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Distribution of foot load in a group of people with femoroacetabular impingement recreationally practising long-distance running

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Purpose: The aim of this work was to assess the effect of a conservative therapeutic intervention on the changes in the foot load distribution in people with femoroacetabular impingement (FAI) syndrome practising long-distance running. *Methods*: The study involved 44 men, aged 30 to 50 years, practising long-distance running. Two rounds of tests were conducted in the Laboratory of Biokinetics of the AWF in Kraków. The first measurements were carried out in January 2020, and the second ones – after a 6-month therapeutic intervention in July 2020. The measurements of the distribution of foot pressure on the ground in static conditions and during barefoot running were performed with the use of the FOOTSCAN 7.111 podobarographic platform. Parameters showing the distribution of pressure in the individual foot areas and the trajectory of force distribution during the contact of feet with the ground were measured. *Results*: After the completion of the physiotherapy protocol, the FAI group differed significantly from the n-FAI group in relation to the Max F range in the areas of the first, fourth and fifth metatarsal bones, and as far as the impulse in the areas of the first, fourth, and fifth metatarsal bones and in the big toe area. *Conclusions*: A comparison of the results of the first and second run of tests showed more positive changes in the FAI group than in the n-FAI group. This demonstrates a favourable effect of the conservative physiotherapy protocol in people with FAI – it can be an effective alternative to the surgical treatment.

Key words: *conservative treatment, long-distance running, femoroacetabular impingement, podobarographic platform*

1. Introduction

Running, just as walking, is one of the most natural ways to move around [8]. The rules and technique of running are so simple and commonly known that many people can easily undertake this form of physical activity. However, disturbances in the statics and dynamics of the pelvic girdle can interfere with the rhythm of the run and directly affect its technique. Abnormal functioning of the hip joints can lead to many dysfunctions. One of them is femoroacetabular impingement (FAI). It relates to morphological abnormalities in the femoral neck-head connection (*cam*-FAI), or within the acetabulum (*pincer*-FAI) [31]. According to Leunig et al. [24], FAI should not be treated as a disease, but only as a pathomechanical process that can cause weakening of the hip joint. This claim, however, cannot be considered unequivocal, because many authors classify the femoroacetabular impingement as one of the most important factors in the development of hip osteoarthritis [1], [34].

The research by Hashimoto et al. [14] points to inflammation within the articular cartilage in the area of the femoroacetabular impingement. In the case of FAI, articular cartilage shows metabolic hyperactivity, which confirms the hypothesis that FAI is a cause of hip degeneration. Cross et al. [6] declared hip osteoarthritis to be the 11th most common cause of disability world-

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wide. A growing number of people affected by osteoarthrosis suggests that there is a need to assess the factors predisposing to its development. FAI, as one of the most important factors of osteoarthrosis development, requires early diagnosis, targeted therapy and elimination of accompanying compensations in the motor system.

Until now, the most commonly assessed aspect in FAI patients, was the impact of hip joint surgery on changes in foot load distribution during walking and running [4], [7], [16]. Therefore, it was extremely important to assess the effect of a conservative 6-month therapeutic intervention on changes in the foot load distribution in people with FAI, practising recreational long-distance running. Similar results obtained in the control group, consisting of people practising recreational running without hip joint pathology, represented the reference system.

2. Materials and methods

2.1. Participants

The study involved 44 men, aged 30 to 50 years, regularly practising recreational long-distance running. The weekly distance covered by the subjects ranged from 20 to 100 kilometres (47.7 ± 26.9 km, on average). The subjects were members of amateur runner groups from southern Poland (Table 1).

Table 1. Subjects' characteristics

Variable	The FAI Group $n = 22$	The n-FAI Group $n = 22$
Age [years]	38.55 ± 7.45	36.36 ± 6.31
Body weight [kg]	79.69 ± 11.81	74.84 ± 9.23
Body height [m]	1.78 ± 0.05	1.76 ± 0.05
BMI [kgm^{-2}]	22.38 ± 2.85	21.23 ± 2.21
Number of kilometres per week [km]	49.21 ± 28.44	46.26 ± 26.28
Max. training run speed [ms^{-1}]	3.54 ± 0.21	3.82 ± 0.26
Min. training run speed [ms^{-1}]	2.86 ± 0.16	3.08 ± 0.19

Two runs of tests were conducted in the Laboratory of Biokinetics of the AWF in Kraków. The first measurements were carried out in January 2020, and the second ones – after a 6-month therapeutic intervention, in July 2020. The research project gained the approval of the Bioethics Committee of the Regional Medical Chamber in Cracow (Opinion No. 175/KBL/OIL/2020 of July 14, 2020).

