Aerial and Terrestrial Patterns: A Novel Approach to Analyzing Human Running

Authors C. Gindre[1], T. Lussiana[1,2], K. Hebert-Losier[3], L. Mourot[2,4]

Affiliations Affiliation addresses are listed at the end of the article

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- training
- coaching
- biomechanics
- subjective scale

Abstract

Biomechanical parameters are often analyzed independently, although running gait is a dynamic system wherein changes in one parameter are likely to affect another. Accordingly, the Volodalen® method provides a model for classifying running patterns into 2 categories, aerial and terrestrial, using a global subjective rating scoring system. We aimed to validate the Volodalen® method by verifying whether the aerial and terrestrial patterns, defined subjectively by a running coach, were associated with distinct objectively-measured biomechanical parameters. The running patterns of 91 individuals were assessed subjectively using the Volodalen® method by an expert running coach during a 10-min running warm-up. Biomechanical parameters were measured objectively using the OptojumpNext® during a 50-m run performed at 3.3, 4.2, and 5 $m \cdot s^{-1}$ and were compared between aerial- and terrestrial-classified subjects. Longer contact times and greater leg compression were observed in the terrestrial compared to the aerial runners. The aerial runners exhibited longer flight time, greater center of mass displacement, maximum vertical force and leg stiffness than the terrestrial ones. The subjective categorization of running patterns was associated with distinct objectively-quantified biomechanical parameters. Our results suggest that a subjective holistic assessment of running patterns provides insight into the biomechanics of running gaits of individuals.

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Bibliography
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Correspondence
Thibault Lussiana
Laboratoire C3S Culture Sport Santé Société
Université de Franche Comté
31, avenue de l'épitaphe
25000 Besançon
France
Tel.: +33/632/424 343
Fax: +33/383/355 288
thibault.lussiana@gmail.com

Introduction

The subjective appreciation of sports movements is an important quality for any coach seeking to improve athletic performance [22]. However, to be effective, observations must be centered on the essential parameters of the activity [29]. Interviews with expert sprint coaches emphasize that posture, hip position (i.e., center of mass and pelvis position), arm action, as well as ground contact are key parameters in running performance [29]. The scientific literature supports most of these beliefs. For instance, contact time is suggested to be the most important kinematic parameter for generating differences between elite sprinters, whereby faster sprinters exhibit shorter contact times [6] and develop greater mass-specific forces during that time [30]. Even in endurance runners, contact time has been related to 5-km time-trial performances ($r = -0.49$, $p < 0.05$) [26]. Arm swing reduces the energy cost of running [1], helping to minimize trunk rotation and counterbalancing leg swing [2]. In long-distance runners, the range of elbow motion has been positively correlated to running economy ($r = 0.42$, $p < 0.25$) [28], indicating value in observing arm action while running.

Such biomechanical parameters, i.e., arm motion and body posture, are usually assessed independently. However, the running gait pattern is a dynamic system in which the evolution of one parameter is likely to affect another. For instance, a decrease in contact time, without adjusting step frequency, leads to an increase in flight time that can promote vertical displacement of the center of mass [9]. Alterations in step width and arm motion has also been shown to alter running gait, increasing the cost of running and challenging lateral balance [1]. Individuals with excessive pronation demonstrate lower peak adduction and greater peak flexion at the knee during stance, with rearfoot strikers also exhibiting greater peak knee flexion [16]. Taken together, all biomechanical parameters generate a global running pattern or style that is specific to individuals and can be used by coaches to differentiate runners from one another. It may even be possible to categorize specific running styles in which runners display similar movement patterns. For example, McMahon et al. [20] termed running with excessive knee flexion "Groucho running", which is typically associated with increased contact time and step length and decreased flight time and vertical oscillation of the body. On the other hand, Ardense et al. [3] investigated "Pose running", characterized by mid-forefoot striking, short contact times and step lengths, and less knee flexion during stance.

Our laboratory has been using a holistic approach, the Volodalen® method, to classify running patterns subjectively for several years. The Volodalen® method considers runners to be a global and dynamic system. Running patterns are subdivided into 2 main groups according to 5 subjectively-evaluated criteria. Using a standardized grid and rating system, coaches can classify running patterns as being *aerial* or *terrestrial* to assist in better understanding and training individuals. Overall, the aerial pattern is characterized by a more spring-like vertical bouncing gait, and the terrestrial pattern by a more grounded horizontal gait. Considering the entire running pattern of individuals allows coaches to adapt their instructions and address deficiencies by implementing targeted exercise programs on the basis of a holistic approach.

