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ORIGINAL ARTICLE

Do subjective assessments of running patterns reflect objective parameters?

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Abstract
Running patterns are often categorized into subgroups according to common features before data analysis and interpretation. The Volodalen® method is a simple field-based tool used to classify runners into *aerial* or *terrestrial* using a 5-item subjective rating scale. We aimed to validate the Volodalen® method by quantifying the relationship between its subjective scores and 3D biomechanical measures. Fifty-four runners ran 30 s on a treadmill at 10, 12, 14, 16, and 18 km h^{-1} while their kinematics were assessed subjectively using the Volodalen® method and objectively using 3D motion capture. For each runner and speed, two researchers scored the five Volodalen® items on a 1-to-5 scale, which addressed vertical oscillation, upper-body motion, pelvis and foot position at ground contact, and footstrike pattern. Seven 3D biomechanical parameters reflecting the subjective items were also collected and correlated to the subjective scores. Twenty-eight runners were classified as *aerial* and 26 as *terrestrial*. Runner classification did not change with speed, but the relative contribution of the biomechanical parameters to the subjective classification was speed dependent. The magnitude of correlations between subjective and objective measures ranged from trivial to very large. Five of the seven objective parameters significantly differed between *aerial* and *terrestrial* runners, and these parameters demonstrated the strongest correlations to the subjective scores. Our results support the validity of the Volodalen® method, whereby the visual appreciation of running gait reflected quantifiable objective parameters. Two minor modifications to the method are proposed to simplify its use and improve agreement between subjective and objective measures.

Keywords: *Coaching, motor control, biomechanics, measurement, testing*

Highlights

- Subjective assessment provides a reasonable estimation of objectively-quantified running kinematics.
- Aerial and terrestrial running patterns exhibit distinct 3D kinematic parameters.
- The relative importance of the five key elements on the running patterns classification appears to be speed dependent.

Introduction

The existence of more than a single functional gait pattern in healthy individuals has been reported for both walking (Simonsen & Alkjær, 2012) and running (Hoerzer, von Tscharner, Jacob, & Nigg, 2015; Phinyomark, Osis, Hettinga, & Ferber, 2015). Variability in running kinematics has been shown to exist within relatively large samples of healthy runners, even when accounting for internal (e.g. age, height, and body mass) and external (e.g. running speed and footwear) factors (Grau, Maiwald, Krauss, Axmann, & Horstmann, 2008; Phinyomark et al., 2015). Omission to consider the heterogeneity in movement patterns can confound results and their subsequent interpretation. Cluster analysis has been employed to identify clusters of

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runners that exhibit similar characteristics (Hoerzer et al., 2015; Phinyomark et al., 2015), thereby stratifying a larger heterogeneous population into smaller more homogenous subgroups. Applying such methods, Hoerzer et al. (2015) identified eight functionally distinct running patterns in 88 healthy runners, whereas Phinyomark et al. (2015) identified two subgroups in 121 runners. The results from these studies suggest that uninjured individuals employ distinct strategies to achieve similar movement outcomes. However, although statistical approaches like cluster analyses are helpful in identifying functional subgroups within a larger population, undertaking and understanding such analyses is intricate and impractical for most clinicians and coaches.

Practically, it is more common to classify runners into subgroups exhibiting specific movement characteristics through visual observations; for example, based on footstrike. The qualitative assessment of running kinematics (including footstrike) using subjective scales has been reported as reliable (Pipkin, Kotecki, Hetzel, & Heiderscheit, 2016), supporting the use of visual observations of movement by coaches and clinicians. The visual categorization of runners into subgroups can be done rapidly; however, this categorization often considers only one running characteristic. As human locomotion is a global system wherein changes in a single parameter can influence several others (Dickinson et al., 2000), it may be advisable to focus on global movement patterns when classifying runners (Gindre, Lussiana, Hébert-Losier, & Mourot, 2016).

A few researchers have studied global running patterns. McMahon, Valiant, and Frederick (1987) introduced "Groucho" running characterized by excessive knee flexion and long contact time, which can reduce mechanical shock transmission but increase oxygen cost (McMahon et al., 1987). Arendse et al. (2004) presented "Pose" running characterized by limited knee flexion and short contact time, which can limit reductions in the horizontal velocity of the centre of mass during ground contact (Fletcher, Bartlett, Romanov, & Fotouhi, 2008), but increase Achilles tendon strain due to a more forefoot footstrike (Lyght, Nockerts, Kernozek, & Ragan, 2016). In these studies (Arendse et al., 2004; McMahon et al., 1987), Groucho and Pose were compared to self-selected running patterns after interventions aiming to alter self-selected patterns. However, letting individuals select their preferred and comfortable running style could limit running injuries (Nigg, Baltich, Hoerzer, & Enders, 2015) and optimize running efficiency (Moore, 2016). Hence, examining differences between self-selected and modified running patterns in the same individuals can lead to confounding and misinterpretation of results.

