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Laterality versus ankle dorsi- and plantarflexion maximal torques

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Purpose: The aim of the study was to analyze the connections between the functional asymmetries of lower limbs, taking into account morphological feet features, and ankle dorsi- and plantarflexion maximal torques in men and women. Methods: The study population consisted of 56 young subjects among which there were 30 women and 26 men. The assessment of upper and lower limbs' side dominance was performed on the basis of surveys, verified with simple motor tasks that resembled the actions characteristic of the upper and lower limbs. The measurements of body build, as well as foot build, were performed with the use of accepted instruments according to the anthropometry standards. The measurements of longitudinal foot arches were conducted using the pantographic method. Ankle dorsi- and plantarflexion maximal torque values were measured under static conditions. Results: We found a positive correlation between the functional dominance of lower limb and greater strength only for ankle plantarflexion maximal torque values in correct laterality variants in women and in only one variant in men. No correlation was found between foot morphological asymmetry and the ankle dorsi- and plantarflexion maximal torque values, either in women or in men. Conclusion: Our results support the idea that the functional lower limb dominance is not equivalent to the greater muscle strength.

Key words: *limb laterality, maximal torques, morphological feet asymmetry, functional lower limbs asymmetry, sexual dimorphism*

1. Introduction

Numerous factors influence the functional asymmetry [8], including force asymmetry in humans. Defining the relation between the functional asymmetry and the strength of lower limbs was the aim of studies by numerous authors [12], [19], [22], [24], [26]. Lower limb functional dominance may be determined with the use of a variety of tests [8], [24], [25]. For instance, in their study concerning comparing ankle muscle strength of both lower limbs in young males, Wei-Hsiu Lin et al. [24] determined lower limb functional dominance on the basis of three tests: kicking a ball with precision, stepping onto one stair and taking a step forward in order to regain balance to be lost while standing. In their analysis, functional lower limbs' asymmetry in stabilizing and dynamic tasks, Grouios et al. [10] pointed out the lack in the relationship between determining limb dominance with the surveys and with the tasks and advised to perform both means of asymmetry assessment. Carey et al. [3] expressed a similar opinion. Studies by Wang and Newell [23] confirmed that the type of task had a significant impact on a person's own assessment of functional dominance of both upper and lower limbs.

In order to assess ankle muscle strength, apart from the analysis of dorsi- and plantarflexion maximal torque values under static conditions [6], [14], [18], [22], [27] or under isokinetic conditions [8], [13], [21], an "eversion/inversion" strength ratio may be used. The "flexing/extending" ratio (the ratio of flex-

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ion to extension torques), which is often used in muscle strength measurements of knee flexors and extensors [8], [12], [19], is not taken into consideration in ankle dorsi- and plantarflexion measurements.

The assessment of foot morphological asymmetries impact on the lower limb muscles strength, including ankle muscles strength, was not often discussed in the literature. Ankle plantarflexion is conducted by eight muscles, which, along with other anatomical structures, form a lever referred to as Calf Toes Band [16]. Determining the relations between both morphological and functional feet asymmetries and the ankle muscle strength are important for sport [1], [16] as well as for everyday life activities [6]. It is believed [15], [19] that lower limb muscle strength asymmetry may affect results in sport negative as well as increase the risk of injury.

The aim of this study is to analyze the relationship between lower limb functional asymmetries, taking into account the feet morphological features and ankle dorsi- and plantarflexion maximal torques (under static conditions) in men and women. We formulated the research questions as follows: is there a relationship between lower limb functional asymmetries and ankle dorsi- and plantarflexion maximal torque values?, and is there a relationship between lower limb morphological asymmetries and ankle dorsi- and plantarflexion maximal torque values?

2. Materials and methods

The study population consisted of 56 subjects among which there were 30 women (mean age 20.29 ± 0.59 years; body mass 58.13 ± 4.58 kg, body height 165.60 ± 5.03 cm) and 26 men (mean age 20.41 ± 0.78 years, body mass 78.39 ± 8.42 kg, body height 181.15 ± 6.52 cm). The consent to conduct the tests was obtained from the local Commission of Ethics. The subjects consented to participate in the study. The assessment for the upper and lower limbs was conducted on the basis of the data from interviews which were performed every one week after, and then verified with simple motor tests that imitated characteristic limbs function. The questionnaire consisted of questions concerning a subjects's own upper limb preference, i.e., on right- or left-handedness in everyday activities, and concerning a subjects's own lower limb preference, i.e., on right- or left-footedness in a one-leg vertical jump (the vertical jump test – which limb leads (a countermovement limb) and which is the propulsive limb (a take-off limb), and in kicking a ball (a ball kicking test – which limb kicks a ball and which limb lends support, maintains posture). The tasks to test the lower limb functional preference were chosen from "The Waterloo Footedness Questionnaire" [7]. We chose to accept the interpretation of limb dominance according to Chapman et al. [4], Gabbard and Itey [9], and Peters and Durding [17], who assumed that the mobilizing or leading limb (initiating limb) would be considered the preferred (dominant) limb, and the limb used for support or propulsion would be considered the non-preferred, non-dominant limb. On the basis of subjects' answers and the tests being conducted we determined the functional limb asymmetry. We later established a symbol of a given asymmetry using letters. The symbol informs us which limb is preferred in a given activity. The first letter applies to the upper limb and the second letter applies to the lower limb. For homogeneous laterality, we used the symbols as follows: R-R for right-handed right-footers, L-L for left-handed left-footers. For cross laterality (cross dominance, mixed laterality), we used the symbols as follows: R-L for right-handed left-footers, and L-R for left-handed right-footers. The results of the one-leg vertical jump tests and the ball kick tests did not coincide when we determined the footedness of the subjects. Therefore, we introduced three variants of classification according to Ilnicka et al. [11] (Table 1).

