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The influence of minimalist and conventional sports shoes and lower limbs dominance on running gait

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Purpose: The aim of this study was to determine how minimalist running shoes (MRS), conventional running shoes (CRS) and the dominance of lower limbs influence the running gait. *Methods*: Trained recreational runners ($N = 13$) who have been engaged in regulary running for more than one year were participants in this study. They were experienced with using MRS and CRS for more than half year and they used both types of shoes. An in-shoe pressure measuring system (Pedar-X®, Novel, Munich, Germany) was used to monitor plantar pressure and vertical force and the temporal parameters when running in MRS and CRS during the stance phase, the swing phase and over one stride. *Results*: Running in CRS significantly prolonged stance, swing and stride phases by 2–11%, compared to MRS. In contrast, when running in MRS significantly larger values of maximum pressure (9–14%) and maximum vertical force (3–7%) than in CRS were found. *Conclusions*: For this reason, running in MRS could be recommended to recreational runners only with care. The effect of limb dominance on temporal characteristics was detected when running in CRS. Significantly longer stance phase for dominant limb is associated with a shorter swing. The kinematics variables were significantly higher for dominant limb than for non-dominat limb when running in MRS and CRS (by 12–23%).

Key words: *laterality, kinematic analysis, ground reaction forces, running*

1. Introduction

Running is one of the oldest and most natural human movements and running shoes play an important role in influencing the mechanics of running. In recent years, there has been a significant increase in the interest in barefoot running and running in minimalist running shoes (MRS). The newest definition describes MRS as a "footwear providing minimal interference with the natural movement of the foot due to its high flexibility, low heel-to-toe drop, weight and stack height, and the absence of motion control and stability devices" [1].

Numerous studies have scientifically assessed the impact of different shoes while running [2]–[4]. In the literature three types of foot-strike patterns are described: rearfoot strike (RFS) involves "heel-toe" running in which initial ground contact is made by the rear third of the foot; midfoot strike (MFS) or "toe-heel-toe" running in which initial contact is made on the metatarsal heads and there is a subsequent contact of the heel; and forefoot strike (FFS) in which the initial ground contact is made across the metatarsal heads [5]. The foot-strike pattern may vary depending on the type of the footwear used. A change in the foot-fall characteristics reportedly occurs in runners switching from running in conventional running shoes (CRS) to running barefoot or running in MRS, usually from RFS to MFS or FFS [4], [6]–[9].

The type of footwear also reportedly affects the magnitude of the vertical ground reaction forces during running. For the same type of foot-strike pattern, impact forces are higher in MRS than for CRS [10], [11], which is why runners using MRS modify their foot-strike pattern in order to reduce these impact

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forces [9], [10]. Changing footfall patterns when running in MRS can lead to a reduction in stride length [3], [8], [9]. Moreover, it has been suggested that changing the hardness of shoes will also change various kinematic parameters whereas the total magnitude of the impact forces may not change [12]. Significant differences in contact time, flight time, stride time, stride length and stride frequency between MRS and CRS were observed by Mann et al. [13]. Bergstra et al. [2] demonstrated significantly shorter stance phase in a group of amateur female runners using MRS (0.238 s), compared to CRS (0.247 s), but found no statistically significant difference between the duration of the swing phase (0.483 *vs.* 0.501 s) or the stride phase (0.720 *vs.* 0.748 s). The inconsistency in the research literature concerning these effects may be related to the various studies involving different groups of people with different running experiences [6], [14], [15].

In the sports literature there are diverse opinions about the importance of lateral symmetry in running. The right leg is favoured among 76–86% of the general population [16], which raises the question whether this limb dominance can affect running symmetry. Pappas, Paradisis, and Vagenas [17] found asymmetry between the dominant and non-dominant legs in some characteristics of running gait. Moreover, the bilateral difference in running biomechanics can reportedly be influenced by footwear conditions [18]. However, asymmetry in running appears to be mainly caused by differences in muscle strength, motion, flexibility, balance and mechanics between the two sides of the body and small variations in other factors, such as leg length, scoliosis, joints and pain [19].

The controversy concerning the relationship between temporal and force characteristics of gait when running in different types of running footwear needs to be resolved. Therefore, the first aim of the present study was to determine how minimalist running shoes (MRS) and conventional running shoes (CRS) affect temporal and kinetic variables of the running gait. The next aim of the study was to determine whether lower limb dominance influences running gate in MRS and CRS. In previous studies we have not found the answer to this question. In this study, the hypothesis that there are significant differences in the measured variables of running gait between running in MRS or CRS was tested. With regard to the theoretical assumption of the running-gait symmetry, we assumed that there would be no significant differences between the measured variables for DL and NDL even when running in different shoes.