Our research team has been investigating the Volodalen® method, which classifies self-selected running patterns into two main subgroups: *Aerial* and *Terrestrial*. This method considers runners as global systems in which the change or alteration of one parameter is likely to affect another. Considering the entire running pattern of individuals allows coaches to adapt their instructions and intervention programs to address individual deficiencies in a more holistic manner. Runners are classified based on visual observations of five key elements. Each element is scored on a 1-to-5 scale. The five individual scores are summed to provide a global score ($V^{®}_{\text{score}}$) ranging from 5 to 25. The method suggests that runners employ different strategies to optimize their running performance, with terrestrial relying more on forward propulsion strategies and aerial more on rebound strategies (Gindre et al., 2016; Lussiana & Gindre, 2016; Lussiana et al., 2016).

Although previous studies have shown that aerial runners naturally exhibit shorter contact times, longer flight times, greater leg stiffness during stance, and earlier gastrocnemius lateralis activation than terrestrial runners (Gindre et al., 2016; Lussiana et al., 2016), no study has yet determined whether the five subjectively assessed elements are directly associated with objectively measured parameters that reflect the same constructs. Hence, our aim was to validate the Volodalen® method by quantifying the relationship between its subjective scores and objective 3D biomechanical measures and comparing 3D measures between aerial and terrestrial runners. Secondary aims included assessing the effect of speed on this relationship and determining the relative contribution of 3D measures to the $V^{®}_{\text{score}}$. We hypothesized that the 3D measures would differ between aerial and terrestrial patterns, and that subjective scores would correlate to their objective counterparts whatever the speed considered.

Methods

Participants

Fifty-four trained runners, 33 males (age 31 ± 8 y, height 175 ± 6 cm, body mass 66 ± 9 kg, and weekly running mileage 53 ± 15 km week^{-1}) and 21 females (age 32 ± 7 y, height 162 ± 3 cm, body mass 52 ± 4 kg, and weekly running mileage 50 ± 14 km week^{-1}) participated. Participants were required to be in good self-reported general health, with no current or recent (<3 months) musculoskeletal injuries, and have competed in a road race in the last year with finishing times of 10 km ≤50 min, 21.1 km ≤110 min, or 42.2 km ≤230 min. Participants who were pregnant were not eligible. The ethical committee of the National Sports Institute of Malaysia approved the study protocol (ISNRP: 26/2015), which was conducted in accordance with international ethical standards (Harriss & Atkinson, 2015) and adhered to the Declaration of Helsinki.

Procedure

Participants completed one experimental session in the biomechanics laboratory of the National Sports Institute of Malaysia. After providing written informed consent, participants ran 3 × 400 m on an athletic track as warm-up at a self-selected speed (12.7 ± 1.3 km h^{-1}), which was followed by 2-min at 9 km h^{-1} on a treadmill. Retro-reflective markers were subsequently positioned on individuals in preparation for experimentation wherein participants ran for 30-s at 10, 12, 14, 16, and 18 km h^{-1} during which time 3D kinematics were recorded. On average, runners took 63 ± 5 and 72 ± 8 steps during the 30-s running bouts at 10 and 18 km h^{-1}, respectively. Running trials were interspersed by a 30-s recovery with participants standing, straddling the treadmill banisters. Data were missing for one participant at both 16 and 18 km h^{-1}, and two participants at 18 km h^{-1} due to technical difficulties. All participants were familiar with running on a treadmill and ran in their habitual running shoes.

Data collection

During the 30-s runs, whole-body 3D kinematics were collected at 200 Hz using 7 infrared cameras (5 Oqus300+, 1 Oqus310+, and 1 Oqus311+), the Qualisys Track Manager software (version 2.11., build 2902), and the Project Automation Framework Running package (version 4.4) from Qualisys AB (Gothenburg, Sweden). Furthermore, one Oqus210c (Qualisys AB) and one Sony Handycam (HDR-PJ660, Sony Thai Co., Ltd.) cameras were positioned perpendicular to and in front of the treadmill, respectively, collecting 2D data at 25 Hz to assist in the Volodalen® subjective classification of runners. This sampling frequency was chosen to mimic the usual conditions under which the subjective Volodalen® assessment is done, without adding a potential benefit from high-speed video capabilities.

