SECTION – EXERCISE SCIENCES

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KINEMATICS OF LOWER LIMB AND PELVIC WORK DURING RUNNING IN NEUTRAL AND MINIMALIST FOOTWEAR AMONG A GROUP OF HIGHLY QUALIFIED RUNNERS

Wiesław Chwała [1 ABCDEFG], Wacław Mirek [2 ABDEG], Andrzej Klimek [3 ABCEG], Krzysztof Mirek [4 BCF]

[1] Faculty of Physical Education and Sport, Department of Biomechanics, University of Physical Education in Kraków, Poland.
[2] Faculty of Physical Education and Sport, Department of Physiology and Biochemistry, University of Physical Education in Kraków, Poland.
[3] Faculty of Physical Education and Sport, Department of Track-and-Field Sports, University of Physical Education in Kraków, Poland.
[4] Student, Faculty of Physical Education and Sport, University of Physical Education in Kraków, Poland.

Authors' contribution:

A. Study design/planning
B. Data collection/entry
C. Data analysis/statistics
D. Data interpretation
E. Preparation of manuscript
F. Literature analysis/search
G. Funds collection

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Abstract:

Aim. The aim of the study is to characterise and compare the values of angle changes within the lower limb joints in the sagittal plane and spatial pelvic movements while running in minimalist and neutral footwear.

Materials and methods. Research was carried out among a group of 13 participants (6 men and 7 women), highly qualified male and female athletes from the AZS AWF (University of Physical Education) Kraków club. Registration of the run and analysis of the results was performed using spatial motion analysis via the Vicon system with speeds at 3.94±0.45 m/s for men and 3.97±0.32 m/s for women, and 3.91±057 m/s and 4.1±0.36 m/s for men and women, respectively, in the group of highly qualified athletes.

Results. At the initial point of foot contact with the ground, the minimalist footwear run was characterised by greater plantar flexion totalling about 5º compared to the run in neutral footwear. There was also a 8º higher value of dorsiflexion during the amortisation phase and a lower value by approx. 5º during the swing phase in this joint when running in minimalist footwear. In the knee joint, a value of about 6º higher flexion was observed during the amortisation phase when running in minimalist footwear.

Differences in hip joint angle of approximately 6-8º were found during maximal extension of the joint during the final rebound phase. Spatial pelvic movements were similar during runs in both types of footwear.

Conclusions. The obtained results indicate that some of the amortisation and driving force tasks are taken over by the sports footwear. During the run in minimalist footwear, a key role in the field of body amortisation is played by the increased range of knee flexion, while during the rebound phase, the increased range of hip joint extension predominates.

Introduction

Running is one of the most popular forms of human activity. Nowadays, there is a great interest in this form of movement among running enthusiasts. The positive impact of running on health is only when the correct technique is preserved, which not only serves to economise an effort, but also affects the human movement system. The running technique is particularly important for competitive runners to achieve the highest results in sport. A run at the same intensity in trained runners uses from 20-30% less oxygen than in beginners. The economics of running are influenced, among others, by: length and frequency of the step, vertical oscillation of the center of gravity, contact time of the foot with the ground [1]. Learning technique is a continuous process, therefore, at each stage of sports development, there should be exercises to correct the run. It should be noted that the level of technical performance of a given physical activity depends on the athlete's fitness level.

Various technical styles can be observed in running, but they should not go beyond the model technical norm that allows achieving maximum movement economics. Thanks to increasingly modern methods of assessing the technique and its impact on the human body, its shape and course can be more accurately determined.

When an athlete's running speed increases, the contact time of the foot with the ground decreases, while the duration of the swing phase increases [2].

During a running cycle, as speed increases, the single-support phases are shortened and the flight phase is extended. When running at a natural speed for the runner, these proportions are often 40% (support phase) and 60% (transfer phase). To maintain the natural running structure as speed increases, we observe simultaneous lengthening of the stride and an increase in frequency. In sprinting races, the support phase time decreases to around 20% of the cycle [3].

Modern sport requires thorough and comprehensive assessment of movement technique, which, as noted above, should provide a coach with accurate information to correct errors and thus, improve movement-related economics.

Observation of running in various types of sports footwear, on the other hand, allows researchers to assess the impact of the technologies used (mainly amortisation and properties related to elasticity) in footwear design on the work of the entire biomechanism. To date, no large-scale studies have been conducted on the differences in kinematic parameters of joints during these two types of runs [4]. There is little research in literature on the impact of running without or without shoes on the movement system. The Eslami et al. [5] research team conducted a study which can be viewed as among the more interesting in this area. Other studies deal with the subject of shock absorption during running in and without sports shoes [6]. Therefore, it seems necessary to undertake this research topic in order to clarify and specify the observed phenomena and regularities.

