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Relationship between lower limbs kinematic variables and effectiveness of sprint during maximum velocity phase

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Purpose: The aim of the study was to determine the relationships between time of running over a 15–25 m section of a 30-meter run along a straight line and changes in the angle and angular velocity observed in ankle, knee and hip joints. Therefore, the authors attempted to answer the question of whether a technique of lower limbs movement during the phase of sprint maximum velocity significantly correlates with the time of running over this section. Methods: A group of 14 young people from the Lower Silesia Voivodeship Team participated in the experiment. A Fusion Smart Speed System was employed for running time measurements. The kinematic data were recorded using Noraxon MyoMotion system. Results: There were observed statistically significant relationships between sprint time over a section from 15 to 25 m and left hip rotation (positive) and between this time and left and right ankle joint dorsi-plantar flexion (negative). Conclusions: During the maximum velocity phase of a 30 m sprint, the effect of dorsi-plantar flexion performed in the whole range of motion was found to be beneficial. This can be attributed to the use of elastic energy released in the stride cycle. Further, hip rotation should be minimized, which makes the stride aligned more along a line of running (a straight line) instead of from side to side.

Key words: *angular velocity, inertial sensors, motion pattern, running, young athletes*

1. Introduction

Sprint is a complex motion that engages the whole human body. The effectiveness of this motion (sprint time) determines the level of speed abilities, which are represented by values of kinetic and kinematic variables [17]. The main goal of a sprint is to cover the distance in a shortest possible time through maximization of the horizontal component of velocity of the runners centre of mass. The displacement occurs by means of cyclical movements of lower limbs based on continuous accelerations and decelerations, with the lower limbs acting as springs responsible for lifting the body mass over the surface [11], [16]. An example of a tissue that behaves as a spring is the Achilles tendon, which is long and compliant, alternately collecting and releasing elastic energy during human locomotion. It is estimated that Achilles tendon is able to produce 35% of the mechanical energy necessary for performing a running stride [10].

There are several consecutive phases of a sprint: start, push-off, acceleration and maximum velocity. All the phases are characterized by different technical and physiological demands to maximize motion efficiency. Furthermore, different training programs should be designed to improve individual phases of a sprint [3], [7].

Running velocity is represented by a mathematical product of stride length and stride frequency. In order to maximize running velocity it is necessary to proportionally increase both variables. Furthermore, each running phase requires different length-to-frequency ratios in order to maximize the effectiveness [18],

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[19]. The distance over which a sprinter achieves the maximum running velocity depends on age and sports skill level. In prepubescent sprinters, the maximum running velocity is achieved at a distance between 20 and 30 m [3]. Therefore, the technique of moving in this phase should be the most conducive to achievement of the maximum running velocity.

With the increase in the velocity of moving, the range of motion in the lower limbs becomes greater [20]. However, duration of the support phase is reduced while the flight phase elongates [2], [8]. The ranges of motion in the lower limbs during sprint are reduced with age, which explains the decline in the level of speed abilities in older people [13].

Krell and Stefanyshyn [16] suggest that kinematics of lower limbs plays an essential role during a sprint. However, these authors also found that the contribution of each joint of the lower limb to performance remains unclear. Ansari et al. [1] reported that kinematic variables, such as knee angle, hip angle, ankle angle, shoulder rotation and extension are key importance to sprinting technique and exemplified clear effect on sprint performance. Sławiński et al. [23] concluded that specific synchronization of motion of upper limbs with respect to lower limbs is necessary during a sprint. Ranjan [21] found no relationships between the angles in knee, hip and ankle joint and sprint start performance.

The aim of the study was to determine the relationships between time of running over a 15–25 m section of a 30-meter run along a straight line and changes in the angle and angular velocity observed in ankle, knee and hip joints. Therefore, the authors attempted to answer the question of whether a technique of lower limbs movement during the phase of sprint maximum velocity significantly correlates with the time of running over this section.

2. Material and methods

The examinations of the Lower Silesia Voivodeship Team members were carried out in a group of 265 participants selected from young people who trained team games (soccer, basketball, volleyball and handball). 14 people with the highest potential of speed abilities were selected from this group. The selection occurred based on the maximum height of the countermovement jump [24]. The study group was characterized by the following mean values (±SD): body height – 175.1 ± 17.4 cm, body mass – 61 ± 16.1 kg, age – 14.2 ± 1.2 years. Training experience was 4.5 ± 1.8 years. The experiments were carried out in the Games with Ball Laboratory (with PN-EN ISO 9001:2009 certification). The research project was approved by the Senate's Research Bioethics Commission at the University School of Physical Education in Wrocław, Poland.