The body build measurements were taken with classical instruments and according to the standards accepted in anthropometry. The measurement points and foot features were measured (Figs. 1 and 2).

The measurements of longitudinal arches were performed with the plantographic method on the basis of Clarke's angle to be mapped on a computer foot print. The images were obtained from a podoscope equipped with a camera (produced by POSMED).

The measurements of ankle dorsi- and plantarflexion maximal torques under static conditions were performed with a prototype equipment (JBA, Staniak, Poland) in the sitting position (Fig. 3).

The lower limb joint angles were 90°. The trunk was stabilized with straps and the lower limb was stabilized with a clamping ring over the upper part of thigh. The upper limbs were crossed on the chest. The measurement platform rotation axis, where the foot was placed, coincided with the rotation axis in the ankle (the center of the lateral malleolus of the fibula). The foot was stabilized on the measurement platform with a clamping ring. The measurements were taken in the following order: dorsiflexion–plantarflexion of the functionally dominant limb, then followed by the non-dominant limb. The measurements were taken

Table 1. Classification of subjects [%] according to their limb laterality type – three variants

Sex	Variant I				Variant II				Variant III							
	R-R	R-L	L-L	L-R	R-R	R-L	L-L	L-R	R-RR	R-LR	R-RL	R-LL	L-LL	L-LR	L-RR	L-RL
F (n = 30)	60.0	36.7	3.3	–	86.7	10.0	3.3	–	53.4	33.3	6.7	3.3	3.3	–	–	–
M (n = 26)	65.4	15.4	15.4	3.8	65.4	15.4	11.5	7.7	50.0	15.4	15.4	–	11.6	3.8	3.8	–

Explanations: F – females, M – males, laterality assessments: Variant I – upper limb (the first letter in the formula): eating, writing, combing one's hair, lower limb (the second letter in the formula): in the one-leg vertical jump test – the leading limb; Variant II – upper limb (the first letter in the formula): as in variant I, lower limb (the second letter in the formula): in the ball kick test – the limb kicking a ball; Variant III – upper limb (the first letter in the formula): as in variant I, lower limb (the second letter in the formula): in the one-leg vertical jump test – the leading limb; lower limb (the third letter in the formula): in the ball kick test – the limb kicking the ball.

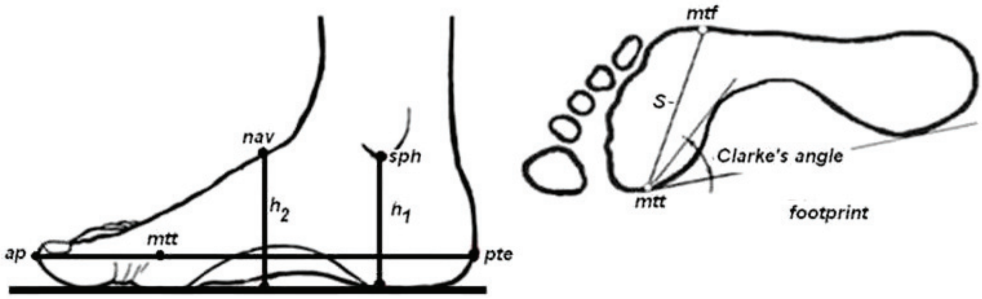

Fig. 1. Measurement points of the foot (as modifited according to Ilnicka et al. [11])
Explanations: *akropodion* (*ap*) at the front of the tip of the longest toe; *metatarsale tibiale* (*mtt*) at the centre of the head of the first metatarsal bone; *naviculare* (*nav*) on the dorsal surface of the navicular bone; *sphyrion* (*sph*) at the lowest point of the medial malleolus; *pternion* (*pte*) at the furthest end of the calcanean tuber; *metatarsale fibulare* (*mtf*) at the outer side of the fifth metatarsal bone; h_1 – the foot height measured from the ground to the *sphyrion* point; h_2 – the foot height measured from the ground to the *naviculare* point; s – foot width measured from the *mtt* point to the *mtf* point; *Clarke's angle* – longitudinal arch angle on the footprint