The aim of the study was to characterise and compare the value of angle changes within the lower limb joints in the sagittal plane and spatial pelvic movements during a run in minimalist and sports footwear among a group of highly qualified athletes.

Research materials and methods

The research material was obtained by performing a series of tests among a group of highly qualified runners from the AZS AWF (University of Physical Education) Kraków club, while running in neutral (training) and minimalist (starting) footwear. The studied athletes had a few years of sporting career experience behind their belts, with many successes. The group of participants consisted of 13 athletes, including 6 men and 7 women. The average age of women was 23.6±5.7 years, and men, 21.2±1.6 years. The average body mass of women was 57.8±6.4 kg, while for men, this was 70.9±4.2 kg. The average body height for women was 1.65±0.049 m, and for men, 1.81±0.055 m. BMI for the experimental group was 20.5±2.56 kg/m^2 for women and 21.7±0.77 kg/m^2 for men, respectively.

Research was carried out using the Vicon 250 spatial motion registration system at the Biokinetics Laboratory of AWF Kraków.

Passive markers were placed at characteristic anthropometric points on the bodies of the subjects. The spatial positions of markers were recorded by cameras operating at 120 Hz on the border of infrared and visible bands. Then, the data was collected and analysed using the Polygon Authoring Tool, and the Body Builder as well as Workstation applications.

The subjects performed sport and walk runs several times at individual speeds, in both types of sports footwear (minimalist and neutral) on a 25-meter path, with the task of exposing the optimal individual movement technique. From the many walking and running cycles recorded for each measurement session, 30 steps (15 cycles) of walking and running for both limbs with stabilised speed of movement and frequency of steps were selected for further analysis.

Results

In Figures 1-6, the values of angle changes in the ankle, knee, hip and pelvic spatial settings are demonstrated, which were recorded during running in neutral and minimalist footwear, presented in a normalised running cycle.

The normalised running cycle expressed in % contains two full running steps, one for each lower limb. The 100% area covers the resistance and flight phases, respectively, covering 30% and 20% of the cycle, respectively. The first 30% of the cycle was the contact phase of the foot with the ground of the analysed limb. It was divided into the amortisation (0 15%) and rebound (15-30%) phases of the cycle. The next 20% of the cycle (between 30 and 50% of the cycle), the flight phase occurred, lasting until initial contact of the foot of the other limb with the ground. The analysed lower limb was then in the posterior swing phase, which ends at about 60% of the cycle. Swinging the analysed limb forward lasted from about 60% to 100% of the cycle. During this time, the opposite limb was in the final phase of amortisation (60-65%), followed by the rebound (up to 80% of the cycle) and flight (80-100%) phases.

Changes in ankle joint angle during the normalised running cycle in neutral (ON) and minimalist (OM) footwear were similar. Significant differences relate to the angle of the foot on the ground at the initial phase of the cycle, and then become apparent from approximately 30% of the cycle, when the flight phase begins. The OM run is characterised by slightly greater plantar flexion by approx. 5° compared to the corresponding ON run phase at the initial phase of contact and foot loading. The starting point of foot contact with the ground is characterised by small plantar flexion of the feet, and then, to achieve maximal dorsiflexion in the cycle in a short time to about 15% of the cycle (completion of the amortisation phase by the support limb), ranging from about 17° (ON) to 22° (OM). Then, up to about 30% of the cycle, i.e. the end of the rebound phase, the feet moved in the plantar direction. The plantar flexion arch was characterised by a rapid change in the angle of the joints, reaching a value of approx. 16° to 22° of plantar flexion at the end of the support phase. On average, competitors in minimalist footwear achieved slightly greater flexion.

The flight phase lasted up to approx. 50% of the cycle. It was divided into ascent and descent phases. The ankle joint was stabilised during this phase, and the feet moved only slightly, oscillating at the level of plantar flexion between 16° and 22°.

From this moment on, i.e. the phase of body descent in the flight phase, and then the body weight being absorbed by the opposite limb, movement was noted towards the neutral position of the foot. The minimal value of plantar flexion reached about 75% of the cycle, just before the end of the contact phase of the contralateral foot. Then, the flight phase of the opposite limb began and at the same time, the forward swing phase of the analysed limb was continued.

Up to about 95% of the cycle, a repeated several-degree movement towards plantar flexion was observed. Significantly higher values of plantar flexion (on average, by about 7°) were obtained by runners in minimalist footwear. The last 5% of the cycle was a move towards neutral position, preparing the foot to take on the weight of the body again.