Fifteen-minute warm-up was administered before the measurements. Each participant performed two 30 m runs over a straight line. Additionally, the athletes performed a test trial before the measurement. Analysis was based on the test with shorter time of 30-m sprint obtained by each participants.

A Fusion Smart Speed System (Fusion Sport, Coopers Plains, QLD, Australia) was used to measure the sprint time over individual sections. The system is comprised of gates (each gate is equipped with a photocell with an infrared transmitter and a light reflector) and a RFID reader for athlete identification. The "30-m run over a straight line" test was carried out using 7 gates. A distance of 2 meters was adjusted between the photocell and the light reflector. Individual gates were located at distances of 5 meters (beginning from the start line) between each other to record times of crossing the IR beam. The gate at a distance of 30 meters denoted the finish line. The split times at distances of 5, 10, 15, 20 and 25 m were also recorded. The participants started from a standing position at the light signal.

Noraxon MyoMotion (Scottsdale, AZ, USA) motion analysis system was employed to analyse kinematic variables. MyoMotion Reseach inertial sensors were placed according to the rigid-body model with 16 joint segments used in MR3 software on shoes (top of the upper foot, slightly below the ankle), shanks (frontal on the tibia bone), thighs (frontal attachment on lower quadrant of quadriceps, slightly above the knee cap, area of lowest muscle belly displacement in motion) and bony area of sacrum. Calibration was carried out using the upright position in order to determine the value of the 0^o angle in the joints studied. Sampling frequency for the inertial sensors was set at 200 Hz. Instantaneous changes in joint angles in the area of the lower limb were recorded: hip joint (with respect to the long, transverse and sagittal axes), knee joint (with respect to the transverse axis) and ankle joint (with respect to the long, transverse and sagittal axes) during a 30-m run along the straight line. Positive values of the angle depending on the joint and axis correspond to: flexion, abduction, external rotation, dorsi-flexion and inversion. Angular velocities in the area of these joints were determined based on the derivative of the distance (angle) with respect to time. The analysis was based on two complete cycles of the running stride of the left and right limb (which occurs during the maximum velocity phase) determined with respect to instantaneous angle in the knee joint. The above running strides occurred between 15 and 25 m.

Table 1. Mean values (±SD) of mean sprint velocity at individual 5-metre sections during a 30-m sprint along the straight line

Section (m)	Mean velocity (km/h)
0–5	13.5 ± 3
5–10	23.2 ± 1.8
10–15	25.7 ± 2.1
15–20	27.4 ± 2.2
20–25	28.6 ± 2.9
25–30	27.5 ± 3.1

