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ASYMMETRY INDICES IN FEMALE RUNNERS AS PREDICTORS OF RUNNING VELOCITY

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Abstract

Introduction. This paper aimed to establish relationships between the level of functional and dynamic asymmetry in advanced and intermediate-level runners and running velocity. Furthermore, evaluation of dynamic symmetry (running and vertical jump) was made using indices, taking into account the continuous character of the signals of the ground reaction force and angular positions in individual joints of the lower limb. ***Material and methods.*** Symmetry was assessed in a group of 12 Polish elite female middle-distance runners for the following parameters: 1) strength of lower limb muscles, 2) impulse of the vertical component of the ground reaction force during a CMJ jump, and 3) kinematics of a 50-m run in a straight line. ***Results.*** More advanced athletes (group A) were significantly taller and stronger than the athletes with less training experience (B). They were also characterized by a significantly longer step, a more extended swing phase, and a shorter support phase. There were no statistically significant differences between groups A and B in the level of asymmetry. Running velocity was significantly influenced by muscle strength symmetry ($b = -5.77$; $p < 0.01$) and support phase time symmetry ($b = -6.64$; $p < 0.03$). A reduction in each of these indices leads to an increase in running velocity. ***Conclusion.*** No morphological or functional asymmetry was found in female middle-distance runners with different training experience.

Key words: running symmetry, running velocity, muscle force, CMJ jump

Introduction

For middle-distance runners, running on a track is generally considered to be a cause of movement asymmetry. According to Alday and Frantz [1], the length of the inner curve of a 400-m track is 57.8% of the total distance. Given that during stadium events, athletes run in a constant counter-clockwise direction, the body remains positioned asymmetrically for more than half of the distance. This effect is magnified by training. This causes changes in running technique in the form of, for example, more pronounced flexion in the knee joint of the inner (left) limb [2]. Significant differences in the technique of running in a straight line and on a curve were also found in athletes with prostheses, or for running in opposite directions [3, 4, 5, 6, 7]. Beck et al. [8] showed that the increase in running asymmetry manifesting in a 10% time difference in the support phase is associated with a 7.8% increase in the metabolic cost of locomotion. Many authors have analysed the relationships of kinetics, kinematics, and economy of running with running velocity [9, 10, 11, 12]. It was found that shortening the time of foot contact with the ground is positively correlated with running velocity but negatively correlated with its economy, defined as oxygen consumption [10]. Saunders at al. [13] enumerated many morphological, psychological and biomechanical factors, including, among others, optimal stride length and minimal vertical fluctuations in the centre of body weight, that improve running economy, but they failed to mention movement asymmetry. Also in the study by Brughelli et al. [10], the relationship between movement asymmetry and running velocity was not analysed, but the authors focused on the relationship between stride length and stride frequency and ground reaction force. It has also been observed that body kinematics changes significantly with acceleration during running [14, 15]. Furthermore, in the initial phase of a sprint, more substantial differences were found for stride length and stride duration [16, 17]. Few studies have described the level of movement asymmetry in running and its effect on running velocity in the phase of maximum speed.

However, in the case of human gait, the procedure of movement asymmetry analysis is commonly used for evaluating the correctness of gait or the progress of treatment and for predicting injuries [18, 19, 20, 21, 22]. Evaluation of gait asymmetry was initially based on the analysis of indicators derived from characteristic phases of movement, such as the initial contact and terminal stance (heel-off) phases [23, 24]. Nowadays, movement asymmetry is assessed using more advanced parameters. Zifchock and Davis [25, 26] developed an asymmetry coefficient based on the geometric approach. Exell et al. [27] developed it into an index that took into account the velocity of the left and right limb, termed kinematic asymmetry score (KMAS). However, these methods still use input data from single time points. Few studies have attempted to take into account the entire curves describing, for example, angular positions in individual joints in the normal gait cycle [28]. In the case of running, a similar attempt was made using an integral of the function as an asymmetry index, which represented a comparison of the difference of signal from the left and right limbs with the range of variability of both variables [29]. This method makes it possible to examine the level of asymmetry in each percentage of the gait cycle and present one compact SI index. Another problem is the evaluation of athletes in terms of morphological asymmetry related to body build and functional asymmetry determined, among other factors, by strength abilities. It was shown that both types of asymmetry depend on factors such as human lateralization [30] or the sport practised [31].