Thirty-five retro-reflective markers of 12-mm in diameter were affixed over anatomical landmarks of runners using 3M™ double-sided tape, Hypafix® adhesive non-woven fabric, and Mastisol® liquid adhesive following guidelines from the Project Automation Framework Running package (Tranberg, Saari, Zügner, & Kärrholm, 2011). From the marker set, a full-body biomechanical model with 6 degrees of freedom and 15 rigid segments were constructed in Visual3D Professional software version 5.02.25 (C-Motion, Germantown, MD). Segments included the head, upper arms, lower arms, hands, thorax, pelvis, thighs, shanks, and feet.

The measurement volume was calibrated before experimental trials using a 749.9-mm wand and L-frame placed on the treadmill to define the Cartesian origins. Each participant stood in the middle of the volume for 1-s to allow static calibration and case-specific model definition. The local coordinates of all body segments were derived from this static measurement.

Subjective volodalen® parameters

Two researchers with several years of experience using the Volodalen® method classified all participants into either aerial or terrestrial following standard procedures (Gindre et al., 2016). The classification was done using the 2D videos recordings for all runners at the five running speeds. The researchers observed the global movement patterns of participants with a particular focus on the five key elements: [A] vertical oscillation of the head, [B] arms movement, [C] vertical pelvis position at ground contact, [D] foot position at ground contact, and [E] footstrike. Each element was scored from 1 to 5 following the attainment of a consensus. Disagreements between the researchers occurred for 9.5% of all individual scores (126 of 1330 scores), with most of the disagreements associated with [B] (36 of 126 disagreements) and [C] (32 of 126 disagreements). In these cases, the two researchers adopted a consensus following discussion. The consensus scores for each element were subsequently summed to provide a global $V^{®}_{\text{score}}$ used to categorize runners into terrestrial ($V^{®}_{\text{score}} \leq 15$) or aerial ($V^{®}_{\text{score}} > 15$).

Objective biomechanical parameters

The 3D marker data were processed using Visual3D. The marker data were interpolated using a third-order polynomial least-square fit algorithm, allowing a maximum of 20 frames for gap filling, and subsequently low-pass filtered at 20 Hz using a fourth-order Butterworth filter.

Footstrike and toe-off events were derived from the kinematic data using similar procedures to that previously reported (Hébert-Losier, Mourot, & Holmberg, 2015; Maiwald, Sterzing, Mayer, & Milani, 2009). A mid-foot landmark was generated midway between the heel and toe markers.

Footstrike was defined as the instance when the mid-foot landmark reached a local minimal vertical velocity prior to it reaching a peak vertical velocity reflecting the start of swing. Toe-off was defined as the instance when the toe marker reached a peak vertical acceleration before reaching a 7-cm vertical position. All footstrike and toe-off events were verified to ensure correct identification and manually adjusted when required.

Kinematic parameters were calculated using rigid-body analysis and Euler angles obtained from the static calibration. Pelvis and foot-ground angles (°) were computed using an *x*–*y*–*z* Cardan sequence equivalent to the Joint Coordinate System (Grood & Suntay, 1983) with the laboratory coordinate system used as reference. The angle formed between the foot and the laboratory in the sagittal plane was adjusted to the position recorded in the standing static calibration trial so that an angle of 0° would represent foot flat on the ground (Altman & Davis, 2012). At footstrike, a positive and negative angle would indicate dorsi- and plantar-flexion, respectively (Altman & Davis, 2012). The angle formed between the pelvis and the laboratory coordinates in the sagittal plane was reflective of anterior–posterior tilt, with more positive values indicating greater anterior tilt.

For each cycle (i.e. footstrike to footstrike of the same foot), seven biomechanical parameters were extracted: range of vertical displacement of the centre of mass of the head in relation to its vertical position in upright stance, range of horizontal displacement of the elbow and shoulder joint centres (i.e. minimum to maximum horizontal position during each cycle) normalized to upper arm length, vertical position of the centre of mass of the pelvis at footstrike in relation to its vertical position in upright stance, anterior–posterior tilt of the pelvis (°) at footstrike, horizontal distance between the heel marker and pelvis centre of mass at footstrike normalized to lower extremity length, and footstrike angle (°). These parameters were extracted to reflect the subjectively scored Volodalen® elements. More specifically, vertical head displacement for element [A], horizontal displacement of the shoulder and elbow for [B], vertical position of the pelvis and anterior–posterior tilt for [C], horizontal distance between the heel and the pelvis for [D], and footstrike angle for [E].