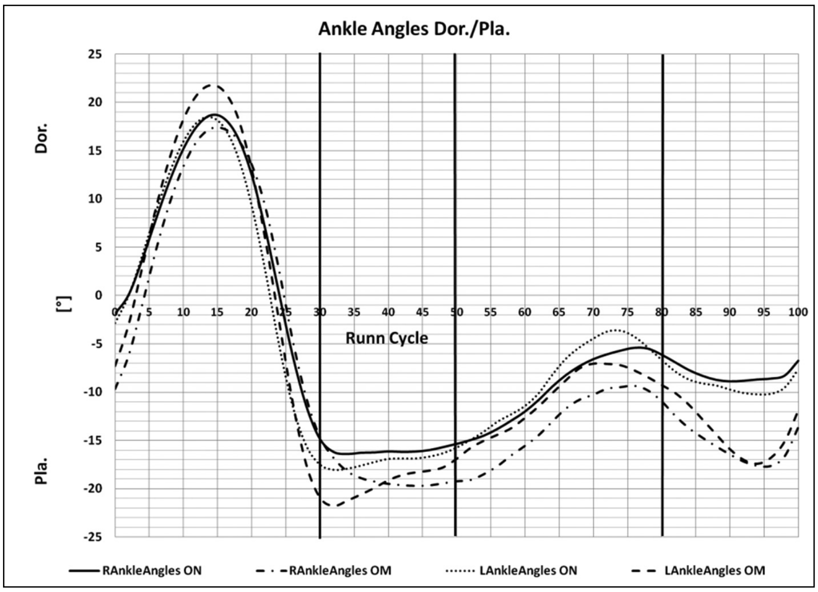

Fig. 1. Mean values of angular changes in the right and left ankle joint during the normalised running cycle in neutral and minimalist footwear

Ankle Angles ON – change in ankle joint angle during run in neutral footwear,
Ankle Angles OM – change in ankle joint angle during run in minimalist footwear
Dor. – dorsiflexion of the foot, Pla. – plantar flexion of the foot, R –right lower limb, L – left lower limb, Runn Cycle – running cycle

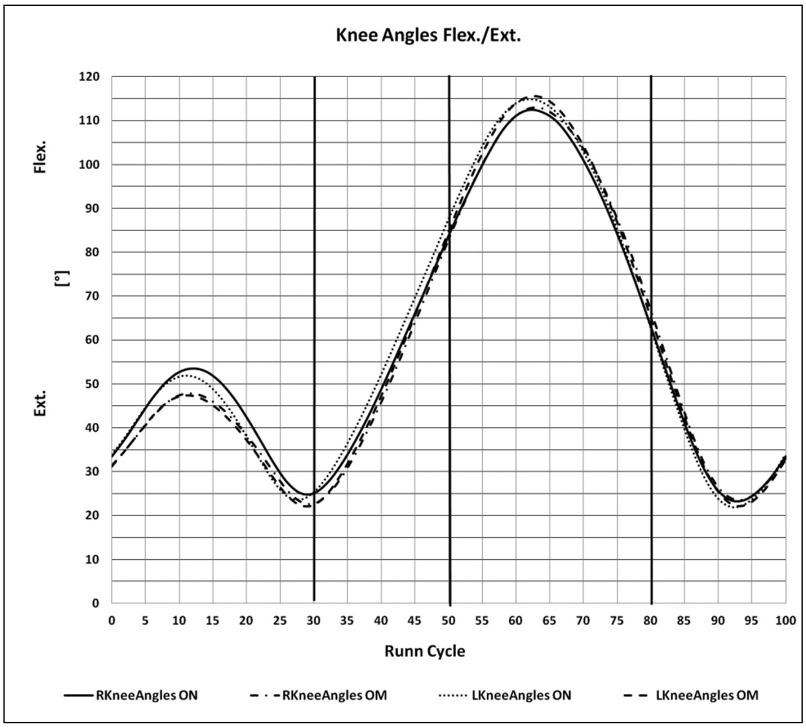

Fig. 2. Mean values of angular changes in the right and left knee joint during the normalised running cycle in neutral and minimalist footwear

Knee Angles ON – change in knee joint angle during run in neutral footwear,
Knee Angles OM – change in knee joint angle during run in minimalist footwear,
Flex. – knee joint flexion, Ext. – knee joint extension

Angle-related changes in the knee joint during a normalised running cycle in neutral (ON) and minimalist (OM) footwear were clearly similar. Small differences concerned only the value of the knee flexion angle during the initial phase of the cycle, when taking over the weight. Running in minimalist footwear was characterised in this cycle range by slightly less knee flexion compared to running in neutral footwear (differences from 2º-6º). The starting point of foot contact with the ground took place when the knee joints were flexed to an angle of about 30º for both types of footwear. Then, in a short time, to about 15% of the cycle, the knee joints reached maximum flexion in the running cycle, which was associated with the end of amortisation and taking over body weight by the support limb. Extreme knee flexion averaged 48º (OM) and 54º (ON), respectively. Then, up to about 30% of the cycle, knee extension movements were observable in the rebound phase. This was characterised by a rapid change in joint angle, lasting up to about 30% of the cycle, i.e. completion of the support phase. At that time, the knee joints were flexed to about 23ºdegrees.