2.2. Qualification of respondents for the project

The criterion for inclusion in the femoroacetabular impingement (FAI) group was the α angle of >55° (*cam*-FAI) and/or the β angle of <30° (*pincer*-FAI), as determined based on an X-ray examination, in one or both hip joints [28]. The inclusion criterion for the non-FAI group (n-FAI) was the α angle of <55° and/or the β angle of >30° and <70° in at least one hip joint [28]. The exclusion criteria included a hip injury and a diagnosis of osteoarthrosis grade >1 according to the Tönnis scale [35] or a reduction in the upper joint space dimension below 2 mm in the A-P projection.

2.3. Examination of somatic features

Body height was measured with the use of an anthropometer with an accuracy of 0.01 m and body weight – with an electronic scale with an accuracy of 0.01 kg.

2.4. Examination on a foot pressure scanner

The measurements of the distribution of foot pressure on the ground in static conditions and during barefoot running were performed with the use of the FOOTSCAN 7.111. podobarographic platform. The choice of barefoot running was dictated by the need to avoid shoe effect on the foot load stereotype. Parameters showing the distribution of pressure in the individual foot areas and the trajectory of force distribution during the contact of feet with the ground were measured. For each foot, 10 consecutive values were recorded (20 running steps for both extremities in total). Repeated testing enabled the determination of the average stereotype of the foot load, which in turn made it possible to reliably reflect the character of run parameters in training conditions [38].

The analysis used variables characterizing the load of individual foot zones, such as Max F (the maximum value of pressure standardized to body weight in the given anatomical zone of the foot, expressed in $Ncm^{-2}kg^{-1}$) and *Impulse* per cm^2 of surface area, standardized to body weight, in the given anatomical area of the foot, expressed in $Nscm^{-2}kg^{-1}$).

2.5. Therapeutic intervention

The original protocol of the exercises was created on the basis of principles presented in the works of

Hernandez-Molina et al. [16], Loudon et al. [26], Griffin et al. [12], Drouin et al. [7], Emara et al. [9] and Xu et al. [38]. These included:

- mobilisation of the hip joint in all physiological planes in a painless and safe range of motion,
- improvement of the slide of the articular surface of the femoral head in relation to the acetabulum in the posterior direction,
- centering of the femoral head in the acetabulum by means of active passive work with use of some aids (belt, blanket),
- active correction of the position of the pelvis in relation to the lower limbs,
- enhancement of the tonic muscle strength by long 3-minute active persistence in the corrected position.

The subjects were asked to perform subsequent exercises for 3 minutes (active work in a given position) so that the full training unit lasted no less than 30 minutes and this was repeated 3 times per week, every other day.

2.6. Statistical methods

Statistical analysis was performed with the use of the STATISTICA v.12 software. Appropriateness of variable distribution was checked with the Shapiro–Wilk test. In order to assess the significance of intergroup differences in the studied variables in the first and second examinations, in the case of normal distributions univariate analysis of variance ANOVA (test F) was used with post-hoc Tukey's test verification. If a non-normal distribution was found, the non-parametric Kruskal–Wallis test and post-hoc Dunn test (Bonferroni test) were used.

To assess the significance of differences in the studied variables measured during the first and second run of tests, the *t*-test for the dependent variables was used. The non-parametric Wilcoxon test was used if there was a non-normal distribution of the results. The differences were considered statistically significant if the level of test probability was lower than the assumed significance level ($p \leq 0.05$).