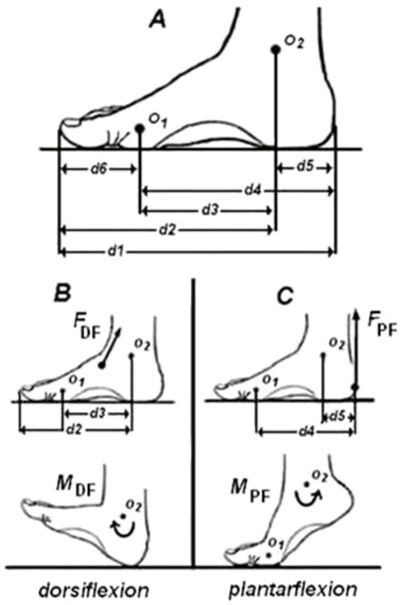

Fig. 2. (a) foot measurements; (b) effect of dorsiflexors muscle force on the foot; (c) effect of the plantarflexors muscle force on the foot
Explanations: d_1 – foot length, d_2 – * forefoot length, d_3 – forefoot length without toes, d_4 – foot length without toes, d_5 – ** hindfoot length, d_6 – hallux length, O_1 – axis of rotation going through metatarsophalangeal joints, O_2 – axis of rotation in the ankle, F_{DF} – dorsiflexors resultant force, F_{PF} – plantarflexors resultant force, M_{DF} – dorsiflexion torque, M_{PF} – plantarflexion torque, * forefoot is the front part of the foot in relation to the transverse axis of the ankle; anatomically, this is the front part of the tarsum, including the metatarsus and toes; ** hindfoot is the back part of the foot in relation to the transverse axis of the ankle; anatomically, this is the back part of the tarsum

twice, though the non-dominant limb was tested first in the second measurement. Prior to the measurements, subjects were acquainted with the equipment. They also did some warm-up exercises for the tested muscles. The task for the subjects was to develop the value of maximal torque for one time of up to 5 seconds. The break between the measurements was 2 minutes long. The highest values in individual measurements were then analyzed.

In order to compare the asymmetries of various features, the following asymmetry indexes were calculated

$$W_{\text{asym}} = \frac{R - L}{(R + L)/2} \times 100 \ [\%] \tag{1}$$

where R denotes the value for the right limb, L denotes the value for the left limb.

Fig. 3. A standard subject position during measurements of ankle dorsi- and plantarflexion maximal torques

Negative values of asymmetry index point to the dominance of the left limb in a given feature. The index absolute value determines the diversity degree – the greater the value is, the greater the diversity.

In order to assess the dimorphic differences, Mollison's index [16] was applied

$$W_{sk.dmf} = \frac{\bar{x}_{\text{F}} - \bar{x}_{\text{M}}}{SD_{\text{M}}} \tag{2}$$

where $\bar{x}_{\text{F}}$ – arithmetic mean of the feature in the group of females, $\bar{x}_{\text{M}}$ – arithmetic mean of the feature in the group of males, $SD_{\mathbf{M}}$ – standard deviation of the feature in the group of males.

Features to be considered dimorphically significant are those where the difference of arithmetic averages is greater than standard deviation (SD) in the group of males. Negative values of Mollison's index point to the dominance of the feature in men. The index absolute value determines the degree of diversity – the greater the value is, the greater the diversity.

We put the test results through a detailed statistical analysis with the Statistica 8.0 program by StatSoft. We analysed the differences between the right feet and the left one separately in the female group and in the male group on the basis of the arithmetic means of chosen features and indexes: the t-test for dependent variables and the Wilcoxon signed-rank test for divergent variances of the features compared. In addition, we carried out the analyses of the differences between sexes and of the differences for the chosen types of laterality (the t-test was conducted for dependent variables; when the distribution of the feature being compared was at variance with the normal distribution in the Shapiro –Wilk test the Mann–Whitney U-test was carried out). The analysis of relationships between the chosen podometric and plantographic features and the ankle dorsi- and plantarflexion maximal torque values was conducted on the basis of the Pearson product-moment correlation coefficient (for the features which presented normal distribution, according to the Shapiro–Wilk test). In addition, for the features whose variances were significantly different, and which were varying from normal distribution according to the strict Shapiro–Wilk test, Spearman's rank correlation coefficient was calculated.

3. Results

Table 1 presents subjects classification according to their limb laterality type.

In assessing footedness based on the leading limb during a one-leg vertical jump, most right-handed subjects indicated the right lower limb as the preferred limb (ipsilateral asymmetry, homogeneous laterality, variant I – the R-R type, right-handed –right-footed). Approximately 37% of the women and approximately 15% of the men indicated the left lower limb (contralateral asymmetry, mixed laterality, variant I, R-L type; right-handed–left-footed). During assessing footedness based on the limb kicking a ball (variant II), the percentage of right-handed men in each laterality type was the same as in variant I; while the percentage of women was significantly different. Classification of the subjects according to their limb preference in variant II revealed that among the right-handed subjects, considerably fewer subjects conducted the tests (the one-leg vertical jump and kicking a ball) with the right lower limb than in variants I and II (Table 1). Statistical analysis was conducted only for the group of right homogeneity (right-handed; right-footed) in two variants of limb laterality type assessment.

With the self-evident differences between sexes in terms of body height and mass, no statistically significant differences ($P \leq 0.05$) were found between arithmetic means of these features in the two variants

Table 2. Arithmetic means (±SD) of chosen traits for right and left feet for all the analysed variants of homogeneous right laterality in females (F) and males (M), as modified according to Ilnicka et al. [11]

