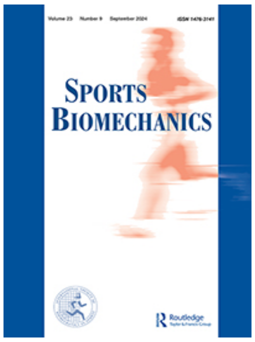

Sports Biomechanics

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/rspb20

A comparison of foot and ankle biomechanics during running drills and distance running

Guillaume Abran, Audrey Berraz, Nadia Dardenne, Kevin Gramage, Stephen Bornheim, François Delvaux, Jean-Louis Croisier & Cédric Schwartz

SPORTS BIOMECHANICS
https://doi.org/10.1080/14763141.2024.2382804

Routledge
Taylor & Francis Group

Check for updates

A comparison of foot and ankle biomechanics during running drills and distance running

Guillaume Abran[a,b], Audrey Berraz[c], Nadia Dardenne[d], Kevin Gramage[a,b], Stephen Bornheim[b], François Delvaux[a,b], Jean-Louis Croisier[a,b] and Cédric Schwartz[a]

[a]LAM – Motion Lab, Liége, Belgium; [b]Department of Physical Activity and Rehabilitation Sciences, University of Liege, Liege, Belgium; [c]Université de Technologie de Compiègne (UTC), Alliance Sorbonne Université, Compiègne, France; [d]University and Hospital Biostatistics Center (B-STAT), University of Liège, Liège, Belgium

ABSTRACT

The aim of this study was to compare the foot-ankle joint mechanics of running drills and running. Seventeen long-distance runners performed five popular running drills (A-skip, B-skip, Bounding, Heel flicks, Straight leg running) and a run at 3.88 m/s. Kinematics, kinetics and power values were calculated for the ankle, midtarsal (MT) and metatarsophalangeal (MP) joints. Electromyographic activity was recorded for the soleus, gastrocnemius medialis, lateralis and abductor hallucis muscle. The A-skip, the B-skip and the Heel flicks induced a smaller ankle ($p < 0.001$, $\eta^2 = 0.41$), MT ($p < 0.001$, $\eta^2 = 0.43$) and MP ($p < 0.001$, $\eta^2 = 0.47$) dorsiflexion peak than running. No difference was found between the running drills and running for ankle, MT and MP moment. The Bounding induces a higher positive ankle power than running (diff: 5.5 ± 7.5 J/kg, $p = 0.014$, $d = 1.05$). The A-skip (diff: 2.8 ± 2.9 J/kg, $p < 0.001$, $d = 1.5$) and the B-skip (diff: 2.7 ± 2.1 J/kg, $p < 0.001$, $d = 1.4$) induce a smaller MT positive power than running. This study offers an analysis of the mechanical behaviour of the foot-ankle complex to help track and field coaches select their running drills in an evidence-based manner.

ARTICLE HISTORY
Received 5 January 2024
Accepted 12 July 2024

KEYWORDS
Multi-segment foot; kinematics; kinetics; EMG; athletics

Introduction

Plyometric training (PT) is particularly used by athletics coaches and can improve running economy (Oxfeldt et al., 2019; Spurrs et al., 2003; Turner et al., 2003). These improvements varied from 2% to 6%, according to the runner's level and plyometric protocol. Pv (1984) described the concept of the 'stretch-shortening cycle' which is a specific contraction mode used during plyometric tasks and running. The stretch-shortening cycle corresponds to cyclic contraction involving a lengthening movement (eccentric) quickly followed by a shortening movement (concentric) (Komi, 1984). Moreover, PT has several benefits such as improving neuromuscular coordination, higher levels of muscle activation, increased rates of force development and increased ankle plantar flexor and toe flexor strength (Goldmann, Potthast, et al., 2013; Goldmann, Sanno, et al., 2013; Oxfeldt et al., 2019).

CONTACT Guillaume Abran guillaume.abran@uliege.be

In the track and field, the most popular PT implemented by coaches is running drills (Whelan et al., 2016). Running drill training is based on exercises that focus on the phases of the running cycle (Azevedo et al., 2015). According to Whelan et al. (2016), the running drills which are the most commonly used in the field are the 'A-skip', 'Heel flicks', 'Bounding', 'B-skip', 'Straight leg running'. Depending on their form, running drills induce different levels of stress on the muscles that make up the ankle plantar flexor group (Trowell et al., 2022). For instance, A-skip induces a lower plantar flexor load than running. In contrast, Bounding induces a higher mechanical load for both plantar flexors (Trowell et al., 2022). However, the study that highlighted these findings used a simplified foot model composed of a single segment. The foot is a complex structure composed of 26 small bones and 33 joints, resulting in high mobility (Leardini et al., 2019). During the last decades, several research groups have used the latter approach to model the foot according to a number of small segments rather that one single rigid segment, generally referred to as multi-segment foot models (Deschamps et al., 2011; Leardini et al., 2019). Multi-segment foot models involve positioning additional markers compared to the simplified model to subdivide the foot into several segments (three to 26 segments) (Cornwall & McPoil, 1999; Oosterwaal et al., 2011). Modelling the foot as a single rigid segment induces an over-estimation of the angular excursion and mechanical power at the ankle joint during hopping (Kessler et al., 2020). Over-estimation of ankle plantar flexor power requirements could lead to inaccurate estimates of the activation and energetics of the plantar flexor muscle group (Kessler et al., 2020). In addition, rigid-foot models do not consider the power generated within the foot. Several studies have shown the importance of the role of the foot in athletic performance, such as horizontal jump performance, the ability to change direction, the personal best in a 50 m run (Goldmann, Sanno, et al., 2013; Hashimoto & Sakuraba, 2014; Yuasa et al., 2018) and in the prevention of running-related injuries (Taddei et al., 2020). Therefore, the function of the foot should be considered as a key component of an athlete's lower limb. Understanding foot mechanics during running drills could help athletic coaches improve their exercise selection to develop foot function.

The aim of this study was to explore the mechanics of the foot-ankle complex during running drills and distance running using a multi-segment foot model. The use of a multi-segment foot model will help to understand the biomechanics within the foot and reduce the risk of inaccurate estimation of the contribution of the plantar flexor muscle group. The research objective is to compare kinematic, kinetic and energetic values at the ankle and the foot from commonly used running drills to distance running at endurance speed. Based on the study of Trowell et al. (2022), it is hypothesised that Bounding will induce higher foot and ankle power than running whereas the A-skip and B-skip will induce less than distance running.

Materials and methods

Participants

An a priori power analysis revealed that a minimum of 16 participants are required for this study (effect size $f = 0.274$, $\alpha = 0.05$, $1-\beta = 0.8$), one group with six tasks (see the tasks description section). Eligibility criteria included age between 18 and 35 years, running in an athletic club for at least 5 years and practise running drills every week. Participants were recruited by convenience via local running clubs. This study was approved by the local ethics committee (19/04/2022; protocol No. 2022/102). Before the beginning of the study, each participant received a written document that explained the study and its requirements. The document included information about the purpose of the study, procedures involved, risks and benefits, confidentiality, and participant rights. Participants were asked to sign the document as an indication of their willingness to participate.