Furthermore, it is known that muscle strength asymmetry results in asymmetry during a vertical jump [32]. Therefore, the evaluation of asymmetry in athletes is not only based on the evaluation of muscle strength but also on the ground reaction force recorded during various types of vertical jumps [33, 34, 35, 36]. Therefore, a comprehensive evaluation of asymmetry in running is needed. It must take into account functional asymmetry evaluated using muscle strength and its effect on the level of dynamic asymmetry described by differences in movement technique, as well as the impact of both types of asymmetry on running velocity. Furthermore, most previous studies have presented the evaluation of the asymmetry of running kinematics on the basis of indices concerning specific selected time points coming from specific movement phases [37, 38]. They have failed to take into account the fact that the ground reaction force patterns during jumping, walking, and running and the changes in angular positions in individual joints vary with time. Consequently, the description of running asymmetry should be made using indicators based on the variability of the signal throughout the gait cycle. Therefore, this paper aims to identify relationships between the level of functional and dynamic asymmetry in advanced and intermediate-level runners and running velocity. Furthermore, an evaluation of dynamic symmetry (running and vertical jump) was made using indices that take into account the continuous character of the signals of the ground reaction force and angular positions in individual joints of the lower limb.

Material and method

The material consisted of 12 elite Polish female middle-distance runners (800-1500 m) divided into two 6-person groups. Group A comprised athletes with at least seven years of training experience, whereas the participants in group B had at least three years of training experience. They were healthy, with no injuries reported in the lower limbs in the last two years. The inclusion criterion for both groups A and B was a maximum 10% of muscle strength asymmetry. According to literature data, strength asymmetry in young people is on average 5% and does not exceed 10% [39, 40]. The study groups did not differ in age or body weight. The athletes from group A were significantly taller, on average by about 9 cm (Tab. 1). It was found, based on anthropometric measurements, that in group A, one participant was characterized by a difference in the length of the lower limbs (height of the anterior superior iliac spine) at a level of 0.5 cm. In group B, however, two athletes had unequal limb length, with a difference of 0.5 cm in one participant and 1 cm in the other. In all cases, the difference was within normal values with the limits set at 2 cm [41, 42].

Table 1. Average values and standard deviations of age, body height, body weight, and difference in length of lower limbs in groups A and B with significance of differences between groups

	A	B	F (p)
Age	23.3 ± 2.5	22.7 ± 0.82	0.385 (0.549)
Body weight	58.7 ± 5.62	57.4 ± 7.73	0.104 (0.753)
Body height	174.0 ± 5.48	165.3 ± 6.80	**5.909 (0.035)**
ΔL-R	0.1 ± 0.38	0.22 ± 0.48	1.325 (0.287)

Bold font indicates statistically significant difference.

Test description

The first step was to measure the length of the lower limbs with the pelvis (to the anterior superior iliac spine) and to determine the difference between the limbs (ΔL-R). After a standardized warm-up with a duration of 10 minutes, the muscle torque of the lower limb was measured, and three CMJ vertical jump trials were performed. Data from three trials were averaged for the analysis. Next, the running kinematics was measured. The subjects made 3 runs over a distance of 50 m from a 20-m run-up, at maximum speed (fast run – FR). Rests allowing for a full recovery were administered between the runs. The analysis was based on the averaged values of kinematic parameters from three 50-m runs.

Muscle force

The values of muscle torque developed under static conditions in the left and right hip, knee, and ankle joints were measured according to the procedure described by Knapik at al. [33]. The sum of muscle torque for the right and left lower limb muscles (ΣMm) and the sum of the muscle torque for the extensor (ΣMm extensor) and flexor (ΣMm flexor) muscles of the knee and hip joints were also computed. Based on the sum of torque for the left and right limbs, the asymmetry index was calculated as a ratio of the double difference in signals to the sum of signals (SI ΣMm = 2x(R-L)/(R+L)) [24]. Furthermore, the ratios of the strength of antagonist muscles (flexors to extensors) were calculated separately for the left and right limbs (W F/E = ΣMm flexors/ΣMm extensors). The indices obtained reflected joint stability and concerned 4 groups of extensors and flexors of the hip and knee joints. Absolute values of SI ΣMm and the W F/E index were used for the analysis.

The remaining part of the research protocol included measurements of the symmetry of the ground reaction force during counter-movement jump (CMJ) and 50-m sprint at a velocity of about 80-90% of the maximum speed (fast run – FR).