3. Results

3.1. Intergroup analysis of the significance of the differences of the mean values of Max *F* and impulse, standardized to body weight, during a run, before and after the intervention

The analysis of variance showed a statistically significant difference between groups in Max *F* values in the following zones: the third metatarsal bone M3, the fifth metatarsal bone M5 and the big toe T1 in the pre-intervention measurement and statistically significant differences in the following zones: the

Table 2. The results of the analysis of variance ANOVA and ANOVA Kruskal–Wallis for the means of standardized maximum pressure values, Max *F*, in the anatomical zones of the foot, during the run, in all groups included into the experiment, before and after the intervention

Variable/ Group	Max *F*_M1 [$Ncm^{-2}kg^{-1}$]	Max *F*_M2 [$Ncm^{-2}kg^{-1}$]	Max F_M3 [$Ncm^{-2}kg^{-1}$]	Max *F*_M4 [$Ncm^{-2}kg^{-1}$]	Max *F*_M5 [$Ncm^{-2}kg^{-1}$]	Max *F*_HM [$Ncm^{-2}kg^{-1}$]	Max *F*_HL [$Ncm^{-2}kg^{-1}$]	Max *F*_T1 [$Ncm^{-2}kg^{-1}$]
E1F – E1NF			0.9952^{T}		0.0057**^{T}			0.9474^{T}
E1F – C1R			0.0753^{T}		0.6526^{T}			0.0173*
E1F – C1L	0.1697^{D}	0.1022^{T}	0.8644^{T}	0.2123^{D}	0.0401*^{T}	0.8200^{D}	0.5007^{D}	0.6426^{T}
E1NF – C1R			0.0420*^{T}		0.1223^{T}			0.0711^{T}
E1NF – C1L			0.7402^{T}		0.9021^{T}			0.9217^{T}
C1R – C1L			0.3436^{T}		0.4136^{T}			0.2599^{T}
E2F – E2NF	0.6316^{D}		1.0000^{D}	1.0000^{D}	0.0741^{D}			
E2F – C2R	1.0000^{D}		0.2578^{D}	0.1354^{D}	1.0000^{D}			
E2F – C2L	0.0364*^{D}	0.2186^{T}	1.0000^{D}	1.0000^{D}	0.0122*^{D}	0.5123^{D}	0.6195^{D}	0.0552^{T}
E2NF – C2R	1.0000^{D}		0.3834^{D}	0.0152*^{D}	0.9506^{D}			
E2NF – C2L	1.0000^{D}		1.0000^{D}	1.0000^{D}	1.0000^{D}			
C2R – C2L	0.4934^{D}		0.0226*^{D}	0.0129*^{D}	0.2766^{D}			

E1F – the affected lower limb in the FAI experimental group before the intervention, E1NF – the non-affected lower limb in the FAI experimental group before the intervention, E2F – the affected lower limb in the FAI experimental group after the intervention, E2NF – the non-affected lower limb in the FAI experimental group after the intervention, C1R – the right lower limb in the n-FAI control group before the intervention, C1L – the left lower limb in the n-FAI control group before the intervention, C2R – the right lower limb in the n-FAI control group after the intervention, C2L – the left lower limb in the n-FAI control group after the intervention.

first metatarsal bone M1, the third metatarsal bone M3, the fourth metatarsal bone M4, and the fifth metatarsal bone M5 in the post-intervention measurement (Table 2).

The values achieved in the zone of the fifth metatarsal bone, M5, differed significantly in the pre-intervention measurement between the affected and non-affected limb in the experimental group and between the affected limb in the experimental group and the left limb in the control group. After the intervention, there was a decrease in the difference between the values of load distribution between the affected and non-affected limbs in the experimental group.

The values achieved in the big toe zone T1 measured before the intervention were higher for the affected limb in the experimental group by as much as 44% ($p < 0.05$), compared to the values achieved by the right limb in the control group. In the post-intervention measurement, a shift of the load to the zone of the first metatarsal bone M1 can be observed, where the values of variable Max F_M1 were significantly higher (by 41%) for the affected limb in the experimental group, compared to the measurement for the left limb in the control group ($p < 0.05$).

Before the intervention, the highest pressure during the run in the zone of the big toe (T1) was found in the affected limb. After the intervention, this trend shifted to the zone of the first metatarsal bone, M1.