Thus, the purpose of this study was to validate the Volodalen® method by verifying whether the 2 subjectively-classified running patterns are in fact associated with distinct objectively-measured biomechanical parameters. We hypothesized that aerial runners would exhibit shorter contact times, greater leg stiffness, and longer flight times than terrestrial runners.

Materials and Methods

Subjects

91 active individuals in good self-reported general health [mean ± standard deviation (SD): females (n = 14): age 31.9 ± 12.7 y, height 166.2 ± 6.3 cm, body mass 59.6 ± 8.6 kg, and training time: 9.1 ± 4.6 $h \cdot week^{-1}$; males (n = 77): age 29.2 ± 11.0 y, height 178.0 ± 6.3 cm, body mass 71.9 ± 8.4 kg, and training time: 6.7 ± 4.3 $h \cdot week^{-1}$] voluntarily participated in this study. All participants were free from lower-extremity injuries and had been injury-free for the previous year. The university's Institutional Review Board approved the study protocol prior to subject recruitment, which was conducted in accordance with International Journal of Sports Medicine ethical standards [10].

Design

Each subject participated in an experimental session lasting 30 min. After providing written informed consent, subjects ran for 10 min as a warm-up at a self-selected speed (range: 2.5–3.5 $m \cdot s^{-1}$). For testing, subjects then ran 3 × 50 m from standstill on an indoor athletic track at 3.3, 4.2, and 5 $m \cdot s^{-1}$ in a randomized order, interspersed with 2-min rest periods during which participants were permitted to walk. Speed of trials was monitored using photoelectric cells (Racetime2, MicroGate, Timing and Sport, Bolzano, Italy) placed at the 20th and 40th meter of the 50-m trial. A running trial was accepted when its speed was within ± 5 % of the specified speed. Otherwise, it was disregarded and repeated after a 2-min rest period, which occurred in less than 20 % of the trials and no more than twice per subject.

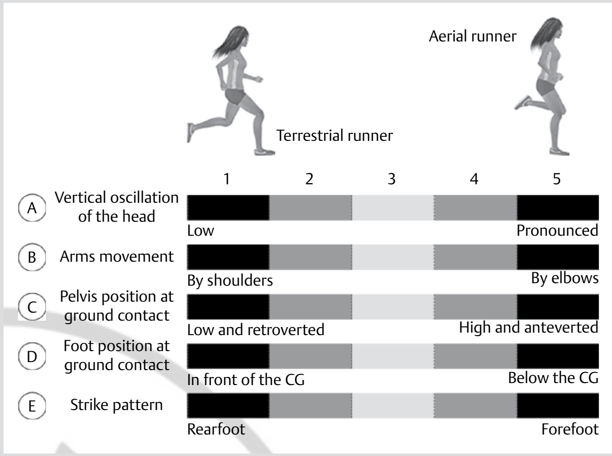

Fig. 1 Subjective grid of the Volodalen® method to assess the individual running pattern. The asterisks (*) indicate a significant difference ($p < 0.05$) between aerial and terrestrial running patterns.

Subjective assessment

During the 10-min warm-up and independently of the objective analysis, subjects' running patterns were observed by an expert running coach (coaching experience > 20 years at a national level) and scored using the Volodalen® method (**Fig. 1**). The coach, who was familiar with this method (more than 10 years of use), focused on the global movement patterns of subjects with particular attention given to 5 key elements (A–E in **Fig. 1**), similar to those sourced by Thomson et al. [29]. Each element was scored from 1 to 5. A global score (*V*®score) was then computed by summing the individual scores of each element. A *V*®score ≤ 15 indicated a terrestrial runner and > 15, an aerial runner. The reliability of the Volodalen® method has been previously examined (unpublished data). Both intra- and inter-rater (expert and novice regarding use of the Volodalen® method) absolute reliabilities of *V*®scores were adequate, with coefficient of variations being 6.1 ± 7.0 % and 6.6 ± 6.5 %, respectively, with no large systematic bias between *V*®scores detected (paired t-test: $p = 0.927$ and 0.250, respectively).