During the flight phase of the analysed limb lasting up to about 50% of the cycle, the knee joints were characterised by progressive flexion. Movement of the knee during the flight phase was dynamic and proceeded much faster than in the case of the resistance phase. At about 60% of the cycle, the knee joints reached a maximal flexion value of approximately 102º-105º. At this moment, the phase of amortisation of the contralateral foot was ending. In the second part of the swing phase of the analysed limb and, at the same time, the support of the opposite limb (rebound phase), the knee joint of the analysed limb performed an extension motion to approx. 92% of the cycle, reaching an angle of approx. 22º at that time.

During the final fragment of the running cycle, a repeated, several-step movement towards knee flexion was noted. This anticipatory flexion demonstrates that the knee joints were ready for the amortisation phase and that the weight was again taken over by the support limb.

The starting point of foot contact with the ground for running in both types of footwear took place at the time of considerable hip flexion ranging from 40º to 42º. Angle changes in the hip joints during the normalised running cycle in minimalist (OM) and neutral (ON) footwear were characterised by similar arches of flexion and extension changes. Significant differences in the flexion angle of the hip joints began to reveal at about 25% of the cycle,

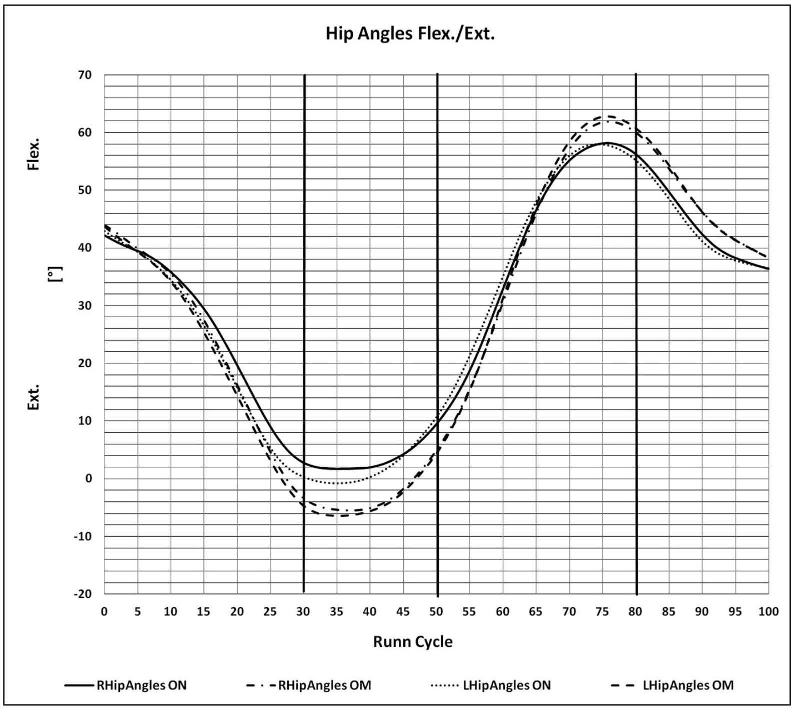

Fig. 3. Mean values of angular changes in the right and left hip joint during the normalised running cycle in neutral and minimalist footwear

Hip Angles ON – change in hip joint angle during run in neutral footwear,
Hip Angles OM – change in hip joint angle during run in minimalist footwear,
Flex. – hip joint flexion, Ext. – knee hip extension