2. Materials and methods

Participants

A group of 13 experienced recreational runners (7 men and 6 women; mean age 34.10, $SD = 6.22$ years, mean body height 1.73, $SD = 0.05$ m, mean body mass 65.80, $SD = 5.87$ kg), who had been engaged in running for more than one year, participated in this research. The participants had trained regularly (they had run at least 4 times a week for more than 1 year and they had run more than 30 km a week. They use MRS at 2 times a week, lieast for more than half year. The study was approved by the Institutional Review Board for testing of human subjects (protocols were performed under license obtained from this board) and were performed in accordance with the ethical standards of the Helsinki Declaration.

Data collection

A Pedar-X® system was used to analyze the stance and flight phases of the running gait. This system allows measurement of longer part of the run than that measured using external force plates combined with 3D kinematic analysis. Multistep measurement provides a more objective analysis. The reaction force perpendicular to the surface was detected by measuring insole with 99 sensors. This measuring system allows data to be recorded to the inner memory with the frequency of 100 Hz. Stored data were downloaded to the computer after the measuring has finished. Measuring insoles enable, in general, to record data with lower frequencies than force plates, but they offer to record data outside the lab and in unlimited space. The accuracy of the Pedar-X® system is ±5%. Participants ran in both MRS (Nike Free 3.0) and CRS (Asics GT-2000). Shoes were new and in different sizes. These types of shoe were used by runners most often.

Protocol

Data were collected for each subject during a single session. The participants were first familiarized with the experimental protocol and subsequently signed an informed consent form. At the beginning of the data collection, anthropometric data (body weight mass, and age) were recorded. The dominant lower extremity limb was determined using a questionnaire [20], [21]. Right DL, defined as kicking a ball with the right foot and taking off in the long jump and the high jump with the left foot, was present in 11 subjects, while left DL, defined as kicking a ball with the left foot and taking off in the long jump and the high jump with the right foot, was present in 2 participants. In terms of limbs dominance, the participants were characterized according to the DL and NDL lower limb (criteria). Data were collected after warming up (duration of 15 minutes, comprising a 1200-m run at moderate intensity, dynamic warm-up and two 80-m sprints). The participants ran 800 m at their preferred speed for long-distance running on the track ($v = 4.50 \pm 0.18$ m/s) and with their habitual foot-fall pattern. The data for the run were always obtained when they were running along a straight 70 m long section that was 500 m from the start. The run in this section was measured and the average speed was calculated (photocells were placed at the beginning and at the end of the 70 m section), for both CRS and MRS. For all participants, the measurements for the first type of shoe were made first, followed by 10 minutes of rest and recalibration of the system, after which the measurements for the second type of shoe were made. At the beginning of each run, the system for measuring the in-shoe pressure was calibrated when standing on one leg separately for each shoe in accordance with the manufacturer's recommendations (Pedar-X®, Novel, Munich, Germany).

Data analysis

Peak pressure [$PP(t)$] and maximal vertical force [$MVF(t)$] were used to evaluate the following temporal and kinetics variables. Temporal variables determined were: duration of the stance phase (STANCE), duration of the swing phase (SWING), duration of one stride (STRIDE). The magnitudes of the kinetics variables were normalized per kg of body mass (BM): maximum pressure per kg of body mass (PP_{rel}), and maximum vertical force per kg BW (MVF_{rel}). [$PP_{rel} = PP_{max}$/kg and $MVF_{rel} = MVF_{max}/G$, where G is the gravitational force acting on the body]. Temporal variables and PP_{max} were evaluated using $PP(t)$ (Fig. 1) and MVF_{max} using $MVF(t)$]. 26 to 28 steps were evaluated over the 70-meter measurement section. The resulting data for DL and NDL are the mean values calculated from 13 to 14 steps on each leg. The number of steps for the analysis was based on the individual length of the step on the measured section. The coefficients of variation (CVs) of the calculated mean values were 1–3%.