Experimental protocol

Muscle activation and biomechanical variables were collected on an indoor 30 m straight running track. Participants performed, in barefoot condition, five running drills (Figure 1) and a run at 3.88 m/s in random order: A-skip, B-skip, Bounding, heel flicks, straight leg running, and running at 3.88 m/s (±5%). The barefoot condition was imposed on the participants because the equipment installed on the foot did not allow them to wear running footwear. A previous study showed that placing material directly on the running footwear does not fully reflect the movement of the foot joint (Perrin et al., 2023).

Tasks description

The A-skip involved participants skipping forward on one leg, while the opposite knee was driven upward by flexing the hip, knee, and ankle. The hip and knee then rapidly extended towards the ground, while the ankle remained in a dorsiflexed position. The skip action required knee lift in the swing leg to occur over two ground contact periods of the stance leg. The B-skip is nearly identical to the A-skip, but requires first extending the leg forward before the foot hits the ground. Bounding involved taking long, leaping strides. The Heel flicks required flexion of the hip as much as during the A-skip and knee flexion in order to hit the buttock with the heel. Finally, the Straight leg running (SLR) involves running forward with the knee locked in extension. The participants were free to use their arms during the running drills. Running was performed by each participant with its self-selected technique. Given their performance level in running, a speed of 3.88 m/s was selected to ensure a sub-maximal running speed and, consequently, a comfortable running technique. Five trials were collected for each single task (running drills and running at 3.88 m/s). For the running task, the running speed was checked after each trial by the experimenter by calculating the speed of the barycentre of the markers placed on the pelvis. Participants received a feedback ('run faster' or 'run slower') after each trial to reach a speed of 3.88 m/s (±5%) in five trials. A period of self-determined recovery was allowed between the trials to minimise fatigue.

Kinematic

Kinematic data were measured using four optoelectronic units (Codamotion system; Charnwood Dynamics; Rothley, UK) with a sampling rate of 200 Hz. Twenty-five active markers were placed by a single-experimented physiotherapist specialised in foot biomechanics on the following anatomical landmarks of the dominant lower limb: distal phalange of the first toe, head of the first, second and fifth metatarsals, base of the first and second metatarsals, posterior calcaneus, navicular tuberosity, and the cuboid bone

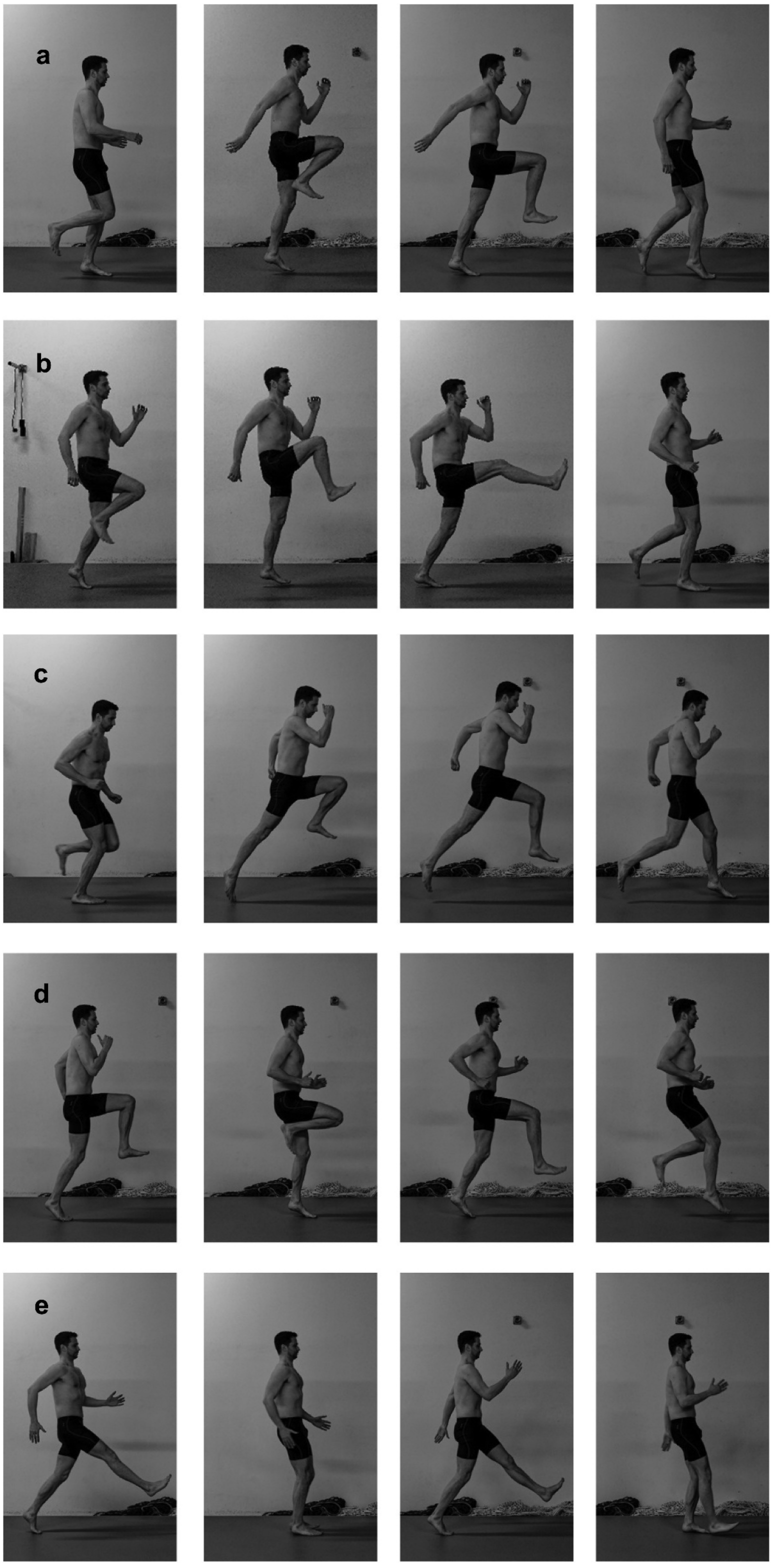

Figure 1. Diagram of each running drills performed by the participant. (a) A-skip; (b) B-skip; (c) Bounding; (d) Heel flicks; (e) Straight leg running (SLR).

(Schwartz et al., 2020). Additional markers were placed on the medial and lateral malleoli, medial and lateral femoral condyles, and the anterior and posterior iliac spines. Clusters of four markers were attached to the lateral thigh and shank (Figure 2). The ground reaction force (GRF) data were simultaneously captured using two consecutive force plates (Kistler, Kistler Group, Switzerland) at a sample rate of 1000 Hz. The four optoelectronic units were placed around the force plates to ensure a good visibility of the markers while the participant is passing.