Foot traits	Sex	Variants of laterality assessment			
		I R-R Females n = 18 Males n = 17		II R-R Females n = 26 Males n = 17	
		Right side	Left side	Right side	Left side
d_1 [cm]	F M	24.65 ± 0.86 27.24 ± 1.20	24.78 ± 0.85 27.36 ± 1.28	24.63 ± 0.74** 27.57 ± 1.37	24.82 ± 0.78** 27.68 ± 1.41
d_2 [cm]	F M	19.41 ± 0.82* 21.39 ± 1.04	19.62 ± 0.74* 21.58 ± 0.99	19.52 ± 0.74* 21.68 ± 1.31	19.72 ± 0.74* 21.84 ± 1.25
d_3 [cm]	F M	13.49 ± 0.60 14.74 ± 0.77	13.48 ±0.56 15.07 ±0.93	13.55 ± 0.63 14.94 ± 0.98	13.60 ± 0.60 15.22 ± 0.92
d_4 [cm]	F M	18.73 ± 0.63 20.59 ± 0.92	18.64 ± 0.63 20.85 ± 1.21	18.67 ± 0.64 20.84 ± 1.02	18.70 ± 0.63 21.06 ± 1.07
d_5 [cm]	F M	5.24 ± 0.37 5.85 ± 0.45	5.16 ± 0.34 5.79 ± 0.47	5.11 ± 0.37 5.89 ± 0.42	5.10 ± 0.34 5.84 ± 0.42
d_6 [cm]	F M	5.92 ± 0.42^x 6.65 ± 0.53	6.14 ± 0.42^x 6.51 ± 0.33	5.97 ± 0.45 6.74 ± 0.58	6.12 ± 0.44 6.62 ± 0.49
s [cm]	F M	9.34 ± 0.41 10.38 ± 0.40	9.33 ± 0.49 10.41 ± 0.54	9.31 ± 0.38 10.48 ± 0.63	9.28 ± 0.78 10.55 ± 0.68
h_1 [cm]	F M	6.85 ± 0.41 7.36 ± 0.64*	6.91 ± 0.50 7.54 ± 0.63*	6.90 ± 0.39 7.35 ± 0.63*	6.96 ± 0.48 7.55 ± 0.66*
h_2 [cm]	F M	6.36 ± 0.44 7.06 ± 0.51	6.33 ± 0.42 7.03 ± 0.52	6.46 ± 0.48 7.15 ± 0.59	6.42 ± 0.43 7.16 ± 0.62
Clarke's angle [degrees]	F M	49.29 ± 3.61*** 48.88 ± 10.02	46.63 ± 4.02*** 48.32 ± 9.81	48.29 ± 4.63*** 48.34 ± 10.12	46.23 ± 5.12*** 47.93 ± 9.91

Explanations: statistical significance of differences between right and left sides, for the t test ($^x p \leq 0.10$, i.e., on the limit of the significance threshold set $*p \leq 0.05$; $**p \leq 0.01$; $***p \leq 0.001$); the description of laterality assessment variants: IR-R – upper limb (the first letter in the formula): eating, writing, combing one's hair, lower limb (the second letter in the formula): in the one-leg vertical jump test – the leading limb; II R-R – upper limb (the first letter in the formula): as in variant I R-R, lower limb (the second letter in the formula): in the ball kick test – the limb kicking a ball; the features description: d_1 – foot length, d_2 – forefoot length, d_3 – forefoot length without toes, d_4 – foot length without toes, d_5 – hindfoot length, d_6 – hallux length, h_1 – the foot height measured from the ground (basis) to the sphyrion point; h_2 – the foot height measured from the ground (basis) to the naviculare point; s – foot width measured from the *mtt* point to the *mtf* point; Clarke's angle – longitudinal arch angle on the foot print; other details – see Figs. 1 and 2.

of limb dominance analysed, either in the group of females or in the group of males. Arithmetic means (±SD) of chosen features and indexes for right and left feet for all analysed variants of homogeneous right laterality in women and in men are presented in Tables 2 and 3.

11 podometric indexes were calculated on the basis of the above-mentioned measurements (Table 3).

On the basis of the analysis of arithmetic means of the features under study, we found statistically significant differences in foot length (d1) in right-handed women who in the kick test kicked a ball with the right lower limb (variant II R-R). Their right feet were shorter (P = 0.008; W_{asym} = –0.77%). In women, foot length without hindfoot (d5) was shorter in the right foot for all possible variants of laterality, i.e., in right-handed women whose leading limb during a one-leg vertical jump was the right lower limb (variant I R-R: P = 0.045, W_{asym} = –1.07%); and in the right-handed women who kicked a ball with the right lower limb (variant II R-R: P =0.017, W_{asym} = –1.02%). In the group of men the test for significant differences for dependent variables revealed that the lengths were greater in the left foot (the non-dominant limb): for variant I R-R: P = 0.08, W_{asym} = –1.26%; and for variant II R-R: P = 0.07, W_{asym} = –1.05%; for the foot length with no toes only (d4). Clarke's angle, which characterizes the longitudinal arches, was statistically significantly greater in the female group only, for the dominant right-limb (the variant I R-R: P = 0.00006, W_{asym} = 5.55%;

Table 3. Arithmetic means (±SD) of chosen indexes of right and left feet
for all the analysed variants of homogeneous right laterality in females (F) and males (M),
as modified according to Ilnicka et al. [11]