Objective assessment

An optical measurement system (Optojump Next®, MicroGate Timing and Sport, Bolzano, Italy) sampling at 1 000 Hz was used to record contact (t_c, ms) and flight (t_f, ms) times for 20 m from the 20th to the 40th meter of the 50-m running trials. As described by Morin et al. [23], the spring-mass characteristics of the lower extremity were estimated using a sine-wave model employing t_c, t_f, velocity (v), body mass (m), and leg length (L, the distance between the greater trochanter and the ground measured in barefoot upright stance). Vertical stiffness (k_{vert}, $kN \cdot m^{-1}$) was calculated as the ratio between the maximal vertical force (F_{max}, kN) and center of mass displacement (Δ_z, m) using the following equations:

$$k_{vert} = F_{max} \cdot \Delta_z^{-1} \quad (1)$$

$$F_{max} = mg\frac{\pi}{2}\left(\frac{tf}{tc}+1\right) \quad (2)$$

$$\Delta_z = \left| -\frac{F_{max}}{m}\frac{tc^2}{\pi 2} + g\frac{tc^2}{8} \right| \quad (3)$$

Leg stiffness (k_{leg}, in $kN \cdot m^{-1}$) was calculated as the ratio between the F_{max} and the maximal leg length deformation, i.e., leg spring compression (Δ_L, m), using the following equations:

$$k_{leg} = F_{max} \cdot \Delta_L^{-1} \quad (4)$$

$$\Delta_L = L - \sqrt{L^2 - \left(\frac{vtc - d}{2}\right)^2} + \Delta_z \quad (5)$$

where d represents the distance of the point of force application translation, estimated for each individual to equal 18% of their leg length [18].

Analysis

Descriptive statistics of the data are presented as mean ± SD values. Since all data were normally distributed on the basis of the Kolmogorov-Smirnov test, parametric statistical methods were employed for data analysis. Student t-tests were used to compare the overall $V^{®}$score, scores for each element of the $V^{®}$score, and baseline characteristics between aerial and terrestrial running groups. 2-way (running group × speed) repeated measures analyses of variance, and Holm-Sidak procedures for post-hoc pair-wise comparisons, were used to identify the main effect of running group (aerial *vs.* terrestrial) on the biomechanical parameters, considering interactions between running group and speed. Statistical significance was accepted when the overall p-value was <0.05, with all analyses performed in SigmaStat 12 for Windows (Systat Software Inc., San Jose, CA, USA).

Results

Of the 91 subjects, 48 (n = 5 females) were categorized as being aerial runners and 43 (n = 9 females) as terrestrial runners. Accordingly, the former group had significantly higher $V^{®}$scores than the latter group (18.4 ± 2.0 *vs.* 12.1 ± 2.3), as well as higher scores in each of the 5 key elements assessed. In agreement with the classification schemes presented in **Fig. 1**, rearfoot striking (scale criteria E), foot-ground contact ahead of the centre of gravity (criteria D), retroversed pelvis position (criteria C), arm movement led by the shoulders (criteria B), and low vertical oscillations (criteria A) were more readily observed in terrestrial than aerial runners (**Fig. 2**). Otherwise, the 2 groups were similar in terms of baseline characteristics regarding age, height, body mass, and training time (all $p > 0.05$).

Values of t_c, t_f, f, Δ_L, Δ_z, F_{max}, k_{vert} and k_{leg} are reported in **Table 1**, and were not influenced by the interaction effect (group × speed, all $p \geq 0.569$). On the other hand, group influenced several parameters. Aerial runners exhibited lower t_c and Δ_L with greater t_f, Δ_z, F_{max}, and k_{leg} than terrestrial runners.

Discussion

The Volodalen® method is a practical tool used by running coaches to classify the running patterns of individuals into aerial or terrestrial ones according to visual observations. Here we demonstrate that the subjective classification is in fact associated with specific biomechanical parameters at 3 different running speeds (3.3, 4.2, and 5 $m \cdot s^{-1}$). According to our hypothesis, running with an aerial pattern was associated with shorter contact times, greater leg stiffness, and longer flight times than with a terrestrial pattern. The former running style also demonstrated greater center of mass displacements and maximal vertical forces than terrestrial runners. In the absence of tools that objectively quantify running gait, the Volodalen® method may provide coaches insight into the biomechanical preferences of individuals (i.e., quick contact time with high leg stiffness).