CMJ trial

The participants performed three consecutive vertical jumps with arm swing. The tests were performed on two Kistler platforms (9287 BA; BioWare 5.2.0.2) and recorded at a frequency of 250 Hz. The impulse of the vertical component of the ground reaction force was calculated on the basis of the value of absolute strength separately for the left and right limbs. The analysis was made only for the concentric phase of the movement (I). The beginning of the phase corresponded to the lowest position of the body's centre of gravity, whereas its end was characterized by a decline in ground reaction force to zero [37, 43, 44]. The symmetry index for the impulse of force (SI I) was calculated according to the procedure proposed by Herzog et al. [24].

Fast run trial

Movement kinematics during running was evaluated using the Xsens system based on integrated acceleration sensors, the Earth's magnetic field, and a gyroscope (IMU). A 14-segment human model supplied with Xsens 4.3 software was used to analyse running kinematics. This system provided data on angular position changes in the hip, knee, and ankle joints [45, 46]. For each participant, individual data concerning body height, shoulder range, shoulder and pelvic width, ankle and knee joint height, and foot length were integrated into the model. The analysis concerned two complete running cycles for the left and right lower limbs. Movement velocity (v run), stride length (SL) and stride time (t stride), support phase time (t support), and swing phase (t swing) were calculated. Data on the range of mobility were normalized to 100% running cycle and averaged. The evaluation of movement asymmetry was based on the range of motion in the sagittal plane (flexion/extension) in the hip, knee, and ankle joints. The entire range of lower limb mobility in the sagittal plane (ERLLM) was calculated as a sum of angular positions in the hip, knee, and ankle joints. The asymmetry index (SI ERLLM) was calculated for ERLLM according to the procedure proposed by Nigg et al. [50], as shown below.

$$SI = \int_{t=t_1}^{t_2} A|x_r(t) - x_l(t)|\, dt$$

Statistical analysis

The significance of differences between the left and right limbs in both groups was evaluated by two-way analysis of variance (ANOVA). The one-way analysis of variance ANOVA was employed to test differences between groups A and B in the values of asymmetry indices. A multiple stepwise regression model based on asymmetry variables was used to predict running velocity. The significance level was set at $\alpha = 0.05$.

Results

Running velocity was similar in groups A and B (Tab. 2). Group A was characterized by significantly lower (by about 17 strides/min; $F_{(1.10)} = 12.36$, $p = 0.0055$) running cadence, which was associated with a significantly longer stride (by about 70-80 cm; $F_{(1.20)} = 40.78$, $p = 0.000003$) and duration longer by approximately 0.03 s ($F_{(1.20)} = 17.56$, $p = 0.00045$). The duration of the support phase and the swing phase was similar for both limbs. ANOVA showed statistically significant differences between groups A and B for the sum of lower limb muscle torque ($F_{(1.20)} = 5.275$, $p = 0.032$). Furthermore, both groups were characterized by a similar flexor-to-extensor strength ratio in the lower limbs. A statistically significant tendency for higher values of the impulse of force generated by the participants from group A ($F_{(1.20)} = 3.154$, $p = 0.090$) during CMJ jump was observed. However, there was no significant difference between the left and right limbs.

There were no significant differences in the values of coefficients of functional asymmetry between the groups studied (Tab. 3). The only statistically significant tendency for greater asymmetry of the flexor-to-extensor ratio was observed in group B (SI $W_{F/E} = 8.9 \pm 7.67$; $F_{(1.10)} = 4.148$, $p = 0.069$).

The results obtained for asymmetry were used to design a model aimed to demonstrate a linear relationship between asymmetry and running velocity. The model explains approximately 60% of running velocity variation using the variability of the three asymmetry indices. The value of statistics $F_{(3.8)}$ =

Table 2. Mean values and standard deviations of individual parameters (V run – running velocity; running cadence; ΣMm – sum of muscle torque for single lower limb; WF/E - flexor-to-extensor ratio; I – impulse of force for concentric phase; SL – stride length; t stride – stride time; t support – support phase time; t swing – flight phase time)