Statistics

Since all data were normally distributed according to Kolmogorov–Smirnov tests, parametric statistics were employed. Descriptive data are presented as mean ± SD and correlation coefficients as mean and 90% confidence limits (CL [upper, lower]). Two-tailed Student *t*-tests were used to assess differences in baseline characteristics between aerial and terrestrial runners, and two-way (running pattern × speed) repeated-measures ANOVA with Holm-Sidak procedures for pair-wise post-hoc comparisons were used to investigate whether the objective biomechanical parameters differed between aerial and terrestrial runners, while accounting for running speed. Pearson correlation coefficients (r) were used to quantify the relationship between the subjective Volodalen® scores and their analogous objective biomechanical parameters at each running speed. The following criteria were adopted to interpret the magnitude of the relationships: $r \leq 0.1$, trivial; >0.1–0.3, small; >0.3–0.5, moderate; >0.5–0.7, large; >0.7–0.9, very large; and >0.9–1.0, extremely large (Hopkins, Marshall, Batterham, & Hanin, 2009). The 3D biomechanical parameters that demonstrated non-trivial correlations with subjective scores and significant between-group differences were included in a multiple linear regression analysis to determine the relative influence (i.e. hierarchical importance) of the biomechanical parameters on the $V^{®}_{\text{score}}$ at each speed. Coefficient of determinations (R^2) and standard errors of estimate (SEE) were calculated to quantify the predictive power of the regression model at each speed. The contribution of each 3D parameter to determining the $V^{®}_{\text{score}}$ was expressed both in absolute (adjusted coefficient) and relative (%) terms. Statistical significance was set at $P < .05$ for all analyses. Statistics were performed using SigmaStat 12 (Systat Software, San Jose, USA) and Hopkins' spreadsheets (http://www.sportsci.org).

Results

Characteristics of aerial and terrestrial runners

Twenty-eight runners (4 females, 24 males) were classified as being aerial and 26 (17 females, 9 males) as terrestrial. The aerial group had a significantly higher $V^{®}_{\text{score}}$ at all running speeds than the terrestrial group (mean: 19.5 ± 2.1 vs. 10.8 ± 2.3, $P < .001$); but all other baseline characteristics (aerial vs. terrestrial: age 31 ± 8 vs. 32 ± 7 y, height 172 ± 7 vs. 168 ± 7 cm, body mass 63 ± 10 vs. 58 ± 8 kg, and running distance 51 ± 13 vs. 52 ± 16 km week^{-1}, all $P > .060$), including those relating to shoes (aerial vs. terrestrial: shoe mass 227 ± 37 vs. 222 ± 19 g, heel height 24.4 ± 2.5 vs. 25.1 ± 2.7 mm, and heel-to-toes drop 7.1 ± 2.7 vs. 7.9 ± 2.7 mm, all $P > .257$) were similar between groups. The classification of runners did not change with speed.

Differences in objective measures between aerial and terrestrial

Significant running pattern × speed interaction effects were found for footstrike angle, heel-to-pelvis horizontal distance at ground contact, and horizontal displacement of the elbows (all $P \leq .016$), indicating that these parameters evolved differently with speed according to the running pattern. The interaction effect did not significantly impact the other four objective biomechanical parameters (all $P \geq .598$).

Five of the seven biomechanical parameters significantly differed between aerial and terrestrial runners (Table I). Aerial runners exhibited greater vertical head oscillation and higher vertical position of the pelvis at ground contact than terrestrial runners at all speeds. Aerial runners also demonstrated a shorter heel-to-pelvis horizontal distance at ground contact, smaller footstrike angle, and lesser horizontal displacement of the elbows at all speeds. In contrast, no differences were observed between the groups in the horizontal displacement of the shoulders and pelvis tilt angle at footstrike.

Subjective and objective correlations

Across all running, relationships between the subjective and objective measures were very large for vertical head oscillation [A], horizontal displacement of the elbows [B], and footstrike pattern [E], and moderate for the vertical position of the pelvis at ground contact [C] (all $P < .001$, Figure 1). Relationships between subjective and objective measures for foot position at ground contact ([D], all $P < .002$) and horizontal displacement of the shoulders ([B], $.004 \leq P \leq .150$) changed as speed increased from large to moderate and from moderate to small, respectively. However, only trivial correlations were observed between subjective and objective measures for pelvis tilt angle at ground contact ([C], all $P \geq .267$).