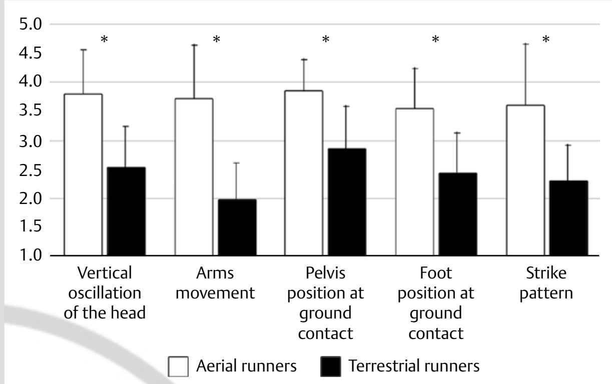

Fig. 2 Subjective scores for each technical criteria included in the Volodalen® method.

It is not always clear in the literature what biomechanical parameters lead to a better running performance and economy, especially when only one parameter is considered in isolation. For instance, both short [26] and long [31] contact times have been linked to enhanced running economy, while other studies report no marked relationship between these variables [27]. Similarly, both rearfoot [25] and mid/forefoot [21] strike patterns are suggested to be more economical. However, several studies also report no marked differences in running economy between rearfoot and forefoot strikers [8], with self-selections of running gait repeatedly reported as the most efficient [1,8]. Differences in running mechanics between studies and individuals can be attributed to several factors [11], including running speed, surface, and training level [11,12]. Even amongst the top-finishers of a race, stride mechanics differ. It is possible that inherent characteristics of individuals, including neuromuscular [19,24] and architectural [19] attributes, contribute to differences in fundamental movement patterns and global motor coordination of runners.

Using a simple, field-based, subjective scale, the Volodalen® method considers several criteria that seem independent (e.g., foot strike and arm swing) and combines them to classify running patterns into aerial and terrestrial. This approach agrees with previous suggestions that a runner needs to be considered as a dynamic system, wherein the alteration in one aspect of the running gait is likely to alter another [21]. Pilot testing suggests acceptable intra- and inter-experimenter reliability of the $V^{®}$score with a CV of 6.1 ± 7.0% and 6.6 ± 6.5%, respectively. Although a more extensive reliability study is warranted to confirm results, it appears that the Volodalen® method can be reliably used by both novice and expert coaches to better understand and train runners on the basis of biomechanical observations. A more detailed biomechanical analysis that investigates each of the criteria presented in **Fig. 1**, their inter-dependence, and their relationship to the Volodalen® classification system is also warranted to further validate this approach. Then, the next step would be to investigate whether coaches need to address the entire running pattern of individuals (e.g., vertical oscillation of

Running group	3.3 m·s⁻¹ Aerial	3.3 m·s⁻¹ Terrestrial	4.2 m·s⁻¹ Aerial	4.2 m·s⁻¹ Terrestrial	5 m·s⁻¹ Aerial	5 m·s⁻¹ Terrestrial	ANOVA running group effect
t_c (ms)	257 ± 18	273 ± 20 *	222 ± 16	236 ± 18 *	198 ± 13	209 ± 16 *	**<0.001**
t_f (ms)	111 ± 19	91 ± 20 *	134 ± 17	116 ± 17 *	143 ± 17	127 ± 16 *	**<0.001**
f (step.s^{-1})	2.73 ± 0.12	2.76 ± 0.17	2.81 ± 0.12	2.84 ± 0.17	2.95 ± 0.14	3.00 ± 0.21	**NS**
Δ_z (cm)	6.7 ± 0.6	6.3 ± 0.8 *	6.3 ± 0.5	6.2 ± 0.7	5.7 ± 0.5	5.6 ± 0.7	**0.020**
Δ_L (cm)	13.5 ± 1.3	14.2 ± 1.8	14.5 ± 1.6	15.5 ± 2.0 *	15.0 ± 1.6	16.3 ± 2.2 *	**<0.001**
F_{max} (kN)	1.54 ± 0.21	1.47 ± 0.22 *	1.73 ± 0.23	1.62 ± 0.23 *	1.86 ± 0.25	1.74 ± 0.23 *	**<0.001**
k_{vert} (kN.m^{-1})	23.3 ± 3.4	23.0 ± 3.5	27.6 ± 4.2	26.5 ± 3.8	31.4 ± 5.0	31.4 ± 4.7	**NS**
k_{leg} (kN.m^{-1})	11.6 ± 2.0	10.4 ± 2.0 *	12.2 ± 2.4	10.6 ± 2.0 *	12.6 ± 2.5	10.9 ± 1.8 *	**<0.001**