Index number	Foot indexes	Sex	Variants of laterality assessment			
			I R-R Females n = 18 Males n = 17		II R-R Females n = 26 Males n = 17	
			Right side	Left side	Right side	Left side
1	h_1/d_1 [%]	F	27.80 ± 1.57	27.90 ± 1.88	28.03 ± 1.40*	28.04 ± 1.79*
		M	27.09 ± 2.65	27.58 ± 2.45	26.70 ± 2.54*	27.34 ± 2.60*
2	d_1/s [–]	F	2.64 ± 0.11	2.69 ± 0.36	2.65 ± 0.11	2.69 ± 0.30
		M	2.61 ± 0.10	2.63 ± 0.13	2.64 ± 0.15	2.63 ± 0.14
3	d_5/d_1 [%]	F	21.26 ± 1.44^x	20.81 ± 1.26^x	20.76 ± 1.46	20.54 ± 1.30
		M	21.46 ± 1.33^x	21.14 ± 1.18^x	21.40 ± 1.48	21.12 ± 1.29
4	d_5/d_2 [%]	F	27.04 ± 2.33*	26.31 ± 2.02*	26.24 ± 2.34	25.89 ± 2.08
		M	27.36 ± 2.17^x	26.83 ± 1.91^x	27.28 ± 2.39	26.80 ± 2.09
5	d_5/d_3 [%]	F	38.94 ± 3.66	38.31 ± 3.24	37.83 ± 3.64	37.56 ± 3.26
		M	39.75 ± 3.55*	38.48 ± 3.90*	39.62 ± 3.90^x	38.48 ± 3.23^x
6	d_5/d_4 [%]	F	27.98 ± 1.96	27.66 ± 1.69	27.40 ± 1.89	27.27 ± 1.70
		M	28.40 ± 1.81*	27.76 ± 1.51*	28.33 ± 2.02^x	27.75 ± 1.69^x
7	d_4/d_1 [%]	F	75.99 ± 1.25	75.24 ± 1.35	75.79 ± 1.57	75.35 ± 1.43
		M	75.59 ± 1.47	76.17 ± 1.34	75.59 ± 1.48	76.10 ± 1.11
8	d_4/d_2 [%]	F	96.54 ± 2.60*	95.03 ± 2.39*	95.68 ± 2.95	94.86 ± 2.60
		M	96.27 ± 2.55	96.62 ± 2.47	96.21 ± 2.65	96.50 ± 2.29
9	d_3/d_1 [%]	F	54.73 ± 1.69^x	54.43 ± 1.75^x	55.03 ± 1.88	54.81 ± 1.74
		M	54.13 ± 1.93*	55.03 ± 1.57*	54.18 ± 2.04^x	54.98 ± 1.55^x
10	d_3/d_4 [%]	F	72.01 ± 1.87	72.34 ± 1.69	72.60 ± 1.89	72.73 ± 1.71
		M	71.60 ± 1.81*	72.24 ± 1.51*	71.67 ± 2.01^x	72.25 ± 1.68^x
11	d_2/d_1 [%]	F	78.74 ± 1.44^x	79.19 ± 1.26^x	79.23 ± 1.46	79.46 ± 1.30
		M	78.54 ± 1.33^x	78.86 ± 1.18^x	78.60 ± 1.48	78.88 ± 1.29

Explanations: differences between sides significant for $*p \le 0.05$; $^x p \le 0.10$, i.e., on the limit of the significance threshold set; for the description of laterality assessment variants: IR-R – upper limb (the first letter in the formula): eating, writing, combing one's hair, lower limb (the second letter in the formula): in the one-leg vertical jump test – the leading limb; II R-R – upper limb (the first letter in the formula): as in variant I R-R, lower limb (the second letter in the formula): in the ball kick test – the limb kicking a ball; the description of measurement points and segments: d_1 – foot length, d_2 – forefoot length, d_3 – forefoot length without toes, d_4 – foot length without toes, d_5 – hindfoot length, h_1 – the foot height measured from the ground (basis) to the sphyrion point; s – foot width measured from the *mtt* point to the *mtf* point; other details – see Figs. 1 and 2; indices: 1 – ($h_1/d_1 \times 100$) longitudinal arch index; 2 – (d_1/s) transverse arch Wejsflog's index; 3 – ($d_5/d_1 \times 100$) lever arm length for plantarflexion relative to the ankle joint, in percentage of foot length; 4 – ($d_5/d_2 \times 100$) lever arm length for plantarflexion relative to the ankle joint, in percentage of lever arm length with toes for dorsiflexion; 5 – ($d_5/d_3 \times 100$) lever arm length for plantarflexion relative to the ankle joint, in percentage of lever arm length without toes for dorsiflexion; 6 – ($d_5/d_4 \times 100$) lever arm length for plantarflexion relative to the ankle joint in percentage of lever arm length for plantarflexion relative to the metatarsophalangeal joints; 7 – ($d_4/d_1 \times 100$) lever arm length for plantarflexion relative to the metatarsophalangeal joint in percentage of foot length; 8 – ($d_4/d_2 \times 100$) lever arm length for plantarflexion relative to the metatarsophalangeal joint in percentage of foot length without hindfoot, i.e., in percentage of lever arm length with toes for dorsiflexors (extensors); 9 – ($d_3/d_1 \times 100$) lever arm length without toes for dorsiflexion (extension) in percentage of foot length; 10 – ($d_3/d_4 \times 100$) lever arm length without toes for dorsiflexion (extension) in percentage of laver arm length for plantarflexion relative to metatarsophalangeal joint; 11 – ($d_2/d_1 \times 100$) lever arm length with toes for dorsiflexion (extension) in percentage of foot length.

the variant II R-R: P = 0.00007, W_{asym} = 4.36%. In males, Clarke's angle was similar in both right and left feet, and the foot height to the *sphyrion mediale* point (h_1), considered in the longitudinal arch index, was statistically greater in the left, non-dominant limb (propulsive during a jump and lending support while kicking a ball) in all the analysed laterality assessment variants (variant I R-R: P = 0.039, W_{asym} = –2.42; variant II R-R: P = 0.02, W_{asym} = –2.69%).