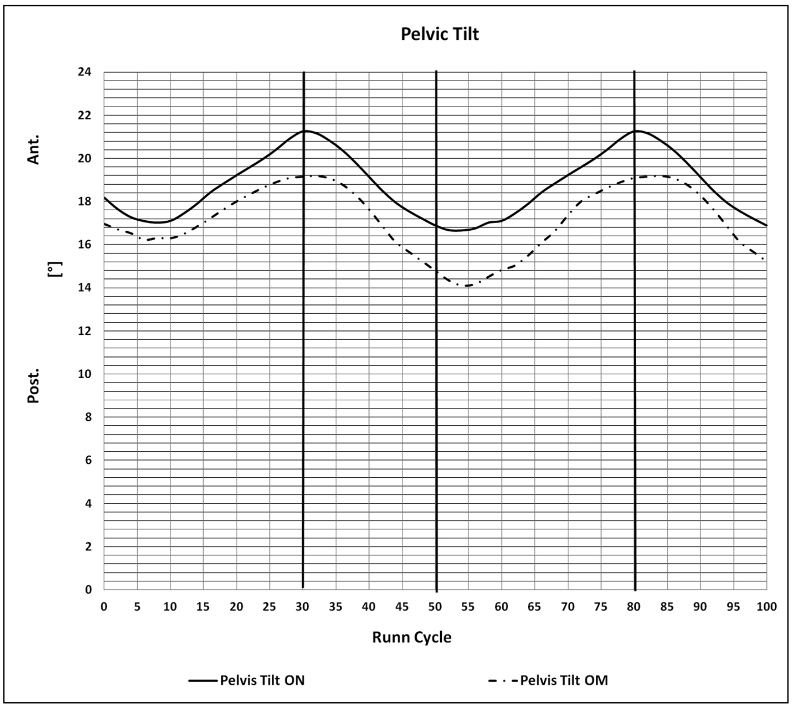

Fig. 4. Mean values of angular changes in the pelvic tilt in the sagittal plane during the normalised running cycle in neutral and minimalist footwear

Pelvis Tilt ON – change in pelvic tilt angle in the sagittal plane during run in neutral footwear,
Pelvis Tilt OM – change in pelvic tilt angle in the sagittal plane during run in minimalist footwear,
Ant. – anterior pelvic tilt, Post. – posterior pelvic tilt

when the hip joints approached the zone of maximum extension at the final stage of the rebound phase. The differences increased to approx. 35-37% of the cycle and amounted to approx. 6-8°. During the run in minimalist footwear, the hip joints reached several-degree hyperextension, while during the run in neutral footwear, they only came close to the 0° position.

When taking over the weight of the body, the hip was stabilised for a short period of time, and then, up to about 35% of the cycle, rapid extension was noted.

Another slight difference in the use of both types of footwear for running appeared at about 75% of the cycle, when the analysed limb started to approach the end of the forward swing phase, while the opposite limb was completing the contact phase. The run in minimalist footwear at that time was characterised by greater flexion range by approximately 5° on average, compared to running in neutral footwear.

The recorded range of hip flexion during the flight phase was significant, reaching 62° for ON and 58° for OM (max. of about 75% of the cycle). From this moment on, the extension movement continued to reduce the joint flexion value, which maintained until the end of the support phase in the next cycle. At the end of the running cycle phase, just before re-placing the foot on the ground, the angle in the hip joints reached a value of about 36°-38° flexion.

Changes in pelvic tilt angle in the sagittal plane during the normalised running cycle of running were similar to each other and are characterised by alternating several-degree arches of anterior and posterior tilts. Minimal differences between the charts for runs in both types of footwear occurred throughout the entire cycle and averaged about 2°. The run in minimalist footwear was characterised by slightly smaller pelvic tilt. During the whole cycle, the anterior pelvic tilt oscillated between 14°- 9° for the OM run and 15°-21° for ON.

The highest pelvic tilt values were recorded at the end of the rebound and backward swing phases, 19° (OM) and 21° (ON), respectively

The pelvic movement diagrams in the frontal plane for both experiments practically coincided throughout the entire cycle. The only visible difference was slightly greater pelvic descent during running in sports footwear, observed at the end of the amortisation phase. At that time, the foot was placed on the ground, the pelvis was raised approximately 4° relative to the neutral position. At the initial phase of amortisation up to about 10° cycle, the pelvis was stabilised, and then, during the rebound phase, a rapid descent movement was performed to

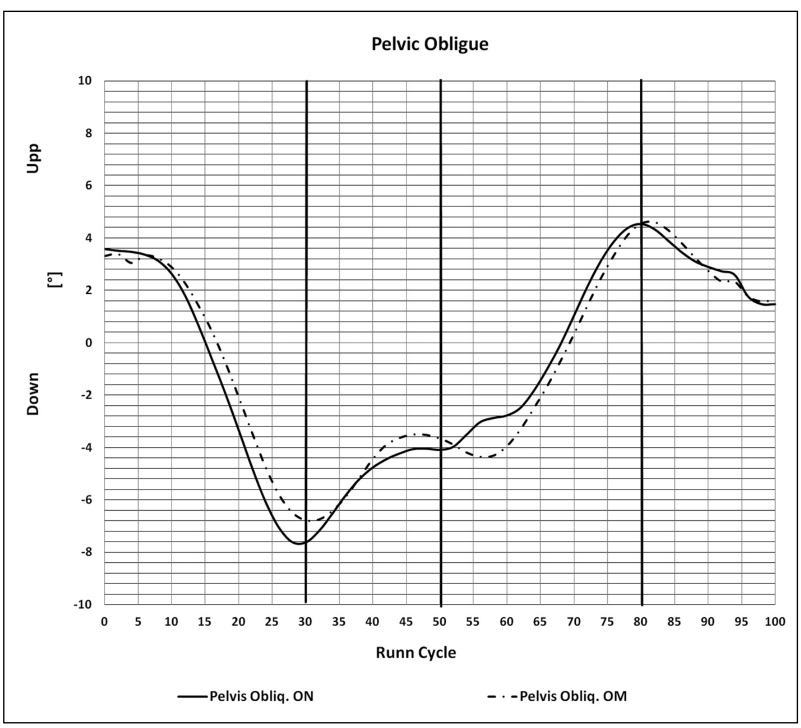

Fig. 5. Mean values of angular changes in pelvic tilt in the frontal plane during the normalised running cycle in neutral and minimalist footwear