Electromyography

Surface electromyographic (EMG) signals were simultaneously collected with Trigno Standard sensors (Delsys, Boston, MA, USA) using silver-contact wireless bipolar bar electrodes with fixed 10 mm inter-electrode spacing. Electromyographic signals were recorded on the two heads of the gastrocnemius muscle, the soleus and the abductor hallucis. Electrode placement and skin preparation were performed based on the recommendations of Barbero et al. (2012) and Branthwaite et al. (2019). Data were acquired at a sample frequency of 1000 Hz.

Kinematic, kinetic and electromyographic devices were connected to a central control unit (CodaHub, Charnwood Dynamics, UK), which ensure the synchronisation of all the inputs.

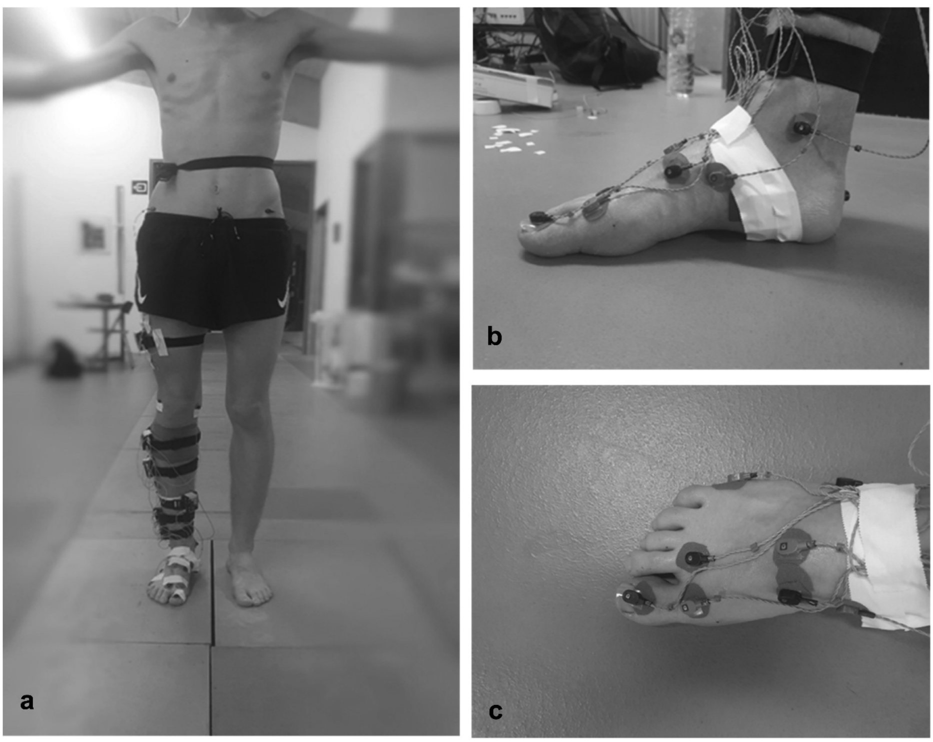

Figure 2. (a) Illustration of a volunteer equipped with the active markers and the EMG electrodes on the right lower limb. (b) Medial view of the foot after material placement. (c) Top view of the foot after material placement.

Data analysis

GRF data were filtered using a 50-Hz, zero-phase low-pass fourth-order Butterworth filter as described in Takabayashi et al. (2021). The stance phase was defined between the instant when the vertical GRF increased above 20 N and the instant when it fell below 20 N. All the biomechanics variables were analysed during the stance phase.

Visual 3D software (C-motion Inc., Germantown MD, USA) was used for biomechanical modelling and analysis. A three-segment kinetic foot model was created, from (Bruening et al., 2012a), containing a hindfoot, midfoot, and phalanges, separated by midtarsal (MT) and metatarsophalangeal (MP) joints. The MT joint centre was positioned midway between the cuboid bone and navicular markers, and the MP joint centre was positioned midway between the first and fifth metatarsal heads. The ankle and MT joint motions were modelled with six degrees-of-freedom (DOF), whereas the MP joint was modelled with two DOF.

Marker trajectories from the running drills and the running trials were low-pass filtered using a zero-phase 4th order Butterworth filter (12 Hz cut-off) as described by previous author (Leardini et al., 2021). The joint angles were derived using a typical Cardan angle rotation sequence (1-sagittal, 2-frontal, 3-transverse) (Leardini et al., 2021). Joint angles were expressed relatively to the individual static position (standing upright, arms by their sides and looking forward). Ankle, MT and MP dorsiflexion and plantarflexion were defined as kinematic output measures. Concerning kinetics, inverse dynamics were used to calculate the net internal moments and powers at each joint of the foot and ankle (Bruening et al., 2012b). The net internal moments and powers were normalised to body weight (BW) for each participant.

EMG signals were first band pass filtered (20–500 Hz, zero-phase 4th order Butterworth filter) and then processed using a root mean-square filter (100 ms moving window). The peak of the EMG signals was extracted for each task repetition. Then, the median of the peaks of the EMG signals was kept as the EMG output measure. The EMG signals were expressed in mV. The EMG signals were expressed in mV. The trials were not included in the analysis when the participant's foot did not land distinctly on one of the two force plates.

The means of the kinematic and kinetic parameters of the included trials were calculated for the analysis.

Statistical analysis

Statistical analyses were performed using JASP (version 0.17.3, 2023) (Van Doorn et al., 2021). The results were significant at the 5% critical level ($p < 0.05$). Repeated measures analysis of variance (ANOVA) were used to compare the peak of dorsiflexion and plantarflexion, the range of motion, the moments, the positive and negative power of the ankle, the MT and the MP joint across the six tasks (the five running drills and running). If Mauchly's test of sphericity indicated that the assumption of sphericity was violated ($p < 0.05$), a Greenhouse–Geisser test was applied for sphericity correction. The partial eta square was calculated as the measure of effect size defined as small ($\eta^2 = 0.01$), medium ($\eta^2 = 0.06$) and strong ($\eta^2 = 0.14$) (Maher et al., 2013). A post-hoc analysis was performed with a Bonferroni's correction. Repeated measures analysis of variance tests were also used to compare the values of muscle activity of the medial and lateral heads of the gastrocnemius, soleus and abductor hallucis between running drills and running. The Cohens d effect of post-hoc analysis was calculated with effect sizes defined as small ($d = 0.2$), medium ($d = 0.5$) and strong ($d = 0.8$) (Hopkins et al., 2009). As an indication, the percentage of muscle activity of the medial and lateral heads of the gastrocnemius, soleus and abductor hallucis relative to running were calculated for the running drills.

Results

Data were collected for 17 runners (15 males, 2 females, age = 26.6 ± 5.6 years; mass = 67.5 ± 5.5 kg, height = 1.77 ± 0.07 m, personal best in 10.000 metres race = 35.1 ± 4.4 minutes, volume per week = 52.8 ± 22.4 km, experience in running = 9.6 ± 4.1 years).

All mean, standard deviations, p-values and effect sizes for the ankle, MT and MP are shown in Table 1 (kinematic data), Table 2 (kinetic data) and Table 3 (energetic data).