Statistical analysis

Given that some variables did not conform to a normal distribution, a non-parametric Wilcoxon test was used for repeated measurements when testing the study hypothesis. Effect size (ES) [22] and paired t-tests values were also calculated. The paired t-tests were used only for assessments on data that were normally distributed. Computed statistical values were considered significantly different when $p \leq 0.05$. All statistical data are reported as mean ± SD values. Calculations were carried out using the MATLAB program (MathWorks, Natick, MA, USA).

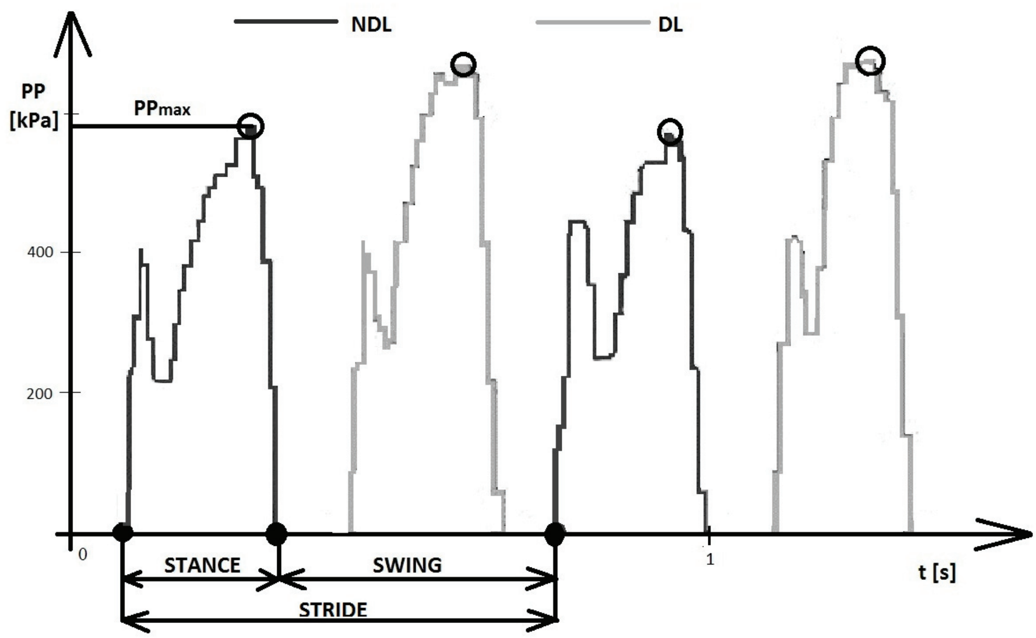

Fig. 1. Schematic representation of the measured time variables and PP_{max} variable. Legend: Temporal variables: STANCE (s), duration of the contact phase; SWING (s), duration of the swing phase; STRIDE (s), duration of one stride. Kinetics variables: PP (kPa), PP_{max} (kPa), maximum pressure. DL, dominant lower limb; NDL, non-dominant lower limb

3. Results

Influence of shoe type on running gait

Statistically significant differences in running in MRS and CRS were detected in most of the temporal and kinetics variables for DL and NDL (Table 1). The durations of STANCE, SWING and STRIDE for both limbs were significantly shorter when running in MRS than in CRS; that is, in the range of 4–11% of the MRS values (only for the swing phase for DL; the 2% difference was not statistically significant). The observed PP_{rel} values for the dominant and non-dominat limbs were by 9 and 14% higher for MRS than for CRS ($p \leq 0.01$; $p \leq 0.05$). The MVF_{rel} values were by 7 and 3% for MRS but the differences were not statistically significant ($p > 0.05$). The ES values of MVF_{rel} (0.33 and 0.81 for the DL and NDL, respectively) suggest that there are significant differences in this variable between the MRS and CRS for both limbs.

Influence of lower limbs dominance on running gait

Statistically significant differences between DL and NDL were found in several variables for running in CRS (Table 1). When running in MRS, the only temporal variable for which there was a statistically significant difference between DL and NDL was the duration of SWING. However, the ES of 0.16 indicates low clinical relevance. When running in MRS, the ES values were very low for all three temporal variables (ES = 0.03 to 0.17) and the differences between DL and NDL in the range of 2–4% can be considered non-significant. When running in CRS, the differences between DL and NDL for the time variables of the durations of the swing phase and one stride were statistically significant. The duration of stride when running in CRS differed only slightly (as a percentage it was identical) and the significance of the differences expressed by ES = 0.06 was negligible in this case. Significant differences between DL and NDL when running in CRS can be considered only for the temporal variables of the durations of SWING ($p \leq 0.05$, ES = 0.51) and STANCE (ES = 0.71) phases. The duration of STANCE was by 7% longer for DL, while the one for SWING was by 4% shorter compared with NDL.