Group	A		B		Statistical significance
V_{run} [$^m/_s$]	7.42 ± 0.26		7.02 ± 0.56		Group: $F_{(1,10)}$ = 2.59; p = 0.13
Cadence [$^n/_{min}$]	213 ± 6.0		230 ± 9.9		**Group: $F_{(1,10)}$ = 12.36; p = 0.0055**
Limb	**R**	**L**	**R**	**L**	
ΣMm [Nm]	885 ± 155.9	887 ± 142.0	752 ± 157.1	741 ± 138.4	**Group: $F_{(1.20)}$ = 5.275; p = 0.032** Side: $F_{df = (1.20)}$ = 0.004; p = 0.947
WF/E	0.42 ± 0.032	0.43 ± 0.038	0.45 ± 0.054	0.43 ± 0.064	Group: $F_{(1.\ 20)}$ = 0.228; p = 0.637 Side: $F_{(1.\ 20)}$ = 0.204; p = 0.656
I [Ns]	139 ± 28.2	141 ± 24.3	117 ± 33.5	119 ± 34.3	Group: $F_{(1.\ 20)}$ = 3.154; p = 0.090 Side: $F_{(1.\ 20)}$ = 0.037; p = 0.848
SL [m]	2.04 ± 0.307	2.04 ± 0.210	1.22 ± 0.253	1.32 ± 0.380	**Group: $F_{(1.20)}$ = 40.78; p = 0.000003** Side: $F_{(1.\ 20)}$ = 0.189; p = 0.667
t stride [s]	0.55 ± 0.011	0.55 ± 0.016	0.52 ± 0.028	0.51 ± 0.023	**Group: $F_{(1.20)}$ = 17.56; p = 0.00045** Side: $F_{(1.\ 20)}$ = 0.03; p = 0.871
t support [s]	0.14 ± 0.005 (26%)	0.14 ± 0.018 (27%)	0.16 ± 0.022 (32%)	0.16 ± 0.016 (33%)	**Group: $F_{(1.20)}$ = 11.72; p = 0.0026** Side: $F_{(1.\ 20)}$ = 0.388; p = 0.540
t swing [s]	0.41 ± 0.014 (74%)	0.41 ± 0.029 (73%)	0.36 ± 0.07 (68%)	0.35 ± 0.017 (67%)	**Group: $F_{(1.20)}$ = 29.94; p = 0.000023** Side: $F_{(1.\ 20)}$ = 0.272; p = 0.608

Bold font indicates statistically significant differences; italics indicate statistical trend.

Table 3. Mean values and standard deviations for asymmetry indices (ΣMm – sum of muscle torque for single lower limb; WF/E – flexor-to-extensor ratio; I – impulse of force for concentric phase; SL – stride length; t stride – stride time; t support – support phase time; t swing – flight phase time; ERLLM – entire range of lower limb mobility)

SI [%]	A $_{n = 6}$	B $_{n = 6}$	Statistical significance
ΣMm	4.3 ± 3.09	3.09 ± 1.57	$F_{(1.10)} = 0.722$; $p = 0.415$
WF/E	2.3 ± 1.93	8.9 ± 7.67	*$F_{(1.10)} = 4.148$; $p = 0.069$*
SL	4.7 ± 2.95	8.6 ± 6.43	$F_{(1.10)} = 1.774$; $p = 0.212$
I	6.6 ± 6.04	4.2 ± 2.07	$F_{(1.10)} = 0.861$; $p = 0.375$
t stride	0.9 ± 0.86	2.5 ± 2.47	$F_{(1.10)} = 2.447$; $p = 0.148$
t support	7.4 ± 9.19	8.6 ± 3.74	$F_{(1.10)} = 0.083$; $p = 0.778$
t swing	4.0 ± 3.09	6.0 ± 3.60	$F_{(1.10)} = 1.078$; $p = 0.323$
ERLLM	9.3 ± 5.73	7.8 ± 3.04	$F_{(1.10)} = 0.334$; $p = 0.575$

Italics indicate statistical trend.

4.0300 and the corresponding test probability of $p < 0.05$ confirm the statistically significant linear relationship of the three asymmetry indicators with running velocity (Tab. 4). An interpretation of the evaluated values of individual parameters leads to the conclusion that the reduction of the asymmetry of the swing phase time and the asymmetry of the sum of muscle torque significantly influenced the increase in running velocity. A decrease in the asymmetry of the impulse of the ground reaction force in the CMJ jump also affects the increase of running velocity. However, in this case, the statistical significance of the effect of this parameter on running velocity was not confirmed.

Table 4. Final multiple forward stepwise regression model of predicted running velocity

Variables	R^2	SEE	b	t(8)	p
SI t swing	0.6	0.34	−5.77	2.917	< 0.01
SI SMm			−6.64	−2.49	< 0.03
SI I			−2.47	−1.59	> 0.05

SEE – standard error of estimate; b – beta coefficient.