Ankle

Ankle plantar flexion peak was similar between the running drills and running ($p = 0.40$, $\eta^2 = 0.58$) whereas the ankle dorsiflexion peak ($p < 0.001$, $\eta^2 = 0.41$) and ankle ROM ($p < 0.001$, $\eta^2 = 0.42$) were different. For ankle dorsiflexion peak, post hoc tests showed that the A-skip (difference (diff): 14.5 ± 18.5°, $p < 0.001$, $d = 1.5$), the B-skip (diff: 13.4 ± 19.3°, $p < 0.001$, $d = 1.4$), the SLR (diff: 10.2 ± 16.3°, $p = 0.01$, $d = 1.0$) and the Heel flicks (diff: 13.4 ± 17.7°, $p < 0.001$, $d = 1.4$) induced smaller values than running. However, only the A-skip (diff: 9.8 ± 7.3°, $p < 0.001$, $d = 1.14$) and the B-skip (diff: 8.7 ± 6.7°, $p = 0.007$, $d = 1.0$) induced a smaller ankle ROM than running.

From a kinetics point of view, differences were only found within the running drills (Bounding vs A-skip & Bounding vs B-skip) but no difference was found between the running drills and running.

For positive ankle power, only the bounding induced a higher value than running (diff: 5.5 ± 7.5 J/kg, $p = 0.014$, $d = 1.05$) whereas the value of the four other running drills was not significantly different to running. No difference was found for negative ankle power between each running drills and running ($p = 0.05$, $\eta^2 = 0.18$).

Midtarsal

MT plantar flexion peak was similar between the running drills and running ($p = 0.35$, $\eta^2 = 0.06$) whereas the MT dorsiflexion peak ($p < 0.001$, $\eta^2 = 0.43$) and MT range of motion ($p < 0.001$, $\eta^2 = 0.29$) were different. For MT dorsiflexion peak, post hoc tests showed that the A-skip (diff: 6.5 ± 5.8°, $p < 0.001$, $d = 1.0$), the B-skip (diff: 6.4 ± 5.3°, $p < 0.001$, $d = 0.9$) and the Heel flicks (diff: 5.2 ± 5.3°, $p = 0.002$, $d = 0.7$) induced smaller values than running. As for the ankle ROM, only the A-skip (diff: 7.7 ± 7.8°, $p = 0.005$, $d = 0.8$) and the B-skip (diff: 6.9 ± 7.9°, $p = 0.007$, $d = 1.0$) induced smaller MT ROM than running.

From a kinetics point of view, a difference was only found between the Bounding and the A-skip ($p = 0.007$, $d = 0.97$) but no difference was found between the running drills and running.

Table 1. Comparison of the ankle, the midtarsal and the metatarsophalangeal kinematics between running drills and running (mean ± SD).

Joint	Tasks	Dorsiflexion peak (Degree)	*p*-value	η²	Post-hoc test	Plantarflexion peak (degree)	*p*-value	η²	Post-hoc test	ROM (degree)	*p*-value	η²	Post-hoc test
Ankle (Degrees)	A-Skip (1)	1.6 ± 6.6	**<0.001**	0.41		−26.8 ± 9.3	=0.40	0.05		28.5 ± 7.0	**<0.001**	0.42	
	B-skip (2)	2.7 ± 3.6				−26.9 ± 5.0				29.6 ± 6.2			
	Bounding (3)	14.4 ± 7.5			(3) >; (1)***, (2)***, (4)***, (5)*	−29.2 ± 9.6				43.3 ± 10.1			(3) >; (1)***, (2)***, (4)***, (5)*
	Heel flicks (4)	2.7 ± 7.4				−28.5 ± 11.4				31.2 ± 12.7			
	SLR (5)	5.9 ± 5.8				−29.0 ± 7.3				35.0 ± 8.4			
	Running (6)	15.3 ± 16.1			(6) >; (1)***, (2)***, (4)***, (5)*	−23.3 ± 18.4				38.6 ± 6.4			(6) >; (1)***, (2)**
MT (Degrees)	A-Skip (1)	9.6 ± 5.7	**<0.001**	0.43		−13.3 ± 7.0	=0.35	0.06		23.0 ± 3.2	**<0.001**	0.29	
	B-skip (2)	9.7 ± 5.0				−14.1 ± 6.3				23.9 ± 3.1			
	Bounding (3)	14.0 ± 3.8			(3) >; (1)***, (2)***, (4)*	−12.8 ± 7.5				26.8 ± 3.2			
	Heel flicks (4)	11.0 ± 4.6				−13.7 ± 7.1				24.7 ± 3.7			
	SLR (5)	13.7 ± 5.0			(5) >; (1)***, (2)***	−15.2 ± 8.1				29.0 ± 4.9			(5) >; (1)***, (2)**, (5)*
	Running (6)	14.9 ± 6.2			(6) >; (1)***, (2)***, (4)**	−13.2 ± 7.2				28.1 ± 5.9			(6) >; (1)**, (2)*
MP (Degrees)	A-Skip (1)	27.1 ± 7.9	**<0.001**	0.47		1.1 ± 3.9	=0.41	0.06		25.3 ± 9.4	**<0.001**	0.43	
	B-skip (2)	26.1 ± 7.6				−0.1 ± 1.9				25.7 ± 8.3			
	Bounding (3)	30.1 ± 7.4			(3) >; (4)*	1.0 ± 2.7				28.3 ± 8.4			
	Heel flicks (4)	25.0 ± 7.6				1.1 ± 3.7				23.4 ± 8.5			
	SLR (5)	32.0 ± 8.0			(5) >; (1)*, (2)*, (4)***	0.7 ± 3.0				30.5 ± 8.1			(5) >; (1)*, (2)*, (4)***
	Running (6)	35.6 ± 9.1			(6) >; (1)***, (2)***, (3)*, (4)***	0.9 ± 2.9				33.9 ± 9.1			(6) >; (1)***, (2)***, (3)**, (4)***

*MT = midtarsal; MP = Metatarsophalangeal; ROM = Range of Motion; Repeated measures ANOVA followed by Bonferroni's correction : p > 0.05, not significant; * symbol represents a p-value for post-hoc test inferior to 0.05; ** symbol represents a p-value for post-hoc test inferior to 0.01; *** symbol represents a p-value for post-hoc test inferior to 0.001. Tasks are represented by a number from 1 to 8 in post-hoc test. ANOVA, Analysis of Variance; SD, Standard deviation:.*

Table 2. Comparison of ankle, midtarsal and metatarsophalangeal kinetics between running drills and running (mean ± SD).

