological foot indices and balance indices within one limb can add up, but their impact on the global assessment of balance indices will depend on the efficiency of the balance system, which controls the individual components of the motor system in order to counteract both the internal and external forces that may disrupt this balance [5].

This study showed that the increase in the disproportion in the feet width is accompanied by an increase in the statokinesiogram values of path length, which is longer also in the medio-lateral axis. The increase in the value of the difference between the width of the feet leads to a surge in both the mean deflection and the COP velocity in the left-right direction. High COP velocity reaching the limits of stability is an alarming rate manifesting postural instability and qualifying the tested person to a group of people at high risk of falling [12]. The analysis of the two feet shows that COP shift occurs toward the foot with the smaller width. The disparity in the feet width also causes an increase in the field marked by the COP in quiet standing. Another factor deteriorating the balance is an increase in the toe V varus deformity angle. The analysis of the correlation of this indice with balance indices shows that a larger toe V varus deformity angle is associated with increased sway path in the medio-lateral direction, the mean sway and velocity of the COP in this axis as well as the field of COP during the test. In our research it was determined that the increased right hallux valgus angle was accompanied by an increase in the number of COP sways in the sagittal axis, and the greater heel angle in the left foot (higher transverse metatarsal arch) was associated with a decreasing COP sway path and the velocity in the medio-lateral axis. The increased values of Clarke’s angle of the right foot were accompanied by higher values of the COP sway path and the shift velocity in the medio-lateral axis.

Many authors [14], [20], studied the effect of foot structure and the types of diseases, such as those disrupting proprioception, on the indices of the postural control and gait, determining the relationships between these indices. Our studies showed the occurrence of similar correlations in the elderly, whose feet are subject to involution changes, which according to some authors [7], [24] lead to, among other things, shifting the loading on the passive part of the motor organ and increased muscle stiffness.

The results presented in this study demonstrate that the assessment of the structural changes of the feet and their consequences affecting the equilibrium system should be one of the directions of research in the field of physiotherapy, geriatric medicine, and monitoring the aging process. This research has diagnostic value and therapeutic importance. The structure disorder leads to the impairment of the function, which may increase the disorders within the structure. In the process of rehabilitation of the elderly, in addition to increasing their muscle strength [1], a large emphasis should be put on functional proprioceptive training. Enhancing the efficiency of the postural control helps to improve equilibrium reactions [18]. Increased capacity of postural control in a changing environment is a major goal of imbalances therapy, and knowledge of the predictors of these disorders allows for quick and targeted preventive and corrective action.

5. Conclusions

1. The differences between the indices and morphological indices for the right and the left foot are not significant, which indicates the proportionate formation of feet in the individual life.
2. The increased differences in the width indices between the right and the left foot lead to balance deterioration.
3. Larger angles of valgity and varus deformity of toes and indices describing the longitudinal arch and transverse front arch of the foot have the greatest impact on the deterioration of balance in the medio-lateral axis.

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