Analysis of longitudinal arch index (h_1/d_1), which expresses the foot height to the *sphyrion mediale* point as the percentage of foot length, confirmed the greater index values for the left side (P = 0.048) for the laterality variant II R-R only, i.e., in the group of right-handed men whose left lower limb was the supportive limb (Table 3).

The remaining indexes analysis of right and left lower limbs, both in the female group and in the male group, did not reveal any statistically significant differences between the variants of limb laterality considered. In the male group, the hindfoot index (d_5/d_4) was statistically significantly greater for the right side (variant I R-R: P = 0.024; variant II R-R; P = 0.063). With the self-evident, statistically significant dimorphic differences in absolute values of anthropometric features of female and male feet (for most differences, a statistical significance of $P \leq 0.001$), we found no such differences when comparing the percentage foot indexes, nor did we find such differences when comparing the Clarke's angle values for longitudinal arches. The only exception, which presented itself in the limb laterality variant II R-R, was the longitudinal arch index for the right foot, which expressed the foot height up to the *sphyrion mediale* point as the percentage of foot length with toes (h_1/d_1). In the light of these indices, female right-handed right-footers (in the test for kicking a ball – variant II R-R) had better longitudinal foot arches in the right feet as compared to men (women $\bar{x}$ = 28.03; men $\bar{x}$ = 26.70; P = 0.032). In the male group right-handed right-footers (in laterality assessment variants) we found statistically significant differences for hindfoot indices (d_5/d_3 and d_5/d_4) for right and left feet. The relative hindfoot index was greater in the right foot (the dominant limb, i.e., leading limb during one-leg vertical jump, the limb kicking a ball). In the left foot (non-dominant) this measurement in the relation to the foot length with no toes was shorter. The remaining indices comparison of the right and left lower limbs, did not reveal any other statistically significant differences between the analyzed laterality assessment variants (footedness), neither in women, nor in men.

With the self-evident and statistically significant differences between sexes in terms of absolute values for length, width, and height of male and female feet, in all the analysed limb laterality assessment variants (dimorphism index from approximately –1 to approximately –3 SD), we did not find significant differences when comparing neither percentage foot indexes, nor Clarke's angle values for longitudinal arches. The exception was, for variant II R-R, the longitudinal arch for the right foot, which expresses the foot height up to the *sphyrion mediale* point as the percentage of foot length with toes. Mean male feet were longer by approximately 3 cm, wider by approximately 1 cm, and higher by approximately 0.7 cm as compared to female feet, whereas the Clarke's angle values of longitudinal arches were similar in both sexes – between 46° and 49°.

We compared arithmetic averages of the groups (without considering the lower limb preferences) and found highly significant differences between sexes in most absolute feet measurements; however, we did not find the differences in either longitudinal or transverse arches. When we divided the subjects according to their limb preferences (into two laterality assessment variants), then only in variant II R-R, i.e., right-handers who kicked a ball with their right feet, we found significant statistical differences between sexes, with higher values in women in two longitudinal arch indexes.

Female right-handed right-footers had morphological asymmetry in the foot length, and foot length with no hindfoot – these measurement values were higher for the left foot; and in Clarke's angle, which was greater in the right foot. In male right-handed right-footers, we found asymmetry in the foot length without toes (left feet were longer) and in the foot height up to the *sphyrion mediale* point (left feet were higher). Two indices for longitudinal arches were statistically significantly higher in women for the right foot.

Table 4 presents ankle dorsi- and plantarflexion maximal torque values measured under static conditions.

Figure 4 presents a comparison of the asymmetry index values for the variables discussed above. In the female group there were statistically significant differences between the right limb and left one in the maximal torque values in plantarflexion in the two laterality variants (P = 0.009; P = 0.0012, respectively). In the male group, the statistical significant differences were found in the variant II R-R only (P = 0.04), while in the variant I R-R the differences were on the brink of significance (P = 0.06). We found no statistically significant differences when we compared maximal torque values in ankle dorsiflexion of right and left feet in the groups under study.

All the differences between sexes in the analyzed torque values were highly significant ($P \leq 0.001$).

In addition, we calculated the „dorsiflexors-plantarflexors" foot index (DF/PF) which denotes the proportions between antagonist muscles (Table 5). We found no differences in this index values for right and left limbs either in women, or in men.

Table 4. Mean (±SD) ankle dorsi- and plantarflexion maximal torque values (static conditions) in two homogeneous right laterality assessment variants

Maximal torque [N m]	Laterality assessment variants	Females		Males	
		Right limb	Left limb	Right limb	Left limb
Plantarflexion (PF)	I R-R	211.3 ± 62.19**	194.2 ± 46.02	287.9 ± 66.64[x]	262.9 ± 51.70
	II R-R	213.0 ± 59.47***	196.4 ± 47.33	301.5 ± 65.06*	276.0 ± 54.40
Dorsiflexion (DF)	I R-R	51.9 ± 10.95	50.7 ± 9.68	84.3 ± 17.04	80.0 ± 23.41
	II R-R	50.8 ± 10.63	48.6 ± 10.77	90.9 ± 20.59	86.5 ± 22.40

Explanations: statistical significance of difference between right and left limbs for the *t* test ($^xp \le 0.10$; $*p \le 0.05$; $**p \le 0.01$;$***p \le 0.001$); the description of laterality assessment variants: I R-R (Females, $n = 18$, Males, $n = 17$) – upper limb (the first letter in the formula): eating, writing, combing one's hair, lower limb (the second letter in the formula): in the one-leg vertical jump test – the leading limb; II R-R (Females, $n = 26$, Males, $n = 17$) – upper limb (the first letter in the formula): as in variant I R-R, lower limb (the second letter in the formula): in the ball kick test – the limb kicking a ball.