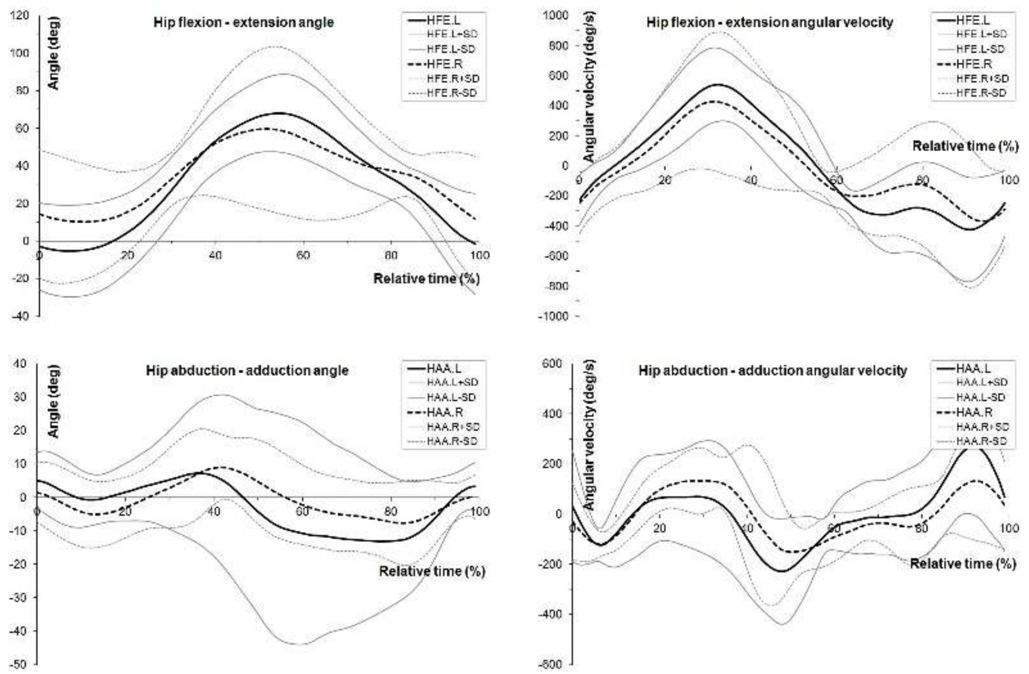
Table 1 contains values of mean sprint velocity at individual 5-metre sections during a 30-m sprint along the straight line. It can be adopted based on mean sprint velocity that the velocity remains relatively constant between 15 and 30 meters. Therefore, both running stride cycles were normalized with respect to time and averaged. Mean profiles of changes in the angle and angular velocity were calculated with standard deviations for both lower limbs separately. Before graphical presentation shown in Fig. 1, the profiles were smoothed. According to Table 1, maximum value of the running velocity is expected to occur between 20 and 25 meters. The last five meters of the run were neglected for the analysis as a phase of maximum velocity in order to avoid the effect of deceleration of the subject. The section from 15 to 25 m was adopted as a phase of maximum velocity during a 30 m sprint along a straight line in order to select two running strides.

In order to analyse the relationships between the sprint time over the section of 15–25 m and individual kinematic variables there was used Spearman's rank correlation coefficient due to the lack of normal distribution of the variables studied. For the same reason, the Wilcoxon matched pairs test was used for evaluation of the differences between the right and left body side. The level of significance was set at $\alpha = 0.05$.

3. Results

Figure 1 presents instantaneous changes in the angle and angular velocity in the area of lower limb joints: hip joint (with respect to the long, transverse and sagittal axes), knee joint (with respect to the transverse axis) and ankle joint (with respect to the long, transverse and sagittal axes) during the maximum velocity phase of a 30-m run along the straight line.

Table 2 contains mean values of the maximum angle (α_{max}), minimum angle (α_{min}) and range of motion (ROM) of the lower limb joints with respect to specific axes during the maximum velocity phase of a 30 m run along a straight line. Furthermore, Table 3 contains mean values of the maximum angular velocity (ω_{max}), minimum angular velocity (ω_{min}) and range of angular velocity (ROAV) of the lower limb joints with respect to specific axes during the maximum velocity phase of a 30 m run along the straight line.