Values are mean ± SD. The asterisks (*) indicate a significant difference (p < 0.05) between aerial and terrestrial running patterns at a given speed identified using Holm Sidak procedures during post-hoc analysis

Table 1 Contact (t_c) and flight (t_f) times, step frequency (f), displacement of the centre of mass (Δ_z), leg compression during stance (Δ_L), maximal force (F_{max}), and vertical (k_{vert}) and leg (k_{leg}) stiffness in aerial and terrestrial runners at the 3 speeds investigated.

the head, pelvis position, and foot strike) simultaneously and base recommendations according the Volodalen® classification system rather than focusing on a single parameter (e.g., foot strike) to enhance performance.

The aerial pattern was objectively associated with a shorter contact time and a higher leg stiffness than the terrestrial pattern, and subjectively associated with a mid-forefoot strike pattern. All these characteristics are proposed to increase the ability of the lower-extremity to store and release elastic energy via the spring-mass model during running [7], engaging the plantar arch and Achilles tendon differently than when using a rearfoot strike pattern [14]. Kyröläinen et al. [17] have suggested that stiffer muscles around the ankles and the knees during touch-down can enhance force potentiation during push-off, and increase the mechanical efficiency of runners. Theoretically, the aerial pattern could rely on a better utilization of the stretch-shortening cycle compared to the terrestrial pattern to optimize running performance and reduce energy cost.

In contrast, the terrestrial pattern was objectively associated with a shorter flight time, longer ground contact time, and a higher leg compression than the aerial pattern, and subjectively associated with a rearfoot strike pattern and a low vertical oscillation. These parameters do not promote the store and release of elastic energy through the mechanisms suggested above. Instead, the mechanical efficiency of terrestrial runners theoretically relies on their ability to generate forces over a longer period of time and minimize vertical displacements. Indeed, longer contact times permit forces to be generated over a longer period of time, with an inverse relationship existing between the energy cost of running and ground contact time [15]. Shorter flight times are usually associated with decreased vertical oscillations of the center of mass [13], which is recognized as being more economical [9,31]. In summary, the terrestrial pattern could utilize energy to propel the body forward rather than upward to a greater extent than the aerial pattern.

The above presents a paradox whereby aerial and terrestrial running both presents with advantages regarding running economy and performance. Based on biomechanical analysis, we hypothesized that the aerial pattern relies on the stretch-shortening cycle and the return of elastic energy to minimize energy expenditure, whereas the terrestrial pattern minimizes energy expenditure through reduced vertical oscillation and external work. Consequently, we believe that there may be a generally beneficial set of mechanical parameters for aerial runners and another for terrestrial runners.

Yet, in agreement with previous studies [1,7], we also believe that runners select movement patterns that optimize their own running economy and that there may be an optimal set of parameters at an individual level. To a certain extent, the Volodalen® method can be perceived as a sliding scale, whereby adjusting different parameters would lead to enhanced performance based on preferred running style. Athletes and coaches can use the Volodalen® method to evaluate and modify the running technique, favoring either the aerial or terrestrial pattern depending on what might benefit the athlete the most. Here, the training prescription would rely on the subjective evaluation of the coach, with the training aiming to either encourage certain characteristics of an individual's pattern (e.g., promote forefoot strike in aerial runners) or promote the alternate pattern when characteristics are overly expressed (e.g., reduce vertical oscillation in an aerial runner with excessive vertical displacements).

Furthermore, it could be that aerial and terrestrial runners respond preferentially to different types of training interventions geared towards improving their performance. For instance, integrating plyometric training in aerial runners might enhance their running economy, but minimally influence terrestrial runners. In contrast, resistance training that improves leg strength and power might further benefit terrestrial rather than aerial runners, which would need to be verified through a standardized intervention study.