The significance of the differences between DL and NDL in the PP_{rel} and MVF_{rel} variables is confirmed both statistically ($p \leq 0.05$; ES = 0.68 to 1.50). The values of kinetics variables were always higher for DL when running in both MRS and CRS.

Table 1. Differences in measured variables when running in MRS and CRS

	MRS				CRS				MRS *vs.* CRS		
	Mean ± SD	DL *vs.* NDL			Mean ± SD	DL *vs.* NDL			% CRS	*p*	*d*
		% NDL	*p*	*d*		% NDL	*p*	*d*			
STANCE (s)											
DL	0.185 ± 0.017	98	0.133	0.17	0.206 ± 0.025	93	0.291	0.71	111	**0.011**	0.98
NDL	0.182 ± 0.018				0.191 ± 0.016				105	**0.046**	0.53
SWING (s)											
DL	0.446 ± 0.027	104	**0.046**	0.16	0.453 ± 0.036	104	**0.011**	0.51	102	0.291	0.22
NDL	0.450 ± 0.023				0.470 ± 0.033				104	**0.011**	0.93
STRIDE (s)											
DL	0.631 ± 0.034	99	0.500	0.03	0.659 ± 0.036	100	**0.046**	0.06	104	**0.002**	0.92
NDL	0.630 ± 0.034				0.661 ± 0.033				105	**0.002**	0.91
PP_{rel} (kPa/kg)											
DL	9.376 ± 2.073	88	0.133	0.68	8.547 ± 2.201	83	0.134	0.79	91	**0.002**	0.39
NDL	8.226 ± 1.238				7.076 ± 1.420				86	**0.046**	0.86
MVF_{rel} (N/G)											
DL	3.325 ± 0.746	78	0.133	1.23	3.098 ± 0.643	77	**0.046**	1.50	93	0.133	0.33
NDL	2.603 ± 0.359				2.370 ± 0.187				97	0.500	0.81

Legend: MRS – minimalist running shoes; CRS – conventional running shoes; DL – dominant lower limb; NDL – non-dominant lower limb; STANCE – duration of the contact phase; SWING – duration of the swing phase; STEP – duration of one step; PP_{rel} – maximum pressure per 1 kg of body weight (PP_{max}/kg, where kg is the body weight); MVF_{rel} – maximum vertical force per 1 kg of body weight (MVF_{max}/G, where $G = m \cdot g$, $g = 9.81\ m \cdot s^{-2}$); % NDL – value for NDL as a percentage of the DL value (DL = 100%); % CRS – value for CRS as a percentage of the MRS value (MRS = 100%); *P* – significance level in the Wilcoxon test; $P < 0.05$ indicated by boldface; *d* – Cohen effect size.

4. Discussion

The purpose of this study was to determine how the shoe type and the lower limbs dominance influence the running gait.

Influence of shoe type on running gait

Differences were found between running in MRS or CRS in both temporal and kinetic variables. In terms of the duration of the phases of the running gait, the differences were largest for the foot contact with the ground (STANCE). When using MRS, the STANCE phase was significantly shorter (by about 5 and 11% for the left and right legs, respectively), which is consistent with the literature [2], [13]. The shorter stance phase is probably caused by the lack of a rearfoot heel strike when using the thin soles of MRS, compared to running in CRS. The swing and stride durations when running in MRS were significantly shorter than when running in CRS, probably as a result of a higher stride frequency [3], [8], [9]. Only during the swing phase there was the difference between MRS and CRS supporting previous findings [2].

The kinetic variables PP_{rel} and MVF_{rel} always had larger magnitudes when running in MRS than in CRS. The missing heel strike while running in MRS reduces the foot contact with the ground. During the same impact of the foot with the surface, PP_{rel} should increase resulting in a significant difference between MRS and CRS (9 and 14% for the left and right legs, respectively). The relatively small amount of cushioning of MRS combined with a smaller area of contact are the main causes of this phenomenon [10], [11]. Plantar pressure values indicates increased pressure at the foot. It is known that running with MRS influences not only spatio-temporal stride characteristics but also some kinematic parameters like knee angles and hip vertical displacement [9]. The values of MVF_{rel} were higher when using MRS (by 7 and 3% for the left and right legs, respectively), but the differences between the MRS and CRS were not statistically significant. Given the high values of ES (ES = 0.33 and 0.81) for MVF_{rel}, the substantive significance of the differences between the two shoe types should also be taken into consideration.