Pelvis Oblique ON –change in pelvic tilt angle in the frontal plane during run in neutral footwear,
Pelvis Oblique OM –change in pelvic tilt angle in the frontal plane during run in minimalist footwear,
Up – pelvic lift, Down – pelvic fall

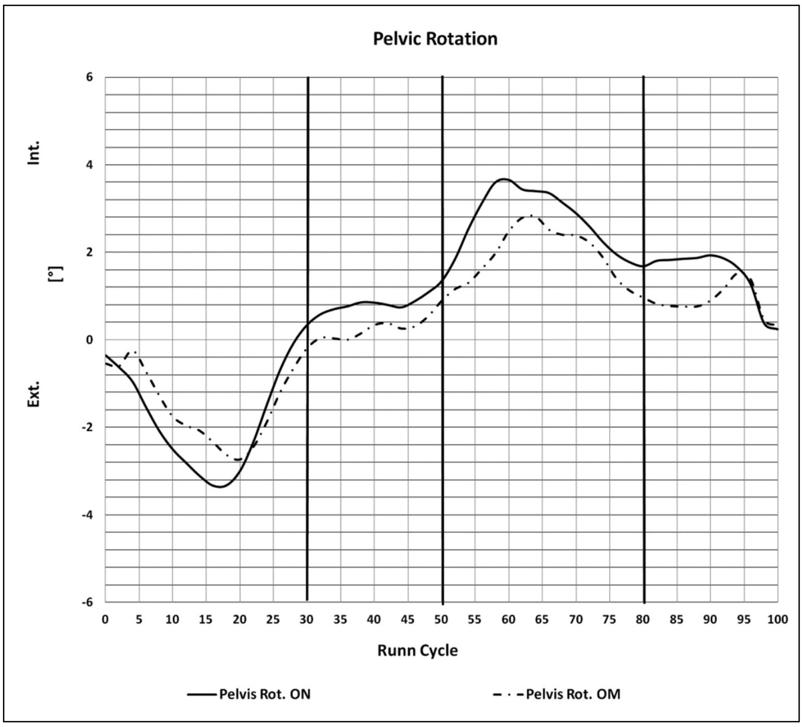

Fig. 6. Mean values of angular changes in pelvic rotation in the transverse plane during the normalised running cycle in neutral and minimalist footwear

Pelvic Rotation ON – change in pelvic tilt angle in the transverse plane during run in neutral footwear,
Pelvic Rotation OM – change in pelvic tilt angle in the transverse plane during run in minimalist footwear,
Int. – internal pelvic rotation relative to the analysed limb, Ext. – external pelvic rotation relative to the analysed limb

about 8°. This value was obtained for running in neutral footwear for about 30% of the cycle. In the flight phase between 30°-50% of the cycle, slight pelvic elevation was observed on the side of the analysed limb. At the end of this phase, the pelvis was in a position about 3-4° below neutral. When the foot contact with the ground was taken over by the opposite limb, the next phase of the stable pelvic position could be observed, so that from the initiation of the forward swing forward (about 60% of the cycle), the pelvis quickly again, this time, rose up to an angle of about 4°. By the end of the cycle and swing phase, the pelvis was characterised by a small-degree range of motion toward neutral position, preparing to take over the body weight by the support limb.

The range of pelvic rotation during the run in both types of footwear was similar to each other and totalled about 7°-8°. The differences in the range of changes in pelvic angle were minimal and did not exceed 2°. When the foot was elevated, the pelvis was near neutral position. Then, in the amortisation phase, external pelvic rotation was noted relative to the studied limb to an angle of about 3°-4°. During the rebound phase, a rapid pelvic return movement was observed close to neutral position, followed by internal rotation, lasting up to approximately 60% of the running cycle. The flight phase is a narrow area of pelvic stabilisation, with a slight tendency towards internal rotation. A clearer movement in this direction was noticed until between 50-60% of the cycle, when the pelvis reached the maximum value of internal rotation at the level of about 3-4°. From this point on, during the forward swing phase of the limb, the pelvis again changed its position towards the neutral one, reducing the value of internal rotation.

Discussion

Along with the increase in the popularity of running and the possibility of competitions at various skill levels, the number of injuries to the musculoskeletal system, mainly due to overloading, has also increased.