Hierarchical importance of biomechanical parameters to $V^{®}_{score}$

The overall predictive power of models ranged from 69.3% to 75.7%, with the SEE of the $V^{®}_{\mathrm{score}}$ ranging from 2.49 to 2.75 (Table II). Footstrike angle was not a significant predictor of $V^{®}_{\mathrm{score}}$ at 10 and 12 km h^{-1} (9.5% and 12.6% relative contribution, respectively), but became significant at higher speeds (31.9% at 18 km h^{-1}). Oppositely, the heel-to-pelvis horizontal distance at ground contact was a significant predictor of $V^{®}_{\mathrm{score}}$ only at 10, 12, and 14 km h^{-1}. At the slowest speed, the vertical head oscillation and pelvis position at ground contact contributed to determining $V^{®}_{\mathrm{score}}$ the most. However, at the highest speed, the most predictive parameters were the horizontal displacement of the elbows and footstrike angle.

Discussion

Although subjective assessments of running patterns by coaches, clinicians, and sports scientists are common practice and perceived as an essential tool for the individualization of training programs (Gindre et al., 2016) and optimization of performance (Thompson, Bezodis, & Jones, 2009), there are few studies that have validated subjective measures against gold-standard biomechanical measures (Altman & Davis, 2012; Markbreiter, Sagon, Valovich McLeod, & Welch, 2015). The results from our study substantiate the existence of significant and meaningful relationships between subjective and objective assessment of human movement, and support the validity of the Volodalen® method for classifying running patterns. Five of the seven objectively measured parameters significantly differed between aerial and terrestrial runners. The two objective parameters that were similar between groups were also the ones demonstrating no strong relationships with the subjective Volodalen® scores.

Objective and subjective correlations

Subjective assessment of movement patterns is widely used in field conditions and clinical settings, and has been recommended for examining jump-landing biomechanics (Markbreiter et al., 2015) and running footstrike patterns (Altman & Davis, 2012) when technological devices or lab-based testing are not feasible. Specifically for running, a recent investigation has confirmed that running kinematics assessed visually using 2D video recordings provided reliable intra- and inter-rater results for several body posture and alignment parameters scored on a 3 to 5-point scale, including the amount of tibial inclination or knee flexion at initial contact (Pipkin et al., 2016). Our study highlights that the subjective ratings of running kinematics made by practitioners who frequently observe runners reflect objective measures obtained using gold-standard methods reasonably well. Moreover, it is worth highlighting that the subjective rating was done with videos recorded at 25 Hz, a sampling frequency that does not offer any added benefit to the human eye (Näsänen, Ojanpää, Tanskanen, & Päällysaho, 2006). As such, our subjective ratings are thought to reflect real-world on-field situations where only visual observations are used. In most

Table I. The objective biomechanical parameters collected using 3D motion capture for aerial and terrestrial patterns at the different running speeds. The relevant subjectively rated Volodalen® criterion is denoted in brackets [A to E]