Joint	Tasks	Moment (N.m/kg)	*p*-value	η^2	Post-hoc test
Ankle	A-Skip (1)	3.01 ± 0.53	**=0.016**	0.02	
(N.m/kg)	B-skip (2)	3.15 ± 0.45			
	Bounding (3)	3.66 ± 0.72			(3) >; (1)**, (2)*
	Heel flicks (4)	3.30 ± 0.61			
	SLR (5)	3.41 ± 0.51			
	Running (6)	3.40 ± 0.66			
MT (N.m/kg)	A-Skip (1)	1.95 ± 0.47	**=0.039**	0.16	
	B-skip (2)	2.13 ± 0.44			
	Bounding (3)	2.36 ± 0.47			(3) >; (1)**
	Heel flicks (4)	2.16 ± 0.47			
	SLR (5)	2.22 ± 0.28			
	Running (6)	2.21 ± 0.35			
MP (N.m/kg)	A-Skip (1)	0.32 ± 0.17	=0.49	0.04	
	B-skip (2)	0.47 ± 0.26			
	Bounding (3)	0.42 ± 0.44			
	Heel flicks (4)	0.37 ± 0.19			
	SLR (5)	0.40 ± 0.21			
	Running (6)	0.40 ± 0.18			

*MT = midtarsal; MP = Metatarsophalangeal. Repeated measures ANOVA followed by Bonferroni's correction: p > 0.05, not significant; * symbol represents a p-value for post-hoc test inferior to 0.05; ** symbol represents a p-value for post-hoc test inferior to 0.01; *** symbol represents a p-value for post-hoc test inferior to 0.001. Tasks are represented by a number from 1 to 8 in post-hoc test. ANOVA, Analysis of Variance; SD, Standard deviation.*

For positive MT power, the A-skip (diff: 2.8 ± 2.9 J/kg, $p < 0.001$, $d = 1.5$) and the B-skip (diff: 2.7 ± 2.1 J/kg, $p < 0.001$, $d = 1.4$) induce a smaller value than running. No difference was found for negative MT power between each running drills and running ($p = 0.052$, $\eta^2 = 0.16$).

Metatarsophalangeal

MP plantar flexion peak was similar between the running drills and running ($p = 0.41$, $\eta^2 = 0.06$) whereas the MP dorsiflexion peak ($p < 0.001$, $\eta^2 = 0.47$) and MT range of motion ($p < 0.001$, $\eta^2 = 0.43$) were different. For MP dorsiflexion peak, post hoc tests showed that the A-skip (diff: 7.2 ± 6.5°, $p < 0.001$, $d = 1.0$), the B-skip (diff: 8.1 ± 4.7°, $p < 0.001$, $d = 1.1$), the Bounding (diff: 4.2 ± 5.3°, $p = 0.015$, $d = 0.69$) and the Heel flicks (diff: 9.2 ± 6.0°, $p < 0.001$, $d = 1.3$) induced smaller values than running. Similarly, the A-skip (diff: 7.3 ± 6.6°, $p < 0.001$, $d = 0.9$), the B-skip (diff: 7.0 ± 3.5°, $p < 0.001$, $d = 0.9$), the bounding (diff: 4.4 ± 6.2°, $p = 0.009$, $d = 0.64$) and the Heel flicks (diff: 9.3 ± 6.4°, $p < 0.001$, $d = 1.2$) induced a smaller MP ROM than running.

No difference was found between the running drills and running for MP moment ($p = 0.49$, $\eta^2 = 0.04$), positive MP power ($p = 0.13$, $\eta^2 = 0.11$) and negative MP power ($p = 0.75$, $\eta^2 = 0.136$).

Muscle activity

All mean, standard deviations, values of muscle activation, p-values and effect sizes for the abductor hallucis, gastrocnemius medialis, lateralis and soleus are shown in Table 4.

Table 3. Comparison of ankle, midtarsal and metatarsophalangeal power data between running drills and running.

		Ankle, midtarsal and metatarsophalangeal Positive/Negative power (J/kg) (Mean ± SD)							
Joint	Tasks	Positive power (J/kg)	*p*-value	η^2	Post-hoc test	Negative power (J/kg)	*p*-value	η^2	Post-hoc test
Ankle	A-Skip (1)	11.16 ± 4.37	**<0.001**	0.35		−12.98 ± 6.62	=0.050	0.18	
	B-skip (2)	10.05 ± 2.83				−13.06 ± 5.73			
	Bounding (3)	17.27 ±5.51			(3) >; (1)***, (2)***, (4)***, (5)***, (6)*	−19.45 ± 7.08			
	Heel flicks (4)	11.60 ± 2.68				−18.85 ± 13.47			
	SLR (5)	11.09 ± 2.13				−15.81 ± 5.59			
	Running (6)	13.05 ± 5.17				−13.91 ± 6.09			
MT	A-Skip (1)	4.64 ± 2.09	**<0.001**	0.39		−4.05 ± 2.53	=0.052	0.16	
	B-skip (2)	4.79 ± 2.03				−4.59 ± 2.95			
	Bounding (3)	8.24 ± 2.77			(3) >; (1)***, (2)***	−6.32 ± 2.46			
	Heel flicks (4)	6.59 ± 3.15				−6.30 ± 3.06			
	SLR (5)	8.03 ± 2.82			(5) >; (1)***, (2)**	−5.92 ± 3.29			
	Running (6)	8.86 ± 3.59			(6) >; (1)***, (2)***	−5.66 ± 1.52			
MP	A-Skip (1)	0.92 ± 0.73	=0.13	0.11		−1.36 ± 0.72	=0.07	0.13	
	B-skip (2)	1.51 ± 1.11				−1.78 ± 1.09			
	Bounding (3)	1.05 ± 0.94				−1.49 ± 1.00			
	Heel flicks (4)	1.55 ± 1.26				−1.98 ± 1.21			
	SLR (5)	1.58 ± 1.56				−2.17 ± 1.51			
	Running (6)	0.90 ± 0.87				−2.13 ± 1.32			

*MT = midtarsal; MP = Metatarsophalangeal. Repeated measures ANOVA followed by Bonferroni's correction: $p > 0.05$, not significant; * symbol represents a p-value for post-hoc test inferior to 0.05; ** symbol represents a p-value for post-hoc test inferior to 0.01; *** symbol represents a p-value for post-hoc test inferior to 0.001. Tasks are represented by a number from 1 to 8 in post-hoc test. ANOVA, Analysis of Variance; SD, Standard deviation.*

Table 4. Comparison of muscle activation between running drills and running at different speeds.