The analysis of variance showed statistically significant differences between the studied groups in the impulse values in the following zones: the first metatarsal bone M1, the third metatarsal bone M3, the fourth metatarsal bone M4, the fifth metatarsal bone M5 and the big toe T1 in the post-intervention measurement (Table 3). Both before and after the intervention, the highest impulse values were found for the affected limb.

In the post-intervention measurement, the highest impulse values in the zone of the first metatarsal bone, M1, were found for the affected limb in the experimental group, and these values were higher by as much as 50% ($p < 0.05$) than the value measured in the left limb in the control group. Before the intervention, this difference was only 32%. In the big toe zone, T1, before the intervention, the impulse values were lower by 21% for the affected limb in the experimental group and by 17% for the non-affected limb in the experimental group than the values measured for the left lower limb in the control group. After the intervention, the values of the IMPULSE_T1 variable for the affected limb in the experimental group were lower than these measured for the left limb in the control group by 31% and the values of this variable were lower by 42% in relation to the values achieved by the right limb in the control group.

In the post-intervention measurement, the amplitude of the inter-group differences increased. In zone M4, the non-affected limb reached 38% ($p < 0.05$) higher values than the affected limb in the experimental group. In zone M5, in the post-intervention measurements after the intervention, the values found for the affected limb were lower by 66% ($p < 0.005$) than the values found for the left limb in the control group and lower by 50% ($p < 0.05$) than the values achieved for the non-affected limb in the experimental group. In the measurements performed in zones M4 and M5, there was a trend towards an increase in the differences between the results of both groups.

Table 3. The results of the analysis of variance ANOVA and ANOVA Kruskal–Wallis for the means of standardized IMPULSE values, in the after intervention anatomical zones of the foot, during the run, in all groups included into the experiment, before and after the intervention

Variable/ Group	IMPULSE_ M1 [$Nscm^{-2}kg^{-1}$]	IMPULSE_ M2 [$Nscm^{-2}kg^{-1}$]	IMPULSE_ M3 [$Nscm^{-2}kg^{-1}$]	IMPULSE_ M4 [$Nscm^{-2}kg^{-1}$]	IMPULSE_ M5 [$Nscm^{-2}kg^{-1}$]	IMPULSE_ HM [$Nscm^{-2}kg^{-1}$]	IMPULSE_ HL [$Nscm^{-2}kg^{-1}$]	IMPULSE_ T1 [$Nscm^{-2}kg^{-1}$]
E1F – E1NF	0.1199^{D}	0.5771^{T}	0.1415^{T}	0.2424^{D}	0.0596^{D}	0.7956^{D}	0.6281^{D}	0.2057^{T}
E1F – C1R								
E1F – C1L								
E1NF – C1R								
E1NF – C1L								
C1R – C1L								
E2F – E2NF	0.5766^{D}	0.5771^{T}	1.0000^{D}	0.8046^{T}	0.0333*^{D}	0.2666^{D}	0.7499^{D}	1.0000^{D}
E2F – C2R	1.0000^{D}		0.8698^{D}	0.1669^{T}	0.7156^{D}			0.1789^{D}
E2F – C2L	0.0272*^{D}		1.0000^{D}	0.3878^{T}	0.0013***^{D}			0.0898^{D}
E2NF – C2R	1.0000^{D}		0.4094^{D}	0.0192*^{T}	1.0000^{D}			0.0923^{D}
E2NF – C2L	1.0000^{D}		1.0000^{D}	0.8995^{T}	1.0000^{D}			0.0440*^{D}
C2R – C2L	0.5626^{D}		0.0298*^{D}	0.0024***^{T}	0.1960^{D}			1.0000^{D}

3.2. The analysis of the significance of differences between mean values of the maximum pressure Max *F* measured in the anatomical zones of the feet, during the run, in the studied groups before and after intervention

The analysis of the significance of differences between the variables from the first and second measurements using the *t*-test for dependent variables and the Wilcoxon test has shown that the majority of Max *F* values found during the second run of measurements were significantly lower than those found during the first measurements, both in the experimental and in the control group ($p < 0.05$). Two variables measured in the control group make an exception here: Max *F* in the M5 zone in the measurement for the left lower limb and in the T1 zone in the measurement for the right lower limb (Table 4).