Effect of lower limbs dominance on running gait

When running in CRS, the effect of dominance of lower limbs appeared to be more important compared to MRS. The differences were statistically significant for SWING when running in either shoe type ($p \leq 0.05$), but not for STANCE ($p > 0.05$). A longer duration of the STANCE for DL when running in CRS suggests a substantive significance of the difference between DL and NDL for this shoe type. A similar situation has been demonstrated less significantly when running in MRS. It can be assumed that the longer contact time of DL with the ground (Table 1) the higher the effect of muscle strength during the take-off, which might be reflected in higher values of kinetics variables on DL when running in both shoe types.

There were minimal differences in the duration of STEP between PRE and NPR when running in MRS and CRS. A combination of a longer stance phase and a shorter swing phase for PRE when running in CRS could have resulted in balanced STRIDE durations for DL and NDL for both shoe types.

The effect of limb dominance significantly affected the kinetic variables where the percentage differences between DL and NDL were higher than for the temporal variables. PP_{rel} and MVF_{rel} were larger for DL when running in either shoe type. The differences between DL and NDL in the kinetic variables were significant only for MVF_{rel} when running in CRS ($p \leq 0.05$). The ES range of 0.68–1.50 for the kinetics variable nevertheless suggested that the differences between DL and NDL can be considered objectively relevant. When running, higher values of kinetics variables for DL are in conformity with the one-foot take off analysis results, where a higher reactive strength index and power in jump were achieved [23]. If the running speed is theoretically the same when running in CRS and MRS, the shorter STANCE for NDL, from a biomechanical perspective, necessitates the production of a higher level of force (theoretically, the impulse of reaction force in both cases should have the identical value). This theoretical reasoning is confirmed by the values of kinetics variables for DL and NDL being higher when running in MRS.

The fundamental cause of injuries is thought to be the magnitude of the forces acting on the musculoskeletal system. The results of this study suggest that differences in the magnitudes of kinetics variables are influenced by shoe type and also by the lower limbs dominance. The type of running shoes had greater effect on the kinetics variables, with the effect of the dominant limb having a smaller effect. If the forces acting on the musculoskeletal system while running in MRS are higher [10], [11], and the current research results indicate that they are, the following question needs to be considered: what are the benefits of running in MRS compared to CRS? One positive factor of wearing MRS while running is preventing overloading of the heel resulting from a change in the footstrike pattern [9], [11]. The local pressure on the heel can be reduced by adopting a flatter foot placement (i.e., a midfoot footfall pattern) since then the initial ground contact covers a larger plantar area [10]. Miller et al. [24] found that runners using MRS developed significantly stiffer arches with relatively larger crosssections for several of the intrinsic foot muscles indicating that the foot adapted to the greater demands required by such type of shoes. The results of the present study suggest that the benefits of running in MRS mentioned in literature are associated with higher values of the forces measured when running in this shoes. Chen, Sze, Davis, and Cheung [25] mention foot muscle growth in the forefoot area when using MRS. However, the long-term use of MRS could result in the above-mentioned higher forces acting on the musculoskeletal system, increasing the risk of injury. For both shoe types, such tendency is more pronounced for DL in which the force affecting the musculoskeletal system when running is higher than for NDL.

The hypothesis that there are significant differences in the measured variables of running gait between running in MRS or CRS was confirmed. There were some significant differences between the measured variables for DL and NDL. Our assumption that there would be no significant differences between the measured variables for DL and NDL even when running in different shoes was not confirmed.