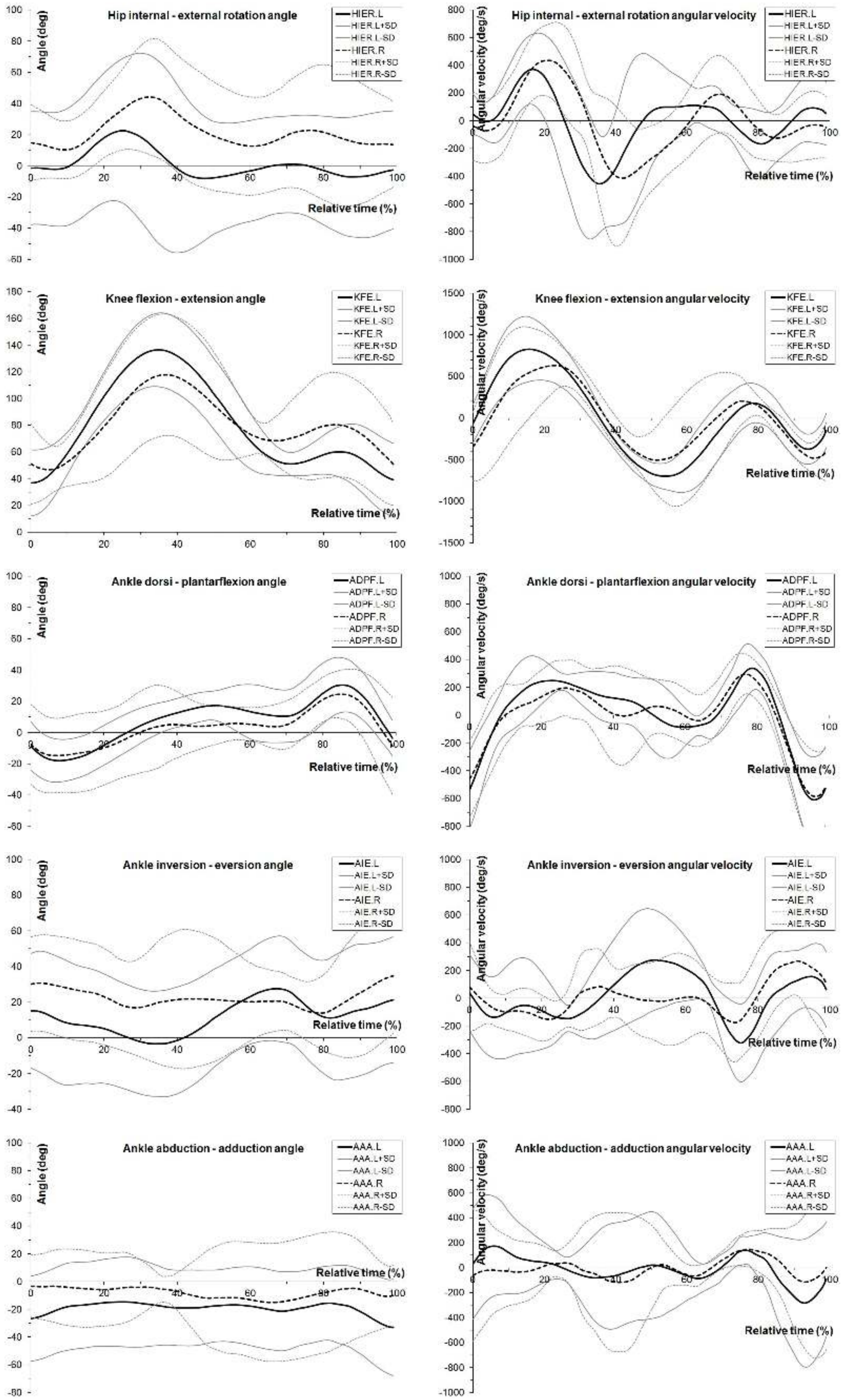


Fig. 1. Instantaneous changes in the angle and angular velocity in the area of lower limb joints with respect to specific axes during 30-m sprint maximum velocity phase along a straight line for the left limb (continuous line) and right limb (dashed line). Continuous or dashed thin grey lines were denoted ±SD for the left and right limb, respectively

Table 2. Mean values (±SD) of maximum angle (α_{max}), minimum angle (α_{min}) and range of motion (ROM) of the lower limb joints with respect to specific axes during the maximum velocity phase of a 30 m sprint along the straight line

	Left body side			Right body side		
	α_{max} (°)	α_{min} (°)	ROM (°)	α_{max} (°)	α_{min} (°)	ROM (°)
Hip flexion-extension	76.7 ± 7.3	–12.3 ± 7.3	89.1 ± 3.3	79.6 ± 12.5	–11 ± 9.9	90.6 ± 6.2
Hip abduction-adduction	19.1 ± 14.5	–22.3 ± 23.2	41.3 ± 29.1	15.4 ± 7.1	–16.1 ± 7.7	31.5 ± 8.8
Hip internal-external rotation	32.8 ± 47.6	–22.2 ± 40.8*	55 ± 23.2	57.7 ± 40.7	–0.2 ± 24.5*	57.9 ± 26.5
Knee flexion-extension	142.6 ± 17.4	–28.6 ± 11.6	114 ± 19.8	141.5 ± 21	–31.5 ± 12.2	110 ± 13.3
Ankle dorsi-plantar flexion	35.2 ± 11.9	–22.7 ± 11.6	57.9 ± 10.4	27.3 ± 16.5	–26 ± 19	53.2 ± 9
Ankle inversion-eversion	41.2 ± 26.3	–14.8 ± 27.8	56 ± 29.5	45.8 ± 30.9	–2.4 ± 21.4	43.3 ± 16.7
Ankle abduction-adduction	9.5 ± 22.8	–47.6 ± 31.1	57.1 ± 32.8	16.9 ± 30.6	–35.8 ± 31.4	52.8 ± 53.5

* statistically significant difference at $p < 0.05$.