Table 4. The results of the analysis of difference significance between mean values of maximum pressure Max *F* in the anatomical zones of the feet, during the run, for analogous variables in the study groups before and after intervention

Variable/ Group	Max *F*_M1 [$Ncm^{-2}kg^{-1}$]	Max *F*_M2 [$Ncm^{-2}kg^{-1}$]	Max *F*_M3 [$Ncm^{-2}kg^{-1}$]	Max *F*_M4 [$Ncm^{-2}kg^{-1}$]	Max *F*_M5 [$Ncm^{-2}kg^{-1}$]	Max *F*_HM [$Ncm^{-2}kg^{-1}$]	Max *F*_HL [$Ncm^{-2}kg^{-1}$]	Max *F*_T1 [$Ncm^{-2}kg^{-1}$]
E1F vs. E2F	0.1295 ^{t}	0.0003****^{t}	0.0001****^{W}	0.0090**^{W}	0.0111*^{t}	0.0007****^{t}	0.0008****^{W}	0.0000****^{t}
E1NF vs. E2NF	0.0014***^{W}	0.0010***^{t}	0.0020***^{t}	0.0045***^{W}	0.0750^{t}	0.0392*^{W}	0.0037***^{W}	0.0000****^{t}
C1R vs. C2R	0.0019***^{W}	0.1056^{t}	0.0075**^{t}	0.0006****^{t}	0.0087**^{t}	0.0008****^{W}	0.0011***^{W}	0.3542^{t}
C1L vs. C2L	0.0015***^{t}	0.0001****^{t}	0.0208*^{t}	0.2360^{W}	0.6148^{W}	0.0716^{W}	0.0050**^{W}	0.0053**^{t}

The largest statistically significant decrease in Max *F* (as much as 61%) was noted in the big toe zone, T1, in the measurement for the affected limb in the experimental group ($p < 0.001$) and a decrease (by 44%) in the measurement for the non-affected limb in the experimental group ($p < 0.001$). In the zone of the first metatarsal bone, M1, a statistically significant decrease in Max *F* was noted in the post-intervention measurements for the non-affected limb in the experimental group and for the right and left limbs from the control group ($p < 0.005$), by 37%, 39% and 36%, respectively. The decrease in the value of the Max F_M1 variable in the measurement for the affected limb in the experimental group was 15% and was not statistically significant.

In zones M4 and M5, the Max *F* value showed the most significant decrease in the measurements for the affected an non-affected limb in the experimental group and for the right limb in the control group, by 27%, 33% and 38%, respectively. There was a significant decrease in the Max *F* values for the zone of the transverse arch of the foot and in the heel zones, by 25 and 37% in the M2 and M3 zones and by 33 and 48% in the HM and HL zones, respectively, in all studied groups.

3.3. The analysis of the significance of differences between mean values of the IMPULSE measured in particular anatomical zones of the feet, during the run, in the studied groups before and after intervention

The analysis of the significance of differences between the variables from the first and second run of measurements using the *t*-test for dependent variables and the Wilcoxon test has shown that almost all results obtained in the second run of measurements were lower than these obtained during the first run, except for two variables in the control group: the impulse in the M5 zone in the measurement for the left limb and in the T1 zone for the right lower limb. Larger decreases in the impulse for the limbs in the experimental group were noted in the lateral heel zone, HL, while for the limbs in the control group – in the medial heel zone, HM (Table 5).

In zone M2, the largest decrease was found in the value of the impulse after the intervention in the measurement for the affected limb in the experimental group and this was 36% ($p < 0.001$). In zones M3 and M4, the largest decrease was noted in the measurement for the non-affected limb in the experimental group, by 33% and 36%, respectively. The decrease in the value in the M1 zone ranged from 18% in the measurement for the affected limb ($p > 0.05$), through 40% in the non-affected limb ($p < 0.005$) in the experimental group, to 41% in the measurement for the right limb in the control group ($p < 0.005$). The decrease of the value

Table 5. Results of the analysis of the significance of differences between mean values of the IMPULSE in the anatomical zones of the feet, during the run, for analogous variables in the study groups before and after intervention