Limitations of this study include the fact that the participants (both men and women) ran at their preferred speed for long-distance running. However, their speed range was small ($v = 4.50 \pm 0.18$ m/s). The nonparametric Wilcoxon test was combined with a statistical evaluation based on the ES. The hypotheses were also verified by paired t-tests, the results of which due to some of the variable not conforming to a normal distribution have not been reported here. The results obtained when testing the significance of differences between the two pairs of variables (MRS *vs.* CRS and DL vs. NDL) using the Wilcoxon test and the paired t-test were identical in most cases. The ES values were particularly high for the kinetics variables (0.68 to 1.54), which suggested the substantive significance of the differences. However, the Wilcoxon test did not confirm this in some cases. The differences between the results for both kinetic variables may be related to the cohort including both women and men. The strength exhibited by females is typically 60–70% of male strength [15], and the measured values of the kinetic variables showed a large variance (CV ranging from 15 to 25%), compared to the temporal variables (CV < 10%). Above mentioned facts could have resulted in some differences in the statistical evaluations of hypotheses between the Wilcoxon test and ES. However, one positive feature of this study was the inclusion of a homogeneous group of healthy people characterized by long-term and regular usage of both MRS and CRS for recreational running. In the next stage of this research it could be useful to focus on racing runners.

5. Conclusions

In conclusion, therefore, it can be emphasised, that the present results have revealed a significant effect of minimalist running shoes (MRS) and conventional running shoes (CRS) and of a lower limbs dominance on the running gait. The durations of STANCE, SWING and STRIDE of the running gait were significantly longer when running in CRS than in MRS. More significant differences between the MRS and CRS were found in the kinetic variables PP_{rel} and MVF_{rel}. When running in MRS, the kinetic variables were significantly higher than when running in CRS.

There were no significant differences in the time of one stride between the dominant leg and the non-dominant leg during running in both the MRS and the CRS and the running gait, from a laterality perspective is symmetrical. The effect of lower limb dominance on temporal characteristics was detected only when running in the CRS. A significantly longer stance phase associated with a shorter swing phase was detected for the dominant leg, compared to the non-dominant leg. When running in the CRS, running gait symmetry is achieved by a combination of longer stance phase and a shorter swing phase on the dominant leg. The above-mentioned time characteristics are associated with higher values of the kinetics varibles on the dominant leg while running in the MRS or the CRS. In terms of injury prevention, two risks factors associated with higher values of kinetics variables during running in the MRS and also on the dominant leg can be mentioned. These results of the study are initiative for further research of lower limb dominance in relation to the different running shoe or insole design and injury prevention.

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References

[1] ESCULIER J.F., DUBOIS B., DIONNE C.E., LEBLOND J., ROY J.S., *A consensus definition and rating scale of minimalist shoes*, J. Foot Ankle Res, 2015, 8, 42, DOI: 10.1186/s13047-015-0094-5.

[2] BERGSTRA S.A., KLUINTENBERG B., DEKKER R., BREDEWEG S.W., POSTEMA K., VAN DEN HEUVEL E.R et al., *Running with a minimalist shoe increases plantar pressure in the fotefoot region of healthy female runners*, J. Sci. Med. Sport, 2015, 18, 463–468, DOI: https://doi.org/10.1016/j.jsams.2014.06.007.

[3] BONACCI J., SAUNDERS P.U., HICKS A., RANTALAINEN T., VICENZINO B.G., SPRATFORD W., *Running in a minimalist and lightweight shoe is not the same as runninsg barefoot: a biomechanical study*, Br. J. Sport Med., 2013, 47(6), 387–392, DOI: 10.1136/bjsports-2012-091837.

[4] HEIN T., GRAU S., *Can minimal running shoes imitate barefoot heel-toe running patterns? A comparison of lower leg kinematics*, J. Sport Health Sci., 2014, 3, 67–73, DOI: http://dx.doi.org/10.1016/j.jshs.2014.03.002.

[5] HASEGAWA H., YAMAUCHI T., KRAEMER W.J., *Foot strike patterns of runners at the 15-km point during an elite-level half marathon*, J. Strenght Cond. Res., 2007, 21, 888–893, DOI: 10.1519/R-22096.1.

[6] AHN A.N., BRAYTON C., BHATIA T., MARTIN P., *Muscle activity and kinematics of forefoot strike runners*, J. Sport Health Sci., 2014, 3, 102–112, DOI: http://dx.doi.org/10.1016/j.jshs.2014.03.007.

[7] HAMILL J., RUSSELL E.M., GRUBER A.H., MILLER R., *Impact characteristics in shod and barefoot running*, Footwear Science, 2011, 3(1), 33–40, DOI: http://dx.doi.org/10.1080/19424280.2016.1142002.

[8] LIEBERMAN D.E., VENKADESAN M., WERBEL W.A., DAOUD A.I., D'AEANDREA S., DAVIS I.S. et al., *Foot strike patterns and collision forces in habitually barefoot versus shod runners*, Nature, 2010, 463, 531–535, DOI: 10.1038/nature08723.