In the cyclic running step, the amortisation phase appears to be one of the most dangerous, where the foot and ankle joint take on the weight of the whole body, and then transfer it to the lower limb and trunk. The foot, in addition to supporting and amortising body weight, transfers the ground's reaction force to other biomechanism structures. Adelaar estimated the values of these forces at the level of about 2.5-2.8 of resting body mass [7].

In their research, Di Caprio et al. indicate hindfoot valgus and hollowing of the foot's arch as the main reasons for the occurrence of lower limb dysfunctions in medium-distance runners representing different sports level [8]. The conclusion of the study was that most injuries were related to plantar fasciitis and Achilles tendon problems.

Willems et al. argue that most injuries and contusions associated with running occur in competitors as a result of repeated training micro-injuries, leading to overloading of the structure of the musculoskeletal system [9]. Therefore, one of the most important factors guaranteeing high results in running and long-term practice of this activity is correct movement technique. It is often based on accurate diagnostics of technical errors, assessment of the impact of footwear used on the stereotype of foot loading, and early detection of risks of overloading the musculoskeletal system. The indicated elements are necessary for the implementation of training recommendations, optimising individual running technique in terms of matching individual morphofunctional features to the objective laws of motion mechanics.

An important issue in the biomechanical analysis of running is to consider the type of footwear in which the experiment is performed. Competitors most often use different footwear for training (so-called neutral footwear) and for taking part in sports competitions (starting footwear also called minimalist). Both types of footwear may differ in elastic and shock-absorbing properties. These, in turn, can affect individual technique, which can be observed in the form of changes in angles in the joints of the lower limbs and spatial movements of the pelvis during a run.

Jaakko compared the results of running without shoes and in different types of sports footwear [10]. The results of research show significant differences in the maximum range of dorsiflexion in the ankle during the amortisation phase. Maximal dorsiflexion was clearly higher when running without shoes (around 23º) compared to running in training shoes (around 19º). The results of this study are very similar regarding the values obtained during running in neutral shoes, usually used during running training. Maximal dorsiflexion of the feet while running in minimalist footwear was, in turn, similar to the results obtained when running without shoes.

Differences were also observed at the moment of the foot's initial contact with the ground during the amortisation phase. Competitors running in minimalist footwear showed increased plantar flexion, while during tests in neutral footwear, foot contact with the ground occurred in neutral position. Ferber and Macdonald report that runners beginning foot contact with the ground from a heel strike, position the foot at about 15º dorsiflexion. This is a clear difference from the results obtained in this research, in which the participants were highly qualified athletes [11].

In the knee joint during the amortisation phase, Jaakko obtained higher maximal flexion values during running in training shoes (at a level of about 45º) than in a run without shoes (about 42º) [10]. Comparing the results obtained in this study, it should be stated that a similar regularity was obtained, however, the average knee flexion values during the amortisation phase were slightly higher and were, on average, about 47º in the case of running in neutral shoes (ON), while in the case of minimalist shoes, this totalled approx. 53º.

The author points out small, but statistically significant differences in flexion of the hip joint during initial contact of the foot with the ground. The results of this study did not indicate the existence of such a relationship, while the differences were clearly visible at the end of the resistance phase during rebound.

Other comparisons of kinematic and kinetic variables of running on the treadmill and on flat terrain were presented in the work of Riley et al. These authors show clearly higher (on average about 12º) values of maximal flexion in the knee joint in terrain running, compared to running on the treadmill [12].

Interesting research results were also presented by Willy and Davis, who conducted a study among runners in minimalist and standard footwear on a treadmill with a strain gauge path. The researchers noted statistically significant differences between the initial foot position, maximal dorsiflexion of the feet, flexion of the knee joints and the maximal value of ground reaction force in both tested types of footwear [13]. Very similar observations were noticed in the results of this study. The above results are also confirmed in the experiment by Franz et al. based on the analysis of kinematics of limb movement during running in and without sports footwear. The results indicated that during the amortisation phase of running in sports shoes, the ankle joint achieved lower dorsiflexion values. On the other hand, in the knee joint, the results practically did not differ, which is in opposition to the results achieved in this research [14].

The topic of differences in biomechanical variables during running in minimalist and traditional sports footwear and without footwear was also undertaken by the team - Bonacci et al. Their research results indicate that the kinematics of running in minimalist footwear is much more similar to the stereotype of running in minimalist footwear, but it differs in relation to running in training shoes. These regularities were observed in all the lower limb joints of runners [15]. The results obtained in this study are largely consistent with the observations of the cited authors.

The research by Hall et al. confirms the results from this study on increased plantar flexion of the foot and lower maximal flexion of the knee when running in minimalist footwear. It was also noted that the results show an increase in the amortisation function in the ankle and a decrease in this function in the knee joint during running without shoes, the scheme of which is largely similar to running in minimalist footwear [16]. Within these aspects, the observations present in this study coincide with the results of these authors.