Variable/ Group	IMPULSE_M1 [$Nscm^{-2}kg^{-1}$]	IMPULSE_M2 [$Nscm^{-2}kg^{-1}$]	IMPULSE_M3 [$Nscm^{-2}kg^{-1}$]	IMPULSE_M4 [$Nscm^{-2}kg^{-1}$]	IMPULSE_M5 [$Nscm^{-2}kg^{-1}$]	IMPULSE_HM [$Nscm^{-2}kg^{-1}$]	IMPULSE_HL [$Nscm^{-2}kg^{-1}$]	IMPULSE_T1 [$Nscm^{-2}kg^{-1}$]
E1F vs.E2F	0.0619 ^{W}	0.0001**** ^{t}	0.0003**** ^{t}	0.0033*** ^{t}	0.0061** ^{t}	0.0186* ^{W}	0.0006**** ^{t}	0.0015*** ^{W}
E1NFvs.EF	0.0012*** ^{W}	0.0032*** ^{t}	0.0037*** ^{W}	0.0033*** ^{W}	0.1154 ^{W}	0.0028*** ^{t}	0.0030*** ^{t}	0.0001**** ^{t}
C1R vs. C2R	0.0012*** ^{W}	0.0627	0.0026*** ^{t}	0.0004**** ^{t}	0.0061** ^{t}	0.0003**** ^{W}	0.0007**** ^{W}	0.2142 ^{t}
C1L vs. C2L	0.0030*** ^{W}	0.0002**** ^{t}	0.0014*** ^{W}	0.0446* ^{t}	0.6639 ^{W}	0.0013*** ^{t}	0.0130* ^{W}	0.0182* ^{t}

in the M5 zone ranged from 20% in the measurement for the non-affected limb ($p > 0.05$) to 43% in the measurement for the affected limb ($p < 0.01$) in the experimental group. After the intervention, there was a significant decrease in the IMPULSE values in the big toe zone, T1, mainly in the measurements for limbs in the experimental group. The decrease in the value of the IMPULSE_T1 variable was 42% in the measurement for the affected limb ($p < 0.005$) and 50% for the non-affected limb ($p < 0.001$). The values of this variable also decreased in the measurements for the left limb ($p < 0.05$) in the control group.

4. Discussion

Load distribution within the feet during a run means the way in which body weight is transferred to the feet during each step in the contact phase. During the initial contact of the limb with the ground, the reaction forces are transmitted to the foot and, depending on the speed of the run, they can reach values several times the weight of the runner [27]. During the shock absorption phase, the foot takes a pronated position, which allows for lowering of the peak values of the force or pressure during the impact of the foot against the ground and absorption of some energy. When the foot is in full contact with the ground, its load distribution changes and the load shifts mainly to the middle part of the foot. This stabilizes the foot and prepares it for the propulsion phase. During the propulsion phase, the foot bounces off the ground and generates a force that allows to accelerate the run. During this phase, the foot changes its position from pronation to supination, which allows to reduce pressure on the metatarsophalangeal joints [22].

The optimal distribution of the ground reaction forces to the foot during the run depends on many factors: the individual characteristics of the runner, the speed of the run, the type of the surface and the technique of the run. Experienced long-distance runners begin the contact with the ground from the mid-foot. Reduction of the pressure on the heel and shift of the load to the mid-foot and toes is often considered beneficial for the runners. A balanced distribution of load across the feet can help to prevent injuries and improve run quality [3].

The RS Footscan platform was used to assess the foot load distribution in this work [38]. Many studies have shown that it is a reliable tool for the assessment of the dynamic distribution of the pressure on the sole of the foot when walking barefoot and for the assessment of the impact of fatigue on the distribution of the foot load during the run [5], [10], [13], [17]–[19], [23], [29], [37]. Heiderscheit et al. [15] report on the effect of a 20-kilometre run on the distribution of the feet load – a long run caused changes in the distribution of foot pressure measured on the platform. In particular, the heel and forefoot pressure increased, while the mid-foot pressure decreased. Additionally, the study found that runners with different styles of foot hit against the ground (heel, mid-foot) had similar changes in the distribution of foot pressure after they finished the run. The authors conclude that a long run can lead to changes in the distribution of foot pressure, which in turn can worsen run performance and increase the risk of overload injuries. In this work an attempt was made to analyse the variables of the distribution of foot pressure during a barefoot run. Running without shoes allows to observe the natural work of the foot; running in shoes can mask possible pathologies in the foot load due to the cushioning and elastic properties of the soles of the shoes.