Running speed	Running pattern	[A] Vertical head displacement (normalized)[a]		[B] Shoulders horizontal displacement (normalized)[b]	[B] Elbows horizontal displacement (normalized)[b]		[C] Pelvis tilt angle at footstrike (°)	[C] Vertical pelvis position at footstrike (normalized)[c]		[D] Heel to pelvis horizontal distance at footstrike (normalized)[d]		[E] Footstrike angle (°)	
10 km h^{-1}	Terrestrial	0.051 ± 0.005	*	0.250 ± 0.052	0.939 ± 0.171	*	15.5 ± 2.6	0.999 ± 0.009	*	0.169 ± 0.020	*	11.2 ± 3.2	*
	Aerial	0.059 ± 0.006		0.242 ± 0.040	0.808 ± 0.133		15.9 ± 3.3	1.008 ± 0.007		0.147 ± 0.024		6.9 ± 4.8	
12 km h^{-1}	Terrestrial	0.049 ± 0.005	*	0.262 ± 0.052	1.007 ± 0.196	*	15.8 ± 2.6	0.990 ± 0.010	*	0.204 ± 0.021	*	13.3 ± 3.7	*
	Aerial	0.057 ± 0.006		0.255 ± 0.046	0.865 ± 0.149		16.4 ± 3.4	1.000 ± 0.006		0.182 ± 0.025		8.2 ± 4.9	
14 km h^{-1}	Terrestrial	0.046 ± 0.005	*	0.276 ± 0.055	1.072 ± 0.203	*	16.3 ± 2.9	0.983 ± 0.010	*	0.237 ± 0.022	*	15.8 ± 4.1	*
	Aerial	0.054 ± 0.005		0.271 ± 0.050	0.904 ± 0.149		16.8 ± 3.2	0.995 ± 0.006		0.214 ± 0.027		9.3 ± 5.1	
16 km h^{-1}	Terrestrial	0.043 ± 0.006	*	0.288 ± 0.048	1.152 ± 0.233	*	17.2 ± 2.7	0.980 ± 0.012	*	0.272 ± 0.029	*	19.7 ± 5.4	*
	Aerial	0.051 ± 0.005		0.283 ± 0.049	0.946 ± 0.157		17.3 ± 2.9	0.991 ± 0.006		0.239 ± 0.027		10.8 ± 5.8	
18 km h^{-1}	Terrestrial	0.039 ± 0.006	*	0.293 ± 0.046	1.225 ± 0.264	*	17.4 ± 2.2	0.975 ± 0.013	*	0.291 ± 0.028	*	20.1 ± 5.3	*
	Aerial	0.046 ± 0.005		0.290 ± 0.047	0.995 ± 0.157		17.6 ± 3.2	0.986 ± 0.008		0.261 ± 0.029		11.9 ± 6.4	
Running pattern effect		**<0.001**		0.734	**0.007**		0.731	**0.001**		**0.002**		**<0.001**	
Running speed effect		**<0.001**		**<0.001**	**<0.001**		**<0.001**	**<0.001**		**<0.001**		**<0.001**	
Interaction effect		0.927		0.968	**<0.001**		0.618	0.598		**0.016**		**<0.001**	

Notes: Values are mean ± SD. Level of significance set at $P < .05$. Significant differences identified by the two-way repeated-measures analysis of variance (RM ANOVA) are indicated in bold. Asterisks (*) indicate a significant difference between groups showed by Holm-Sidak post-hoc testing procedures. Subjectively rated Volodalen® criterion [A], Vertical oscillation of the head [B], Arms movement [C], Pelvis position at ground contact [D], and Foot position at ground contact [E] Strike pattern. Values were normalization to: [a]vertical position of the head segment in upright stance, [b]upper arm length, [c]vertical position of the pelvis segment in upright stance, and [d]lower extremity length.