Age has been shown to influence self-selected running strategies and might have confounded our results. More precisely, Cavagna et al. [5] observed that older vs. younger subjects (mean age: 73.6 *vs.* 20.8 years) run with lower vertical oscillations of the center of mass and shorter flight times, implying lesser storage-and-release of elastic energy during the gait cycle. According to the Volodalen® classification, older individuals might preferentially adopt a terrestrial running pattern, whereas younger individuals might self-select an aerial one. However, this assumption requires a more precise investigation given that no difference in the mean age of our terrestrial and aerial runners was observed.

Contact and flight time were the only 2 parameters measured in this study and employed to model the spring-mass variables. Although the use of a force platform would have been desirable, Morin et al. [23] have validated the computational approaches that we employed here, reporting low bias (from 0.1 to 6.9%) between force platform and modeled values for leg stiffness, vertical stiffness, leg length changes, maximal force, and centre of gravity displacements during running. As such, we can be relatively confident that our modeled results would approximate those measured directly from a force platform. Another limitation of this study was the focus on temporal and spring-mass variables without quantification of joint biomechanics or energetic cost. Of course, running economy and mechanics rely on complex interactions between the metabolic, cardiorespiratory, biomechanical, and neurological systems [4]. More comprehensive biomechanical and bioenergetics investigations are needed to validate the underlying premises to the Volodalen® method and confirm whether subjective parameters of the classification system (e.g., vertical head displacements) are associated with objective biomechanical measures (e.g., measured head displacement using linear transducers or motion analysis).

Conclusion

The aerial and terrestrial patterns determined subjectively by an expert coach using the Volodalen® method demonstrated distinct running biomechanics parameters, providing preliminary validation of the usefulness of this method. The terrestrial pattern was associated with a longer contact time and greater leg compression than the aerial pattern, while the latter was associated with greater flight time, center of mass displacement, maximal vertical force, and leg stiffness. These findings highlight that qualitative assessments of running patterns using a holistic subjective approach provides insight into the biomechanics of running gait of individuals in absence of objective measurement tools. Understanding the running preference of individuals might assist in individualizing their training programs.

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Conflict of interest: The authors have no conflict of interest to declare.

Affiliations

[1] Research and Development department, Volodalen Compagny, Chaveria, France
[2] Research unit EA4660, Culture Sport Health Society and Exercise Performance Health Innovation platform, Franche-Comté University, Besançon, France.
[3] National Sports Institute of Malaysia, National Sports Complex, Kuala Lumpur, Malaysia
[4] Clinical Investigation Centre, INSERM CIT 808, CHRU, Besançon, France