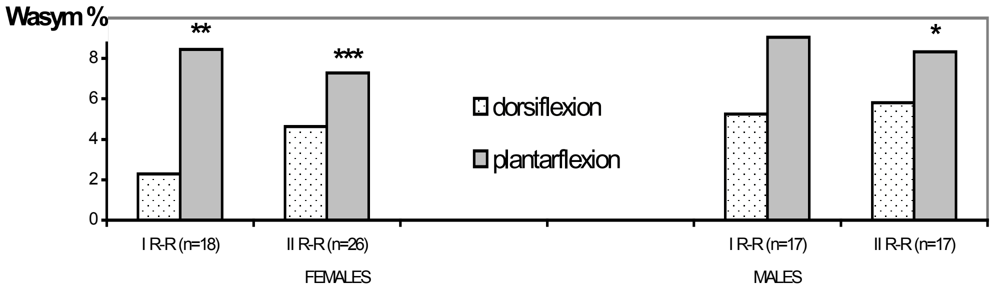

Fig 4. Mean asymmetry index values (W_{asym}) [%] of the ankle dorsi- and plantarflexion maximal torques (static conditions) for all homogeneous right laterality assessment variants (types I R-R, II R-R). Explanations: positive asymmetry index values denote higher values for the right limb: the description of laterality assessment variants: IR-R – upper limb (the first letter in the formula): eating, writing, combing one's hair, lower limb (the second letter in the formula): in the one-leg vertical jump test – the leading limb; II R-R – upper limb (the first letter in the formula): as in variant I R-R, lower limb (the second letter in the formula): in the ball kick test – the limb kicking a ball; statistical significance set at $*p \le 0.05$; $**p \le 0.01$;$***p \le 0.001$

Table 5. Mean (±SD) "dorsiflexors-plantarflexors" foot index values (DF/PF) of foot in females (F) and males (M) in two laterality assessment variants

Index [%]		Laterality assessment variants			
		I R-R		II R-R	
		Females $n = 18$	Males $n = 17$	Females $n = 26$	Males $n = 17$
DF/PF	R	25.74 ± 6.48	30.73 ± 8.63	24.93 ± 6.32	31.04 ± 7.51**
	L	26.91 ± 5.96	31.37 ± 9.77	25.59 ± 6.29	31.81 ± 7.56**

Explanations: significant difference between females and males set at $**p \le 0.01$; limb right (R) and (L); the description of laterality assessment variants: I R-R – upper limb (the first letter in the formula): eating, writing, combing one's hair, lower limb (the second letter in the formula): in the one-leg vertical jump test – the leading limb; II R-R – upper limb (the first letter in the formula): as in variant I R-R, lower limb (the second letter in the formula): in the ball kick test – the limb kicking a ball; the "dorsiflexors-plantarflexors" foot index values (DF/PF) of foot calculated according to the following formula: $M_{DF}/M_{PF} \times 100$, where M_{DF} denotes ankle dorsiflexion maximal torque value, and M_{PF} denotes ankle plantarflexion maximal torque value.

The ankle plantarflexors are approximately 4 times stronger than ankle dorsiflexors in the female group. The difference is slightly smaller, and amounts to approximately 3–3.5 times in the male group. We found no differences between sexes in DF/PF values for variant I R-R. We found statistically significant differences between sexes in these index values for variant II R-R ($P \leq 0.01$).

The analysis of the Pearson product-moment correlation coefficient values – without taking into account the unilateral right laterality type – revealed that significant relationships between ankle dorsi- and plantarflexion maximal torques and chosen anthropometric features (measurement segments and foot arch features) are present in few cases only. In the female group, the DF (right) value correlates with the d_4 (right) value (r = 0.38); while in the male group it correlates with the d4 (right) value (r = 0.44) and d_3 (right) values (r = 0.42). The DF (left) value in women correlates with the d_4 (left) value (r = 0.39) and d_5 (right) value (r = 0.46), and in males with d_3 (left) value (r = 0.41) and d_4 (right) value (r = 0.41). In male group, the DF (right) value correlates with h_2 (left) value (r = 0.50), while the PF (right) value correlates with the s (right and left) value (r = 0.45 and r = 0.57, respectively) and h_2 (right and left) value (r = 0.51 and r = 0.48, respectively).

In both groups we found a significant correlation between the ankle dorsi- and plantarflexion maximal torque values of the right limb and left one, and the values of the correlation coefficient were between 0.49 and 0.93. We found no significant correlations between ankle dorsi- and plantarflexion maximal torque values as well as the body height and body mass of the subjects.