There is no description in the literature on spatial changes in pelvic positioning during a run. Therefore, the data presented in the 'Results' chapter appear to be valuable. The pelvis is the connector between the lower limbs and the trunk. If there are disturbances of the work of the lower limbs in the running stereotype, they are transferred to the upper body via the pelvis. In this study, no significant differences were observed between pelvic movement patterns in individual planes depending on the neutral and minimalist footwear used during the run.

Movement of the pelvis in the sagittal plane took place over the entire range of the running cycle at a few-degree anterior tilt with variations of a few degrees regarding its positioning.

The highest pelvic tilt values were recorded at the end of the rebound and backward swing phases.

The pelvic movement in the frontal plane had a two-way nature of changes, and its range oscillated around 12º. Pelvic descent was observed in the range from 80% of the previous cycle to 30% of the analysed cycle, while pelvic lift was noted between 30% and 80% of the cycle.

Pelvic rotation movements also were of two-way nature, ranging, on average, around 7º. External rotation was recorded between 60% of the previous cycle and 15% of the analysed cycle. In the remaining area, opposite pelvic movement occurred from the outer to the inner position.

Conclusions

1. The research results indicate that running in minimalist footwear increases the range of dorsal flexion in the ankle joint during the phase of taking over the weight and positioning the foot in increased plantar flexion.
2. In the research, it was noted that knee flexion increases in the phase of body weight amortisation when using minimalist footwear.
3. Spatial pelvic movements do not differ significantly when running in neutral and minimalist shoes.

References:

[1] Bompa TO, Haff GG: Periodyzacja. Teoria i metodyka treningu. Warszawa: Biblioteka Trenera; 2010.

[2] Huei-Ming Ch: *Biomechanics of Running. Taipei: 柴惠敏 at School of Physical Therapy.* National Taiwan University; 2003.

[3] Hoffman J, Lewandowska A, Ratuszek-Sadowska D, Hoffman A, Kuczma M, Landowski P, et al.: *The running pattern and its importance in running long-distance gears*. J Educ, Health Sport. 2017; 7(7):969-977.

[4] 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.

[5] Eslami M, Begon M, Farahpour N, Allard P: *Forefoot–rearfoot coupling patterns and tibial internal rotation during stance phase of barefoot versus shod running*. Clin Biomech. 2007; 22:74–80.

[6] McNair P, Marshall RN: *Kinematic and kinetic parameters associated with running in different shoes*. Br J Sp Med. 1994; 28(4).

[7] Adelaar RS: *The practical biomechanics of running.* Am J Sports Med. 1986 Nov–Dec; 14(6):497–500.

[8] Di Caprio F, Buda R, Mosca M, Calabro A, Giannini S: *Foot and lower limb diseases in runners: assessment of risk factors*. J Sports SciMed. 2010 Dec; 9(4):587–596.

[9] Willems TM, De Ridder R, Roosen P: *The effect of a long-distance run on plantar pressure distribution during running*, Gait Posture. 2012 Mar; 35(3):40–59.

[10] Jaakko S: *Kinematic and kinetic differences between shod and barefoot running, Master´s*. Jyväskylä: Thesis in Biomechanics Department of Biology of Physical Activity University of Jyväskylä; 2016.

[11] Ferber R, Macdonald S: *Running Mechanics and Gait analysis*. Human Kinetics; USA; 2014.

[12] Riley POJ, Dicharry J, Franz UD, Croce RP, Wilder DC, Kerrigan A:. *Kinematics and Kinetic Comparison of Overground and Treadmill Running*. Med. Sci. Sports Exerc. 2008; 40(6):1093–1100.

[13] Willy RW, Davis IS: *Kinematic and kinetic comparison of running in standard and minimalist shoes*. Med Sci Sports Exerc. 2014; 46(2):318-23.

[14] Franz JR, Wierzbinski CM, Kram R: *Metabolic cost of running barefoot versus shod: is lighter better?*. Med Sci Sports Exerc. 2012; 44(8):1519-25.

[15] Bonacci J, Saunders UP, Hicks A, Rantalainen T, Vincenzio T, Spratford W: *Running in a minimalist and lightweight shoe is not the same as running barefoot: a biomechanical study*. Br J Sports Med. 2013; 47:387-392.

[16] Hall JP, Barton C, Jones PR, Morrissey D: *The biomechanical differences between barefoot and shod distance running: a systematic review and preliminary meta-analysis*. Sports Med. Dec. 2013; 43(12):1335-53.

Author for correspondence:

Wiesław Chwała,
E-mail: wieslaw.chwala@awf.krakow.pl; wachwala@cyf-kr.edu.pl
Phone: +48 683-10-01