References

1 *Arellano CJ, Kram R.* The effects of step width and arm swing on energetic cost and lateral balance during running. J Biomech 2011; 44: 1291–1295
2 *Arellano CJ, Kram R.* The metabolic cost of human running: is swinging the arms worth it? J Exp Biol 2014; 217: 2456–2461
3 *Arendse RE, Noakes TD, Azevedo LB, Romanov N, Schwellnus MP, Fletcher G.* Reduced eccentric loading of the knee with the pose running method. Med Sci Sports Exerc 2004; 36: 272–277
4 *Barnes KR, Kilding AE.* Strategies to improve running economy. Sports Med 2015; 45: 37–56
5 *Cavagna GA, Legramandi MA, Peyré-Tartaruga LA.* Old men running: mechanical work and elastic bounce. Proc Biol Sci 2008; 275: 411–418
6 *Coh M, Milanović D, Kampmiller T.* Morphologic and kinematic characteristics of elite sprinters. Coll Antropol 2001; 25: 605–610
7 *Dumke CL, Pfaffenroth CM, McBride JM, McCauley GO.* Relationship between muscle strength, power and stiffness and running economy in trained male runners. Int J Sports Physiol Perform 2010; 5: 249–261
8 *Gruber AH, Umberger BR, Braun B, Hamill J.* Economy and rate of carbohydrate oxidation during running with rearfoot and forefoot strike patterns. J Appl Physiol 1985 2013; 115: 194–201
9 *Halvorsen K, Eriksson M, Gullstrand L.* Acute effects of reducing vertical displacement and step frequency on running economy. J Strength Cond Res 2012; 26: 2065–2070
10 *Harriss DJ, Atkinson G.* Ethical standards in sport and exercise science research: 2014 update. Int J Sports Med 2013; 34: 1025–1028
11 *Hatala KG, Dingwall HL, Wunderlich RE, Richmond BG.* Variation in foot strike patterns during running among habitually barefoot populations. PloS One 2013; 8: e52548
12 *Hébert-Losier K, Jensen K, Mourot L, Holmberg H-C.* The influence of surface on the running velocities of elite and amateur orienteer athletes. Scand J Med Sci Sports 2014; 24: e448–e455
13 *Hébert-Losier K, Mourot L, Holmberg H-C.* Elite and amateur orienteers' running biomechanics on three surfaces at three speeds. Med Sci Sports Exerc 2015; 47: 381–389
14 *Ker RF, Bennett MB, Bibby SR, Kester RC, Alexander RM.* The spring in the arch of the human foot. Nature 1987; 325: 147–149
15 *Kram R, Taylor CR.* Energetics of running: a new perspective. Nature 1990; 346: 265–267
16 *Kulmala J-P, Avela J, Pasanen K, Parkkari J.* Forefoot strikers exhibit lower running-induced knee loading than rearfoot strikers. Med Sci Sports Exerc 2013; 45: 2306–2313
17 *Kyröläinen H, Belli A, Komi PV.* Biomechanical factors affecting running economy. Med Sci Sports Exerc 2001; 33: 1330–1337
18 *Lee CR, Farley CT.* Determinants of the center of mass trajectory in human walking and running. J Exp Biol 1998; 201: 2935–2944
19 *Mangine GT, Fukuda DH, Townsend JR, Wells AJ, Gonzalez AM, Jajtner AR, Bohner JD, LaMonica M, Hoffman JR, Fragala MS, Stout JR.* Sprinting performance on the Woodway Curve 3.0(TM) is related to muscle architecture. Eur J Sport Sci 2014; 1–9
20 *McMahon TA, Valiant G, Frederick EC.* Groucho running. J Appl Physiol 1985 1987; 62: 2326–2337
21 *Di Michele R, Merni F.* The concurrent effects of strike pattern and ground-contact time on running economy. J Sci Med Sport 2014; 17: 414–418
22 *Moreno FJ, Reina R, Luis V, Sabido R.* Visual search strategies in experienced and inexperienced gymnastic coaches. Percept Mot Skills 2002; 95: 901–902
23 *Morin JB, Dalleau G, Kyröläinen H, Jeannin T, Belli A.* A simple method for measuring stiffness during running. J Appl Biomech 2005; 21: 167–180
24 *Nummela AT, Paavolainen LM, Sharwood KA, Lambert MI, Noakes TD, Rusko HK.* Neuromuscular factors determining 5 km running performance and running economy in well-trained athletes. Eur J Appl Physiol 2006; 97: 1–8
25 *Ogueta-Alday A, Rodríguez-Marroyo JA, García-López J.* Rearfoot striking runners are more economical than midfoot strikers. Med Sci Sports Exerc 2014; 46: 580–585
26 *Paavolainen LM, Nummela AT, Rusko HK.* Neuromuscular characteristics and muscle power as determinants of 5-km running performance. Med Sci Sports Exerc 1999; 31: 124–130
27 *Støren Ø, Helgerud J, Hoff J.* Running stride peak forces inversely determine running economy in elite runners. J Strength Cond Res 2011; 25: 117–123
28 *Tartaruga MP, Brisswalter J, Peyré-Tartaruga LA, Avila AOV, Alberton CL, Coertjens M, Cadore EL, Tiggemann CL, Silva EM, Kruel LFM.* The relationship between running economy and biomechanical variables in distance runners. Res Q Exerc Sport 2012; 83: 367–375
29 *Thompson A, Bezodis IN, Jones RL.* An in-depth assessment of expert sprint coaches' technical knowledge. J Sports Sci 2009; 27: 855–861
30 *Weyand PG, Sternlight DB, Bellizzi MJ, Wright S.* Faster top running speeds are achieved with greater ground forces not more rapid leg movements. J Appl Physiol 1985 2000; 89: 1991–1999
31 *Williams KR, Cavanagh PR.* Relationship between distance running mechanics, running economy, and performance. J Appl Physiol 1985 1987; 63: 1236–1245