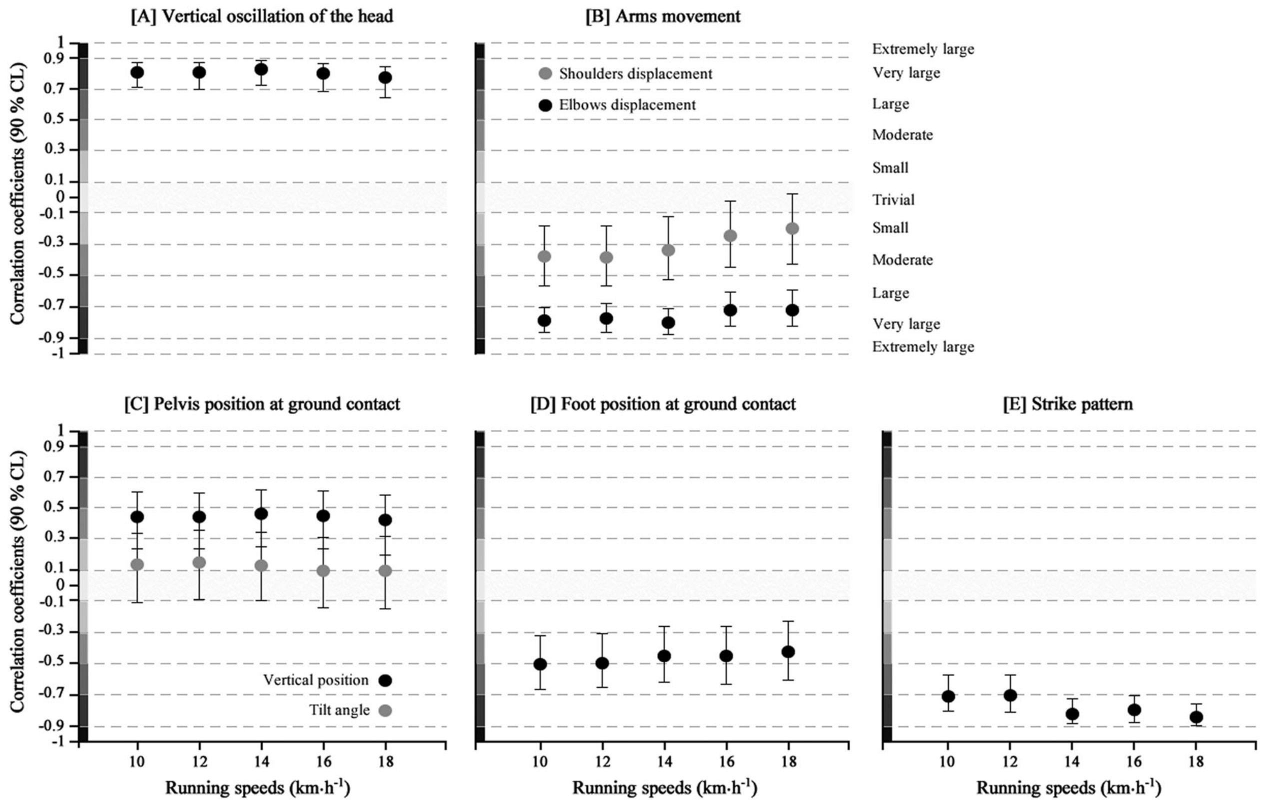

Figure 1. Correlation coefficients with 90% CL between the subjective scores of the five key elements of the Volodalen® method and relevant objective biomechanical parameters extracted from 3D motion capture at the different running speeds.

instances, the subjectively assessed parameters and their objective counterparts demonstrated moderate to very large correlations in our study, except for measures pertaining to the horizontal displacement of the shoulders and the anterior–posterior pelvis tilt at ground contact. Anecdotally, these two parameters were the ones that the two researchers found the most difficult to score given their more axial location and were most often the source of disagreeing scores. In contrast, the elements associated with visual observations with a focal point located more distally and further away from the body's centre of mass, such as vertical head oscillation [A] and footstrike pattern [E], were easier to score and exhibited very large relationships with the 3D parameters. Beyond the sampling frequency, the reliability of visual observations can depend on the types of movement observed (Barris & Button, 2008), with lower reliability for observations of movements of high frequency or short duration. Overall, our results indicate that the visual appreciation of a runner's global movement pattern using the Volodalen® method can provide good insight on that individual's preferred movement pattern. However, caution is advised to proximally located observations, which appear to be more difficult to quantify subjectively through visual observations and less valid estimates of actual kinematics.

Differences between aerial and terrestrial

Consistent with previous investigations (Gindre et al., 2016; Lussiana et al., 2016), aerial and terrestrial runners exhibited different kinematics at the five running speeds examined. Aerial runners had greater vertical head oscillation, smaller horizontal displacement of the elbows, higher vertical position of the pelvis at footstrike, shorter horizontal distance between the heel and pelvis at ground contact, and smaller footstrike angles than terrestrial runners based on the 3D data. However, no differences were observed in terms of horizontal displacement of the shoulders and pelvis tilt angle at ground contact. Combined with the small and trivial correlations observed between these objective measures and their subjective surrogates, and low relative contribution to $V^{®}_{\text{score}}$ determination, these findings warrant modifications to the Volodalen® scoring system. We propose that the current wording for [B] and [C] be changed from "arms movement – by shoulders or by elbows" and "pelvis position at ground contact – low and retroverted

Table II. Results of the multiple linear regression analysis determining the influence of objective parameters on the $V^{®}_{score}$ at different running speeds. The relevant subjectively rated Volodalen® criterion is denoted in brackets [A to E]