A report by Anbarian et al. [2] evaluated the effect of running-induced fatigue on the parameters of pressure of the sole of the foot on the ground in novice runners. The maximum reaction force and impulse in the individual anatomical zones of the feet were measured with the use of the RS Footscan platform in 21 runners with high longitudinal foot arch and 21 runners with low longitudinal foot arch before and after a fatigue protocol in the form of a run at a pace of 3.3 ms^{-1}. Time phases of foot pressure on the ground and the medial to lateral foot side pressure ratio before and after the fatigue protocol were also determined. In the subjects with a low longitudinal arch of the foot, an increase in the maximum reaction force under the first and third metatarsal bone zones and a decrease in this force under the fourth and fifth zones were observed after the run. In the subjects with a high longitudinal arch of the foot, an increase in the peak pressure under the fourth and fifth zones of the metatarsal bones was observed after the protocol. To sum up, it can be concluded that run-induced fatigue intensifies pressure in zones adequate to the type of foot anatomy [2]. In this work, the lowest load values before the intervention in the affected limb were observed in the zone of the fifth metatarsal bone and the highest ones – in the big toe zone. This means that runners with FAI showed asymmetry in the foot load distribution; there was no such observation in the control group. As far as the impulse is concerned, relatively high values were shown for the affected limb in the zone of the first metatarsal bone and low values – in the big toe zone, as compared to the other lower limbs examined. In the zones of the fourth and fifth metatarsal bones, relatively high values of the impulse were found for the non-affected limb, and low values – for the affected limb, relative to the limbs of the control group. This means that there is a high load in the area of the first metatarsal bone and of the big toe in the affected limb which translates into a weaker propulsion from the big toe of this limb. Furthermore, also the outer edge of the foot is underloaded, which suggests its pronation and valgisation of the ankle joint. To the contrary, the non-affected limb, is overloaded on the external side of the foot, which in turn suggests supinatory foot position and varisation of the ankle joint.

The relationships described above have a probable explanation in the compensation mechanism. Puszczałowska-Lizis i Omorczyk [32] pointed out that during training, due to the multiple repetition of the same exercise typical for a specific discipline, sportsmen tend to work out various compensation strategies. According to the authors, this is the result of the specifics of the training itself in each sports discipline. In own research due to movement limitation and weakening of the abductor muscles in the hip joint on the affected limb side, there may be an increase of the impulse in the zone of the first metatarsal bone and of the big toe [20]. Thus, for a stable support, the body weight transferred to the ground by the healthy lower limb may cause an overload of the outer edge of the foot [33]. Such an asymmetric load distribution can lead to a number of consequences associated with motor system overload in specific anatomical areas of the foot and result in an incorrect running technique. Additionally, the observed low impulse in the big toe zone of the affected limb may be indicative of the lack of effective big toe propulsion during the run. Therefore, people with FAI heavily load the inner side of the foot of the affected limb, especially the big toe, and underload the outer edge of the foot. In contrast, the non-affected limb is heavily loaded on the outer edge.

In the context of the dynamics of pressure force changes as a function of the time of contact with the ground during the propulsion phase, there was no difference between the experimental and control groups. The obtained results can be related to the results of studies that showed increased pressure on the medial side of the foot during walking in footballers with an increased alpha angle in the hip joint [21]. The compensation mechanism in hip joint disorders is reflected in the asymmetry of foot load distribution [11], [25]. Due to the pioneering nature of this FAI runner research and infrequent use of the Footscan platform, continuation of this research seems advisable.