Muscles	Tasks	N	Percentage of muscle activation relative to running (%) Mean ± SD	Muscle activation (mV) Mean ± SD	*p*-value	η^2	Post-hoc test
Abd. Hallucis	A-skip (1)	14	107 ± 49.9	256.2 ± 119.0	*p* <0.001	0.04	
	B-skip (2)	14	113.8 ± 56.4	271.5 ± 134.6			
	Bounding (3)	14	155.9 ± 60.1	371.8 ± 143.5			(3) >; (1)***, (2)***, (4)**, (6)**
	Heel flicks (4)	14	121.1 ± 51.8	288.9 ± 123.7			
	SLR (5)	14	130.3 ± 49.5	310.8 ± 118.1			(5) >; (6)**
	Running (6)	14	/	238.4 ± 127.0			
Gastro. Med	A-skip (1)	16	112.5 ± 33.1	288.2 ± 84.9	*p* = 0.017	0.22	
	B-skip (2)	16	103.2 ± 25.6	264.5 ± 65.7			
	Bounding (3)	16	141.5 ± 56.8	362.5 ± 145.5			(3) >; (2)*, (4)*, (5)*, (6)**
	Heel flicks (4)	16	103.8 ± 29.7	266.0 ± 76.2			
	SLR (5)	16	103.5 ± 42.2	265.2 ± 108.1			
	Running (6)	16	/	256.1 ± 76.0			
Gastro. Lat	A-skip (1)	15	96.1 ± 38.0	211.9 ± 83.8	*p* = 0.04	0.22	
	B-skip (2)	15	93.4 ± 34.9	206.0 ± 77.0			
	Bounding (3)	15	122.8 ± 51.4	270.8 ± 113.3			(3) >; (2)* , (5)*
	Heel flicks (4)	15	101.7 ± 31.0	224.2 ± 68.5			
	SLR (5)	15	93.7 ± 46.3	206.6 ± 102.2			
	Running (6)	15	/	220.4 ± 81.7			
Soleus	A-skip (1)	14	101.4 ± 42.6	208.0 ± 87.4	*p* <0.001	0.42	
	B-skip (2)	14	97.7 ± 28.2	200.4 ± 57.9			
	Bounding (3)	14	143.8 ± 56.7	294.9 ± 116.4			(3) >; (1)***, (2)***, (6)***
	Heel flicks (4)	14	100.9 ± 40.1	207.0 ± 82.3			
	SLR (5)	14	121.4 ± 40.1	249.0 ± 82.3			
	Running (6)	14	/	205.0 ± 68.3			

*Abd.hallucis = Abductor hallucis; Gastro.med = Gastrocnemius medialis; Gastro.Lat = Gastrocnemius lateralis. Repeated measures ANOVA followed by Bonferroni's correction was performed in using the values of muscle activation (mV): p > 0.05, not significant; * symbol represents a p-value for post-hoc test inferior to 0.05; ** symbol represents a p-value for post-hoc test inferior to 0.01; *** symbol represents a p-value for post-hoc test inferior to 0.001. Tasks are represented by a number from 1 to 8 in post-hoc test. ANOVA, Analysis of Variance; SD, Standard deviation. As an indication, percentage of muscle activity of the medial and lateral heads of the gastrocnemius, the soleus and the abductor hallucis relative to running at 5.00 m/s were calculated for the running drills..*

The Bounding (diff: 157.0 ± 96.3 mV, $p < 0.001$, $d = 1.04$) and the SLR (diff: 65.0 ± 127.7 mV, $p = 0.009$, $d = 0.56$) induce a higher abductor hallucis activation than running.

On the other hand, the bounding induce a higher gastrocnemius medialis (diff: 138.0 ± 129.3 mV, p = 0.006, $d = 1.10$) and soleus (diff: 131.7 ± 103.2 mV, p < 0.001, $d = 1.06$) muscle activation than running.

Discussion and implication

The aim of this study was to compare the foot-ankle mechanics of running drills with distance running using a multi-segment foot model. Based on the study of Trowell et al. (2022), it was hypothesised that Bounding will induce higher foot and ankle power than distance running whereas the A-skip and B-skip will induce less than distance running. Our findings confirm that Bounding induce a significant higher ankle-positive power than distance running. However, MT and MP positive or negative power were not significantly different between bounding and distance running. Our results have also shown that the A-skip and the B-skip induce less MT positive power than distance running. Contrary to the findings of Trowell et al. (2022), the A-skip and the B-skip do not induce a smaller ankle positive or negative power than distance running. This difference with our results could be explained by the use of multi-segment foot model that more accurately estimates the mechanical power generated at the ankle joint during dynamic activities (Kessler et al., 2020).

The kinematic analysis of our study revealed that all the running drills (except Bounding) induce a smaller ankle, MT and MP dorsiflexion peak than running. Despite this difference in dorsiflexion peak, the Heel flicks and SLR induce similar ankle, MT and MP moment and power than running. Avoiding high amplitudes of ankle dorsiflexion is advised for certain common runner pathologies, such as Achilles tendinopathy, as this may exacerbate pain symptoms (Malliaras, 2022). For this injured population, running can become difficult because of the increased pain during training (Malliaras, 2022). Therefore, the practice of the Heel flicks and SLR could be an interesting alternative to running for maintaining the runner's foot and ankle complex's capacity in limiting the appearance of pain. At the opposite, the practice of Bounding should be avoided before advanced stages of rehabilitation because it requires a high ankle dorsiflexion and power. These statements are consistent with an existing classification of exercise progression for Achilles tendinopathy showing that long forward hopping with one-leg induces a higher loading peak than running (Baxter et al., 2021).

Although the differences are not statistically significant, the analysis of the biomechanics within the foot showed that all the running drills (except the A-skip) induced a higher positive MP power than running (≈50% more). This finding highlights that running drills require a strong propulsion capacity on the forefoot. Parallelly, electromyographic analysis showed that all the running drills induced a higher percentage of abductor hallucis activity than running. In summary, running drills could be useful in improving the capacity of the forefoot to forcefully push into the ground. However, some cautions are necessary for the generalisation of these affirmations in shod conditions, given that the running drills in this study were performed barefoot.

A previous interventional study has shown that performing an intensive program composed by running drills during 3 weeks (≈5000 to 6000 jumps) can improve toe flexor strength (+7% to 16%) (Goldmann, Potthast, et al., 2013). The toe flexor strength improvement was greater whether the program was performed in minimalist footwear condition compared to traditional footwear (Goldmann, Potthast, et al., 2013). Toe flexor strength enhancement could lead to a performance improvement in athletic tasks requiring strong propulsion, such as long-jump, sprinting or ability to change direction (Goldmann, Sanno, et al., 2013). However, it still remains unknown whether functional training (such as running drills) is more efficient than isolated foot exercises in improving toe flexor strength. Despite the absence of longitudinal follow-up, Willemse et al. (2023) showed that functional exercises induce comparable or even greater activation of the plantar intrinsic foot muscles than muscle-specific isolated foot exercises.

In comparison with previous study, a multi-segment foot model was used in our study to better illustrate ankle biomechanics and provide supplementary information on the biomechanics within the foot. The simultaneous analysis of ankle and foot biomechanics is relevant because previous studies have shown that their mechanical behaviour is interrelated (Smith et al., 2015; Welte et al., 2023). Interestingly, in our study, the power generated within the foot was not similar between the running drills. This finding indicates that, as for the ankle, the choice of running drill influences the foot output. Specifically, track and field coaches could use the B-skip to improve the ability of their runners to push into the ground with their forefoot without increasing the load on the midfoot. In contrast, Bounding adds a supplementary load on the midfoot but reduces the amount of propulsive force required with the forefoot in comparison with the other running drills. The power required for the ankle and foot were not similar across the running drills. For example, track and field coaches have to keep in mind that the Bounding exercise induces a low positive power on the MP joint but a high positive power on the ankle compared with the other running drills. From another point of view, this information could also help clinicians implement a progressive loading strategy with runners who have sustained foot injuries (e.g., metatarsal stress fracture or plantar fasciitis).