[9] SQUADRONE R., GALLOZZI C., *Biomechanical and physiological comparison of barefoot and two shod conditions in experienced barefoot runners*, J. Sports Med. Phys. Fitness, 2009, 49, 6–13.

[10] DE WIT B., DE CLERCQ D., AERTS P., *Biomechanical analysis of the stance phase during barefoot and shod running*, J. Biomech., 2000, 33, 269–278, DOI: https://doi.org/10.1016/S0021-9290(99)00192-X.

[11] DIVERT C., MORNIEUX G., FREYCHAT P., BALY L., MAYER F., BELLI A., *Barefoot-shod running differences: shoe or mass effect?*, Int. J. Sports Med., 2008, 29, 512–518, DOI: 10.1055/s-2007-989233.

[12] HENNIG E., VALIANT E.G., LIU Q., *Biomechanical variables and the perception of cushioning for runninsg in various types of footwear*, J. Appl. Biomech., 1996, 12, 141–150.

[13] MANN R., MALISOUX L., URHASEN A., STATHAM A., MEIJER K., THEISEN D., *The effect of shoe type and fatigue on strike index and spatiotemporal parameters of running*, Gait & Posture, 2015, 42, 91–95, DOI: 10.1016/j.gaitpost.2015.04.013.

[14] LIEBERMAN D.E., *Strike type variation among Tarahumara Indians in minimal sandals versus conventional running shoes*, J. Sport Health Sci., 2014, 3, 86–94, DOI: http://dx.doi.org/10.1016/j.jshs.2014.03.009.

[15] MILLER A.E., MACDOUGALL J.D., TARNOPOLSKY M.A., SALE D.G., *Gender differences in strength and muscle fiber characteristics*, Eur. J. Appl. Physiol. Occup. Physiol., 1993, 66 (3), 254–262.

[16] BELL J., GABBARD C., *Foot preference changes through adulthood*, Laterality, 2000, 5, 63–68, DOI: http://dx.doi.org/10.1080/713754351.

[17] PAPPAS P., PARADISIS G., VAGENAS G., *Leg and vertical stiffness (a)symmetry between dominant and non-dominant legs in young male runners*, Hum. Mov. Sci., 2015, 40, 273–283, DOI: 10.1016/j.humov.2015.01.005.

[18] BROWN A.M., ZIFCHOCK R.A., HILLSTROM H.J., *The effects of limb dominance and fatigue on running biomechanics*, Gait and Posture, 2014, 39, 915–19, DOI: https://doi.org/10.1016/j.gaitpost.2013.12.007.

[19] DICHARRY J., *Anatomy for Runners: Unlocking Your Athletic Potential for Health, Speed, and Injury Prevention*, Skyhorse Publishing, New York 2012.

[20] ILNICKA L., TRZASKOMA Z., WISZOMIRSKA I., WIT A., WYCHOWAŃSKI M., *Lower limb laterality versus foot structure in men and women*, Biomedical Human Kinetics, 2013, 5, 11–16.

[21] VALDEZ D., HORODYSKI M.B., POWERS M.E., TILLMAN M., SIDERS R., *Bilateral asymmetries in flexibility, stability, power, strength, and muscle endurance associated with preferred and nonpreferred Legs*, J. Athl. Train., 2004, 39 (2), 108.

[22] COHEN J., *Statistical power analysis for the behavioural sciences*, Hillsdale: Erlbaum, 1988.

[23] FLANAGAN E.P., HARRISON A.J., *Muscle dynamics differences between legs in healthy adults*, J. Strenght Cond. Res., 2007, 21(1), 67–72, DOI: 10.1519/00124278-200702000-00013.

[24] MILLER E.E., WHITCOME K.K., LIEBERMAN D.E., NORTON H.L., DYER R.E., *The effect of minimal shoes on arch structure and intrinsic foot muscle strength*, J. Sport Health Sci., 2014, 3, 74–85, DOI: http://dx.doi.org/10.1016/j.jshs.2014.03.011.

[25] CHEN T.L.W., SZE L.K.Y., DAVIS I.S., CHEUNG R.T.H., *Effect of training in minimalist shoes on the intrinsic and extrinsic foot muscle volume*, Clin. Biomech., 2016, 36, 8–13, DOI: https://doi.org/10.1016/j.clinbiomech.2016.05.010.