Table 3. Mean values (±SD) of the maximum angular velocity (ω_{max}), minimum angular velocity (ω_{min}) and range of angular velocity (ROAV) of the lower limb joints with respect to specific axes during the maximum velocity phase of a 30 m sprint along the straight line

	Left body side			Right body side		
	ω_{max} (°/s)	ω_{min} (°/s)	ROAV (°/s)	ω_{max} (°/s)	ω_{min} (°/s)	ROAV (°/s)
Hip flexion-extension	650.5 ± 63.8	–590 ± 119.4	1240.4 ± 146.3	662.4 ± 62.4	–563 ± 150.4	1225.2 ± 191.9
Hip abduction-adduction	396.6 ± 199.2	–334.9 ± 157.4	731.5 ± 344.9	327 ± 94.6	–280.1 ± 67.2	607.2 ± 141.8
Hip internal-external rotation	558.5 ± 240.8	–731.3 ± 350	1289.7 ± 568.5	577.8 ± 187.6	–592.2 ± 423.3	1169.9 ± 562.2
Knee flexion-extension	934.7 ± 199.2	–760.1 ± 171	1694.9 ± 344.4	907.7 ± 93.6	–829 ± 217.4	1736.7 ± 291
Ankle dorsi-plantarflexion	462.7 ± 157.7	–736.4 ± 149.8	1199.3 ± 225.9	416.7 ± 93.1	–753 ± 138.2	1169.7 ± 213.5
Ankle inversion-eversion	532.9 ± 216.4	–475.5 ± 247.8	1008.5 ± 433.1	483.1 ± 252.1	–440.6 ± 200.8	923.8 ± 446.8
Ankle abduction-adduction	502.8 ± 273.1	–617.6 ± 265.6	1120.3 ± 500.7	441.2 ± 435.1	–517 ± 398.9	958.2 ± 818.2

The instantaneous changes of the angle and angular velocities in individual joints for left and right sides presented in Fig. 1 are not perfectly coincident with each other. No statistically significant differences between left and right body side were found for variables α_{max}, α_{min}, ROM, ω_{max}, ω_{min} and ROAV. One exception was a statistically significant difference between the value of angle for hip internal rotation (α_{min}).

There were observed statistically significant correlations between sprint time over the section from 15 to 25 m and individual kinematic variables only for left hip rotation (positive) and left and right ankle joint dorsi-plantar flexion (negative). Values of correlation coefficients are presented in Table 4.

Table 4. Values of correlation coefficients between running time (t) and maximum angle (α_{max}), minimum angle (α_{min}), range of motion (ROM), maximum angular velocity (ω_{max}), minimum angular velocity (ω_{min}) and range of angular velocity (ROAV) for individual joint motions

	Left body side			Right body side		
	Hip internal-external rotation					
	α_{max}	α_{min}	ROM	α_{max}	α_{min}	ROM
t	0.56*	–0.58*	0.05	–	–	–
	Ankle dorsi-plantarflexion					
	α_{max}	α_{min}	ROM	α_{max}	α_{min}	ROM
t	–0.66*	0.63*	–0.17	–0.4	0.05	–0.82*
	Ankle dorsi-plantarflexion					
	ω_{max}	ω_{min}	ROAV	ω_{max}	ω_{min}	ROAV
t	–	–	–	–0.77*	0.16	–0.69*

* statistically significant relationship between variables at $p < 0.05$.

4. Discussion

Previous measurements of kinematic variables in lower limbs during running have been recorded mainly by means of optical measurement systems based on the use of cameras [1], [3], [4], [6], [8], [11], [13]–[19], [21]–[23]. This causes certain limitations of the measurement space. In the present study, we used Noraxon MyoMotion system, which is entirely independent of external cameras. A small inertial measurement unit (IMU) placed on a body segment tracks its 3D angular orientation. By placing individual IMU sensors on two neighbouring body segments, one can evaluate the range of motion in the joint placed between these segments. This principle might be extended from an individual movement of a joint over simultaneous measurement of the motion of the whole body in individual major joints. The system is entirely wireless and does not need calibration of the measurement space, which allows for measurements outside the laboratory.