This study had some limitations that should be considered before generalising the results. First, the participants performed the trials barefoot. This could lead to a potential over-estimation of the kinematic and kinetic values of the foot and ankle joints (Esculier et al., 2022; Hall et al., 2013; Su et al., 2022). In our study, the equipment installed on the foot (markers and EMG electrodes) did not allow for shoes to be worn. The equipment could not be attached directly to the running footwear because this would overestimate the MTP peak plantar flexion angle and moment compared with markers placed on the skin (Perrin et al., 2023). This overestimation can be explained by the movement of the foot inside the shoe, and by the additional deformation of the shoe measured (Perrin et al., 2023). Therefore, caution should be exercised when applying these findings to shod running. Second, only five trials were performed for each task. The literature recommends that studies involving the analysis of traditional running biomechanical variables should use a minimum of 25 steps from each participant to provide appropriate data stability and statistical power (Oliveira & Pirscoveanu, 2021). However, given the number of running drills assessed in this study, it was not possible for the participants to perform 25 repetitions of each task without risking to induce fatigue. Third, the conclusions from the electromyographic data should be interpreted with caution. The interpretation of surface electromyograms in dynamic contractions contains several sources of errors, such as signal properties, electrode shift and tissue conductivity (Farina, 2006). Moreover, given its size and the variety of its position on the foot, it is advisable to use a fine-wire electrode inserted into the muscle rather than a surface electromyogram to measure the activity of the abductor hallucis. Finally, several multi-segment foot models exist and the results of our study could be slightly different when using another model (Deschamps et al., 2017).

Conclusion

The main contribution of this study is to offer a detailed analysis of the mechanical behaviour of the ankle and joints within the foot during running drills. Running drills (except Bounding) induce a smaller ankle, MT and MP dorsiflexion peak than running. Bounding induces a higher ankle-positive power than running, but does not induce higher MT and MP positive or negative power. The A-skip and the B-skip induce less MT positive power than running but do not induce less ankle positive or negative power. This analysis could help track and field coaches to select their running drills in an evidence-based manner.

Acknowledgments

The authors would like to thank the Wallonia-Brussels Federation for its support.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

The author(s) reported there is no funding associated with the work featured in this article.

ORCID

François Delvaux http://orcid.org/0000-0002-7375-7237
Cédric Schwartz http://orcid.org/0000-0002-7307-7821

References

Azevedo, A. P., Mezêncio, B., Valvassori, R., Anjos, F. O., Barbanti, V. J., Amadio, A. C., & Serrão, J. C. (2015). Usage of running drills in an interval training program: Implications related to biomechanical parameters of running. *The Journal of Strength & Conditioning Research*, *29* (7), 1796–1802. https://doi.org/10.1519/JSC.0000000000000831

Barbero, M., Merletti, R., & Rainoldi, A. (2012). *Atlas of muscle innervation zones*. Springer Milan. https://doi.org/10.1007/978-88-470-2463-2

Baxter, J. R., Corrigan, P., Hullfish, T. J., O'Rourke, P., & Silbernagel, K. G. (2021). Exercise progression to incrementally load the Achilles Tendon. *Medicine & Science in Sports and Exercise*, *53*(1), 124–130. https://doi.org/10.1249/MSS.0000000000002459

Branthwaite, H., Aitkins, C., Lindley, S., & Chockalingam, N. (2019). Surface electromyography of the foot: A protocol for sensor placement. *The Foot*, *41*, 24–29. https://doi.org/10.1016/j.foot.2019.07.001

Bruening, D. A., Cooney, K. M., & Buczek, F. L. (2012a). Analysis of a kinetic multi-segment foot model. Part I: Model repeatability and kinematic validity. *Gait & Posture*, *35*(4), 529–534. https://doi.org/10.1016/j.gaitpost.2011.10.363

Bruening, D. A., Cooney, K. M., & Buczek, F. L. (2012b). Analysis of a kinetic multi-segment foot model part II: Kinetics and clinical implications. *Gait & Posture*, *35*(4), 535–540. https://doi.org/10.1016/j.gaitpost.2011.11.012

Cornwall, M., & McPoil, T. (1999). Three-dimensional movement of the foot during the stance phase of walking. *Journal of the American Podiatric Medical Association*, *89*(2), 56–66. https://doi.org/10.7547/87507315-89-2-56

Deschamps, K., Eerdekens, M., Desmet, D., Matricali, G. A., Wuite, S., & Staes, F. (2017). Estimation of foot joint kinetics in three and four segment foot models using an existing proportionality scheme: Application in paediatric barefoot walking. *Journal of Biomechanics*, *61*, 168–175. https://doi.org/10.1016/j.jbiomech.2017.07.017

Deschamps, K., Staes, F., Roosen, P., Nobels, F., Desloovere, K., Bruyninckx, H., & Matricali, G. A. (2011). Body of evidence supporting the clinical use of 3D multisegment foot models: A systematic review. *Gait & Posture*, *33*(3), 338–349. https://doi.org/10.1016/j.gaitpost.2010.12.018

Esculier, J.-F., Charlton, J. M., Krowchuk, N. M., De Pieri, J., & Hunt, M. A. (2022). Immediate effects of manipulating footwear or cadence on the lower limb biomechanics of female masters runners. *Journal of Applied Biomechanics*, *38*(5), 312–319. https://doi.org/10.1123/jab.2021-0387

Farina, D. (2006). Interpretation of the surface electromyogram in dynamic contractions. *Exercise and Sport Sciences Reviews*, *34*(3), 121–127. https://doi.org/10.1249/00003677-200607000-00006

Goldmann, J.-P., Potthast, W., & Brüggemann, G.-P. (2013). Athletic training with minimal footwear strengthens toe flexor muscles. *Footwear Science*, *5*(1), 19–25. https://doi.org/10.1080/19424280.2012.744361

Goldmann, J.-P., Sanno, M., Willwacher, S., Heinrich, K., & Brüggemann, G.-P. (2013). The potential of toe flexor muscles to enhance performance. *Journal of Sports Sciences*, *31*(4), 424–433. https://doi.org/10.1080/02640414.2012.736627

Hall, J. P. L., Barton, C., Jones, P. R., & Morrissey, D. (2013). The biomechanical differences between barefoot and shod distance running: A systematic review and preliminary meta-analysis. *Sports Medicine*, *43*(12), 1335–1353. https://doi.org/10.1007/s40279-013-0084-3

Hashimoto, T., & Sakuraba, K. (2014). Strength training for the intrinsic flexor muscles of the foot: Effects on muscle strength, the foot arch, and dynamic parameters before and after the training. *Journal of Physical Therapy Science*, *26*(3), 373–376. https://doi.org/10.1589/jpts.26.373

Hopkins, W. G., Marshall, S. W., Batterham, A. M., & Hanin, J. (2009). Progressive statistics for studies in sports medicine and exercise science. *Medicine & Science in Sports and Exercise*, *41*(1), 3–12. https://doi.org/10.1249/MSS.0b013e31818cb278