The authors of this paper, after the use of a therapeutic intervention, showed a decrease in the Max F value in a large part of the foot zones in all examined limbs. A higher percentage value of the decrease in the Max F in the M4 zone in the measurement for the non-affected limb, as compared to the value of this decrease for the affected limb, points to a trend to reduce the disproportions in the load distribution within the outer edges of the feet between the limbs in the experimental group. Importantly, before the intervention, the limbs in the experimental group reached much higher Max F values in the big toe zone, compared to the limbs in the control group. Before the intervention, the highest pressure on the big toe zone during the run was found in the affected limb. The decrease in the value of this variable in the post-intervention measurement indicates a trend to equalize the value of the maximum pressure in the big toe zone among the studied groups. After the intervention, this trend shifted to the zone of the first metatarsal bone. A clear underload of the outer edge of the foot in the affected limb visible before the intervention persisted after the intervention, however, its value decreased in relation to the control group. Before the intervention, the highest load in the non-affected limb was noted in the zone of the fifth metatarsal bone and after the intervention this trend was shifted to the zone of the fourth metatarsal bone. As a result of the applied exercise protocol, there was a reduction of the disproportion in the distribution of the load of the outer edge of the foot between the limbs in the experimental group. A greater decrease in the maximum reaction force measured during the run in the heel zones with lower decrease of values of this variable in the zones of the transverse arch of the foot points to a shift of the higher loads to the forefoot in the post-intervention measurement.

The results of this study also show a decrease in the value of the impulse measured during the run in people with FAI in the examination after the intervention. The greatest decrease in the mean value of the impulse was observed in the heel zones. Larger decreases in the impulse for the limbs in the control group were noted in the medial heel zone, while for the limbs in the experimental group – in the lateral heel zone. In the experimental group, there were significant decreases in the impulse in the transverse foot arch zones of the foot. However, there was only a moderate decrease of the values of this variable in the zones of the first and fifth metatarsal bones.

After the intervention, symmetrisation of the foot load in the subjects with FAI was observed; the load of the big toe of the affected limb decreased. There was a favourable trend in the experimental group – a decrease of the load of the transverse arch zones during the propulsion phase. The applied exercise protocol had a positive effect on the distribution of the foot load in the subjects with respect to symmetrisation of the pressure and relief of the big toe and transverse arch, at the cost of a higher load in the area of the first and fifth metatarsal bones, anatomically adapted to transfer loads. A positive change resulting from the introduction of conservative treatment was reflected in a trend to shift pressure zones and maximum pressure values in the propulsion phase toward the forefoot.

The results cited above indicate an extremely favourable phenomenon – an improvement in the coordination of the foot rolling through the ground in all phases of its contact with the ground during the run. After the intervention, runners used their muscle strength more effectively in both the absorption and propulsion phases, using less energy for a run at the same speed.

The results obtained are consistent with the recommendations on the optimal load on the feet during a run, when excessive pressure on the heel and on the forefoot should be avoided [30]. Excessive pressure on the heels can lead to lower limb overload and, among other things, to inflammation of the plantar aponeurosis. However, excessive pressure on the front part of the foot, in turn, may cause fatigue of the anterior shin muscles and foot joint overload [15]. It is also important to avoid hitting the heel against the ground, which can cause excessive transfer of forces to the structures of the lower limbs, pelvis and spine, and thus excessive exploitation of the shock absorbing mechanisms of the motor system. Instead, it is recommended to place the foot on the ground in a smooth and gentle manner, using the foot as a shock absorber, to reduce the pressure in the individual zones of the foot as well as the total pressure of the entire foot [36].

Standardization of the results to body weight during the analysis allowed for a clearer picture of the foot load during the run as compared to the previous reports.

5. Conclusions

After the completion of the physiotherapy protocol, the FAI group differed significantly from the n-FAI group in relation to the Max F range in the areas of the first, fourth and fifth metatarsal bones and as far as the force impulse in the areas of the first, fourth, and fifth metatarsal bones and in the big toe area. After the intervention, in the experimental group there was a shift of the highest Max F during the run from the big toe area to the area of the first metatarsal bone in the affected extremity. In the post-intervention measurement, the highest impulse values in the zone of the first metatarsal bone, were found in the affected limb in the experimental group. The affected limb was found to have the highest impulse values among all the limbs, both before and after the intervention. A comparison of the results of the initial and control run of tests showed more positive changes in the FAI group than in the n-FAI group. This demonstrates a favourable effect of the physiotherapy protocol on people with FAI. The observations made in this paper, documented by the results of the analyses, allow for practical use of the proposed proprietary, 6-month physiotherapy protocol and a comprehensive, objective protocol for the monitoring of changes in the motor system, in the conservative treatment of physically active people with FAI.

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