4. Discussion

As the lower limb functional dominance may be determined with a variety of tests [8], [24], [25] and there is often no relation between determining dominance with surveys and determining dominance with functional tasks, we applied both kinds of asymmetry assessment (this is in line with the conclusions of Grouios et al. [10], Carey et al. [3], and Wang and Newell [23]). Numerous authors [8], [12], [19] aimed to determine the effect of lower limb functional dominance on greater muscle strength. Their conclusions, however, are ambiguous. Some studies were conducted into the lower limb functional asymmetry and ankle muscle strength [8], [13], [24]. A study on 100 professional football players [8] proved greater strength of functionally dominant limb muscles in ankle dorsiflexion (approximately 4%) and ankle plantarflexion (approximately 2%), under isokinetic conditions. Our study proves that ankle dorsiflexion maximal torque values were higher in the dominant limb (approximately 5% in women and 6% in men) but these differences were not statistically significant. Ankle plantarflexion maximal torque values were significantly higher in the dominant limb in the female group in all the analyzed homogeneous right laterality variants; while in the male group they were higher in one laterality variant only (II R-R). In their study on young men, Wei-Hsiu Lin et al. [24] found no correlation between the lower limb functional dominance and ankle "eversion/inversion" strength ratio values. Wenxin Niu et al. [25] reached similar conclusion in their complex biomechanical measurements (kinematic, kinetic and EMG) to have been conducted during landing after a drop jump from different heights. In their study on healthy subjects, Valderrabano et al. [22] found greater values in the dominant limb during both ankle plantarflexion (dominant limb – 27.1, non-dominant limb 22.9 N m), and ankle dorsiflexion (27.3 and 24.8 N m, respectively). In the literature, there are large differences in the proportions between ankle dorsi- and plantarflexor strength [8], [13], [21], [22]. We found that the ratio of maximal ankle dorsiflexion to the maximal ankle plantarflexion torques, as expressed in the "plantarflexors-dorsiflexors" index of the foot (DF/PF), amounts to approximately 25% in women and approximately 31% in men. Similar DF/PF values were found in professional football players, as re-calculation of measurement values provided by Fousekis et al. [8] points out that the values of this index were amounted to approximately 21%. In their study on 14 male patients, Liu T-Y et al. [13] measured muscle strength of dorsi- and plantarflexors under isokinetic conditions (angular velocity = 30°/s); while the mean values of DF/PF index, calculated on the basis of torque values provided by latter authors, amounted to 56%. Considerably different than the above one, discussed muscle strength ratios of dorsiflexors and plantarflexors; they were provided by Skelton et al. [21]. Mean DF/PF index values, calculated on the basis of force values provided by these authors, were between 268 and 325%. It may seem that such considerable differences in the DF/PF index values resulted largely from the methodology of measurements, and in particular from the position, in which these measurements were taken. Our results are approximately twice as high. This may be due to differences in measurement equipment, populations or test protocol. Using the same equipment, previous studies found similar results to ours [2], [18], [27]. In other studies [8], [14], [22], where the measurement set-up, the test protocol and population tested were different, ankle dorsi- and plantarflexion maximal torque values differ significantly. Probably our results – like with other researchers using the same set-up [2], [27] – may be overestimated as regards the values generally presented in the references due to the mechanical, metrological or computational factors. Further research may focus on prospectively analyzing the possible influence of the measurement condition on ankle dorsi- and plantarflexion maximal torque values.

We found that ankle maximal torques are significantly greater in men, while the differences between sexes concerning the functionally dominant limb (the right limb) were greater in dorsiflexion than in plantarflexion. The DF/PF index values for ankle muscles were not significantly different for the dominant limb and the non-dominant limb, and higher values of this index were found only in variant II R-R for males.

We found no correlations between most of the analyzed indices of foot features and the muscle strength of ankle dorsi- and plantarflexors. Positive correlations occurred in few cases only, and the correlation index values did not exceed 0.51 and are difficult to interpret. On the basis of their study on sprinters and long-distance runners, Baxter et al. [1] suggested that the differences in proportions of human feet and moment arm of the plantarflexors force may have an effect on the run effectiveness. Using the magnetic resonance methods, they proved that sprinters had shorter force arms of plantarflexors, but a longer forefoot than non-sprinters. On the basis of the analysis of computer simulation results, they suppose that a higher value of "forefoot-hindfoot" index allows an increase in activity of plantarflexors during the acceleration phase following the sprint start. Some authors [24] think that lower limb muscle strength asymmetry may be related to a greater extent to lower limb injuries or disorders than to the functional dominance. On the basis of complex biomechanical measurement results Wenxin Niu et al. [25] suggested that the functionally non-dominant limb presents a more effective defence mechanism, which, combined with the common strength dominance, results in a higher risk of injuries for the functionally dominant limb.

In their study on the impact of sensing the strength degree developed with the lower limb muscles on the asymmetry values, Simon and Ferris [20] proved that the asymmetry is smaller if the task for a subject is to develop a certain level of strength in both limbs (the authors used 20, 40 and 60% of maximal strength during lower limb extension) than when the task is to develop maximal strength.

5. Conclusions

1. We found a positive correlation between lower limb functional dominance and the greater muscle strength only for the ankle plantarflexion maximal torque values.
2. We found no correlations between morphological foot asymmetry and ankle dorsi- and plantarflexion maximal torque values either in women, or in men.
3. Our results confirm that lower limb functional dominance is not equal to greater muscle strength.

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