Kessler, S. E., Lichtwark, G. A., Welte, L. K. M., Rainbow, M. J., & Kelly, L. A. (2020). Regulation of foot and ankle quasi-stiffness during human hopping across a range of frequencies. *Journal of Biomechanics*, *108*, 109853. https://doi.org/10.1016/j.jbiomech.2020.109853

Komi, P. V. (1984). Physiological and biomechanical correlates of muscle function effects of muscle structure and stretch-shortening cycle on force and speed. *Exercise and Sport Sciences Reviews*, *12*(1), 81–122. https://doi.org/10.1249/00003677-198401000-00006

Leardini, A., Caravaggi, P., Theologis, T., & Stebbins, J. (2019). Multi-segment foot models and their use in clinical populations. *Gait & Posture*, *69*, 50–59. https://doi.org/10.1016/j.gaitpost.2019.01.022

Leardini, A., Stebbins, J., Hillstrom, H., Caravaggi, P., Deschamps, K., & Arndt, A. (2021). ISB recommendations for skin-marker-based multi-segment foot kinematics. *Journal of Biomechanics*, *125*, 110581. https://doi.org/10.1016/j.jbiomech.2021.110581

Maher, J. M., Markey, J. C., & Ebert-May, D. (2013). The other half of the story: Effect size analysis in quantitative research. *CBE - Life Sciences Education*, *12*(3), 345–351. https://doi.org/10.1187/cbe.13-04-0082

Malliaras, P. (2022). Physiotherapy management of achilles tendinopathy. *Journal of Physiotherapy*, *68*(4), 221–237. https://doi.org/10.1016/j.jphys.2022.09.010

Oliveira, A. S., & Pirscoveanu, C. I. (2021). Implications of sample size and acquired number of steps to investigate running biomechanics. *Scientific Reports*, *11*(1), 3083. https://doi.org/10.1038/s41598-021-82876-z

Oosterwaal, M., Telfer, S., Tørholm, S., Carbes, S., Van Rhijn, L. W., Macduff, R., Meijer, K., & Woodburn, J. (2011). Generation of subject-specific, dynamic, multisegment ankle and foot models to improve orthotic design: A feasibility study. *BMC Musculoskeletal Disorders*, *12*(1), 256. https://doi.org/10.1186/1471-2474-12-256

Oxfeldt, M., Overgaard, K., Hvid, L. G., & Dalgas, U. (2019). Effects of plyometric training on jumping, sprint performance, and lower body muscle strength in healthy adults: A systematic review and meta-analyses. *Scandinavian Journal of Medicine & Science in Sports*, *29*(10), 1453–1465. https://doi.org/10.1111/sms.13487

Perrin, T. P., Morio, C. Y. M., Besson, T., Kerhervé, H. A., Millet, G. Y., & Rossi, J. (2023). Comparison of skin and shoe marker placement on metatarsophalangeal joint kinematics and kinetics during running. *Journal of Biomechanics*, *146*, 111410. https://doi.org/10.1016/j.jbiomech.2022.111410

Schwartz, C., Wang, F.-C., Forthomme, B., Denoël, V., Brüls, O., & Croisier, J.-L. (2020). Normalizing gastrocnemius muscle EMG signal: An optimal set of maximum voluntary isometric contraction tests for young adults considering reproducibility. *Gait & Posture*, *82*, 196–202.

Smith, L., Preece, S., Mason, D., & Bramah, C. (2015). A comparison of kinematic algorithms to estimate gait events during overground running. *Gait & Posture*, *41*(1), 39–43. https://doi.org/10.1016/j.gaitpost.2014.08.009

Spurrs, R. W., Murphy, A. J., & Watsford, M. L. (2003). The effect of plyometric training on distance running performance. *European Journal of Applied Physiology*, *89*(1), 1–7. https://doi.org/10.1007/s00421-002-0741-y

Su, W., Zhang, S., Ye, D., Sun, X., Zhang, X., & Fu, W. (2022). Effects of barefoot and shod on the in vivo kinematics of medial longitudinal arch during running based on a high-speed dual fluoroscopic imaging system. *Frontiers in Bioengineering and Biotechnology*, *10*, 917675. https://doi.org/10.3389/fbioe.2022.917675

Taddei, U. T., Matias, A. B., Duarte, M., & Sacco, I. C. N. (2020). Foot core training to prevent running-related injuries: A survival analysis of a single-blind, randomized controlled trial. *The American Journal of Sports Medicine*, *48*(14), 3610–3619. https://doi.org/10.1177/0363546520969205

Takabayashi, T., Edama, M., Inai, T., & Kubo, M. (2021). Differences in rearfoot, midfoot, and forefoot kinematics of normal foot and flatfoot during running. *Journal of Orthopaedic Research*, *39*(3), 565–571. https://doi.org/10.1002/jor.24877

Trowell, D., Fox, A., Saunders, N., Vicenzino, B., & Bonacci, J. (2022). A comparison of plantarflexor musculotendon unit output between plyometric exercises and running. *Journal of Science & Medicine in Sport*, *25*(4), 334–339. https://doi.org/10.1016/j.jsams.2021.11.037

Turner, A. M., Owings, M., & Schwane, J. A. (2003). Improvement in running economy after 6 weeks of plyometric training. *The Journal of Strength & Conditioning Research*, *17*(1), 60. https://doi.org/10.1519/1533-4287(2003)017<0060:IIREAW>2.0.CO;2

Van Doorn, J., Van Den Bergh, D., Böhm, U., Dablander, F., Derks, K., Draws, T., Etz, A., Evans, N. J., Gronau, Q. F., Haaf, J. M., Hinne, M., Kucharský, Š., Ly, A., Marsman, M., Matzke, D., Gupta, A. R. K. N., Sarafoglou, A., Stefan, A., Voelkel, J. G., & Wagenmakers, E.-J. (2021). The JASP guidelines for conducting and reporting a Bayesian analysis. *Psychonomic Bulletin & Review*, *28*(3), 813–826. https://doi.org/10.3758/s13423-020-01798-5

Welte, L., Holowka, N. B., Kelly, L. A., Arndt, A., & Rainbow, M. J. (2023). Mobility of the human foot's medial arch helps enable upright bipedal locomotion. *Frontiers in Bioengineering and Biotechnology*, *11*, 1155439. https://doi.org/10.3389/fbioe.2023.1155439

Whelan, N., Kenny, I. C., & Harrison, A. J. (2016). An insight into track and field coaches' knowledge and use of sprinting drills to improve performance. *International Journal of Sports Science & Coaching*, *11*(2), 182–190. https://doi.org/10.1177/1747954116636716

Willemse, L., Wouters, E. J. M., Pisters, M. F., & Vanwanseele, B. (2023). Plantar intrinsic foot muscle activation during functional exercises compared to isolated foot exercises in younger adults. *Physiotherapy Theory and Practice*, 1–13. https://doi.org/10.1080/09593985.2023.2204947

Yuasa, Y., Kurihara, T., & Isaka, T. (2018). Relationship between toe muscular strength and the ability to change direction in athletes. *Journal of Human Kinetics*, *64*(1), 47–55. https://doi.org/10.1515/hukin-2017-0183