Discussion

This paper aimed to identify relationships between the level of functional and dynamic asymmetry and running velocity in advanced and intermediate-level runners. The data available in the literature indicate that the difference in the length of the lower limbs causes a pronounced asymmetry in gait [41, 47] and a decline in locomotion economy [8, 42, 48]. In our study, the asymmetry of lower limb dimensions was small (up to 1 cm) and within the normal range [41, 42]. It can be expected that morphological asymmetry is an important element that determines the presence of dynamic asymmetry, but individual compensatory mechanisms responsible for movement control can eliminate this difference. The same conclusion was drawn by Liu et al. [49] and Gurney [50], who found that not all people with a difference in the length of the lower limbs exceeding 2 cm were characterized by gait asymmetry [49, 50].

It can be presumed that the process of movement control by the nervous system is of major importance for the level of running asymmetry. Female track and field athletes with longer training experience were characterized by greater consistency between left and right stride length (A = 4.7% ± 2.95% and B = 8.6% ± 6.43%, respectively; Tab. 3). Also, stride time asymmetry was lower in group A (A = 0.9% ± 0.86%; B = 2.5% ± 2.47%). The significant ability of professional sprinters to adapt running technique to changing external conditions was demonstrated in a study on the differences in the level of movement asymmetry of the lower limbs during a sprint on a curve on the 1st, 4th, and 8th lanes of the running track [2]. It was demonstrated that the level of movement asymmetry was lower in more professional runners [51, 52]. It can be assumed that factors such as greater training experience, significantly shorter foot support time, longer flight phase time, greater muscle strength, and the tendency for higher running velocity observed in group A are conducive to better movement control reflected in lower asymmetry.

It should be noted that female middle-distance runners take part in competitions on 400-m or 200-m running tracks. Running kinematics on a curve of the track has been demonstrated to be characterized by greater asymmetry [2]. We found no effect of training and competitions on asymmetry in a straight run for participants from groups A and B.

Another determinant of movement asymmetry during running is the symmetry of muscle strength. Studies comparing the asymmetry of the strength of knee joint extensors in older women showed a positive correlation with the level of gait asymmetry [42]. Bailey at al. [32] also pointed to the relationship between the asymmetry of movement during vertical jumps and the symmetry of muscle strength. This observation seems to be confirmed by the results of the regression analysis in our study (see Tab. 4). We found that the reduction of asymmetry of the sum of muscle torque (SI ΣMm) in both groups has a statistically significant impact on the increase in running velocity. A positive effect of a decrease in the asymmetry of swing phase time (SI t swing) on running velocity was also observed. In the literature, however, a significant influence of shortening the support phase on increasing running velocity was documented [9, 11]. In our research, the female runners from group A were characterized by a shorter support phase compared to those from group B (about 26% of the cycle and 32% of the cycle, respectively). This indirectly confirms our observations concerning the positive impact of swing phase symmetry on running velocity because a shortening of the support phase is required in both limbs and involves the symmetrical elongation of the swing phase.

Our study found that a decrease in the asymmetry of the impulse of the ground reaction force in the CMJ jump (SI I) also influences running velocity. Although the effect of this parameter on running velocity was not statistically significant in this case, there are studies in the literature which have demonstrated a positive correlation between the level of reaction force and power during the CMJ vertical jump and the level of motion asymmetry in the ankle joint during running [27]. This indirectly confirms the importance of the relationship discussed in this study. The positive effect of low asymmetry of lower limb movement during a vertical jump on running velocity can be explained as follows. The occurrence of motion asymmetry during vertical jumps correlates positively with the motion asymmetry of the lower limbs during running. This in turn results in more pronounced fluctuations of the body's centre of gravity in the frontal plane. The fluctuations lead to longer distance covered in the running cycle and, consequently, a higher energy cost of locomotion and a decline in body velocity. The same conclusions were drawn by Klimek and Chwała [53] and Struzik et al. [15] for a 10-m run.

Experienced elite athletes are more "symmetrical" than good runners [54], but the body structure and movement of elite runners are not necessarily symmetrical. Although running during training may seem to be a reasonable factor explaining asymmetry, the athlete's experience is not the only factor related to improving symmetry. The increase in running velocity also improves take-off symmetry [54]. A possible explanation proposed for this finding is a progressive decline in the work performance of contractile components and the increase in the contribution of passive muscle components along with higher running velocity, which seems to reduce muscle effort [54]. This can also be explained by a higher metabolic cost of exercise due to the increase in running asymmetry [8].

Conclusion

No morphological or functional asymmetry was found in elite female middle-distance runners with different training experience. It was demonstrated that the improvement in symmetry of strength of the lower limb muscles and the time of movement of the limb during the swing phase represent statistically significant determinants of running velocity.

Acknowledgements

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