A statistically significant difference was recorded between the left and right body side for the angle of hip internal rotation during the maximum velocity phase of a 30 m sprint. However, slight functional asymmetry during the movement is typical of human and does not represent pathology if its value is not significant [5]. Greater values of internal rotation angles in the left hip joint might be attributed to asymmetric structure of motion in team sports games. Tables 2 and 3 show relatively high values of standard deviations for certain movements performed in lower limb joints with respect to specific axes during the maximum velocity phase of a 30 m sprint. This might suggest certain interpersonal differentiation of running technique. Additionally, curves of instantaneous changes in standard deviations for the left and right lower limbs have slightly different pattern. This is particularly noticeable for hip flexion-extension angle, hip abduction-adduction angle, hip internal-external rotation angle or knee flexion-extension angle. The causes of this phenomenon can be attributed to predominance of a limb, which leads to slightly different movement pattern during running between left and right lower limb. The right lower limb was dominant for all the young athletes examined in the study (information collected in the form of an interview with study participants).

The study carried out by Ansari et al. [1] showed that kinematic variables, such as knee angle, hip angle, ankle angle, shoulder rotation and extension have essential effect on sprinting technique. Greater range of motion in the knee joint significantly affects performance. For instance, when the heel gets closer to the hips (buttocks), the inertia radius is shortened, which helps achieve higher angular velocity in the knee joint. Biewener et al. [4] also found that the value of knee flexion improves running time. However, no statistically significant correlations were found in our study between running time and values of angles, angular velocities and range of motion in the knee joint.

The athletes who obtained shorter running times were characterized by shorter time of contact with the ground and longer running stride during the maximum velocity phase compared to the slower competitors [2]. In order to elongate running stride it is necessary to improve the range of motion in the lower limb joints. In the present study, however, only greater range of motion in the ankle joint was positively correlated with running time.

The statistically significant positive relationship between the running time over the section of 15 to 25 meters and the angle of left hip rotation suggests minimization of this motion during a sprint in order to improve performance. Therefore, running stride should be performed along a line aligned with the direction of running (straight line) rather than from side to side. Efficient sprint is connected with placing the foot possibly closer to the location of the vertical projection of the centre of gravity of the runner's body on the ground. In order to counteract the horizontal deceleration, the foot, after the contact with the ground, should move towards the rear with respect to the general centre of gravity with the horizontal velocity which is greater than the velocity of the general centre of gravity [18].

There were observed statistically significant negative relationships between sprint time over the section from 15 to 25 m and the range of motion during left and right ankle joint dorsi-plantar flexion. Thus, this motion during the sprint maximum velocity phase should be performed with the fullest possible range. This relationship can be attributed to the use of elastic energy released in the stride cycle. Thanks to the ability of tendino-muscular groups to collect and recovery of elastic energy it is added to the contraction work. Therefore, values of leg stiffness, which represents a quantitative measure of their elastic properties, beneficially affect running performance [9], [12]. Leg stiffness increases with velocity to modulate stride frequency and propulsion energy [15]. Higher range of motion in the ankle joint with respect to the transverse axis will cause greater extension of the Achilles tendon which accumulates and releases elastic energy.

Obviously, the "entire spring" which is used during a running stride is formed by a much more softer tissue, i.e., skeletal muscles [10]. Furthermore, Hamner et al. [14] demonstrated that plantarflexor muscles have a key effect on velocity of the centre of gravity of the runner's body.

The study carried out by Brizuela et al. [6] show that the reduction in the range of motion might be caused by the specific nature of the footwear. Greater support in the ankle joint through high support shoes reduces ankle eversion range but it increases shock transmission, and reduces running and jumping performance. Schulze et al. [22] argue that the range of motion in the ankle joint depends on the properties of the footwear used. However, type of footwear used by the participants was not monitored in our study.

5. Conclusions

1. During the maximum velocity phase of a 30 m sprint, the effect of dorsi-plantar flexion performed in the whole range of motion was found to be beneficial. This can be attributed to the use of elastic energy released in the stride cycle.
2. Hip rotation should be minimized, which makes the running gait aligned more along the direction of running (a straight line) rather than from side to side.
3. No statistically significant differences were found between the left and right body side for kinematic variables in the area of lower limb joints (maximum angle, minimum angle, range of motion, maximum angular velocity, minimum angular velocity and the range of angular velocity) during the maximum velocity phase of a 30-m sprint. One exception was a statistically significant difference in the value of angle for hip internal rotation. The greater value of internal rotation angle was observed in the left hip joint.

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