Running speeds	R^2	SEE		Constant	[A] Vertical head displacement (normalized)[a]	[B] Elbows horizontal displacement (normalized)[b]	[C] Vertical pelvis position at footstrike (normalized)[c]	[D] Heel to pelvis horizontal distance at footstrike (normalized)[d]	[E] Footstrike angle (°)
10 km h $^{-1}$	0.70	2.67	Adjusted coefficients	16.0	1.93	−1.47	1.48	−1.06	−0.62
			Relative contributions (%)		29.5	22.4	22.5	16.2	9.5
			P values		<0.001	0.002	0.001	0.016	0.143
12 km h $^{-1}$	0.69	2.68	Adjusted coefficients	16.0	1.88	−1.37	1.51	−1.32	−0.69
			Relative contributions (%)		28.5	20.9	22.9	20.2	10.6
			P values		<0.001	0.003	0.001	0.002	0.104
14 km h $^{-1}$	0.75	2.49	Adjusted coefficients	15.4	2.14	−1.2	1.49	−1.19	−1.09
			Relative contributions (%)		32.5	18.3	22.6	18.1	16.5
			P values		<0.001	0.006	<0.001	0.004	0.008
16 km h $^{-1}$	0.75	2.75	Adjusted coefficients	14.4	1.95	−1.59	1.59	−0.90	−1.67
			Relative contributions (%)		29.7	24.2	24.2	13.7	25.4
			P values		<0.001	0.002	<0.001	0.066	<0.001
18 km h $^{-1}$	0.76	2.65	Adjusted coefficients	14.6	1.45	−2.12	1.49	−0.81	−2.10
			Relative contributions (%)		22.1	32.3	22.7	12.3	31.9
			P values		0.002	<0.001	<0.001	0.071	<0.001

Notes: Level of significance set at $P < .05$. The coefficient of determination (R^2) and the SEE quantify the predictive power of each multiple linear regression model. Subjectively rated Volodalen® criterion [A], Vertical oscillation of the head [B], Arms movement [C], Pelvis position at ground contact [D], and Foot position at ground contact [E] Strike pattern. Values were normalization to: [a]vertical position of the head segment in upright stance, [b]upper arm length, [c]vertical position of the pelvis segment in upright stance, and [d]lower extremity length.

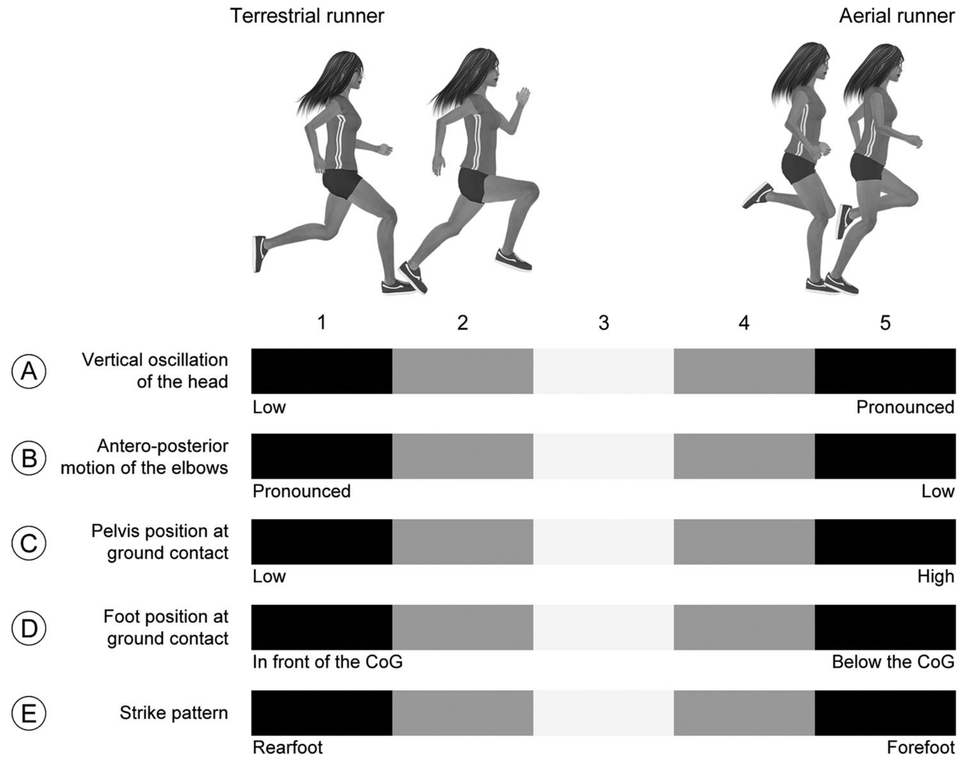

Figure 2. Subjective scoring system of the Volodalen® method with removal of the "horizontal displacement of the shoulders" and "pelvis tilt" wording.

or high and anteverted" to "antero-posterior motion of the elbows – pronounced or low" and "pelvis position at ground contact – low or high" (Figure 2). These amendments should enhance the agreement between the subjective Volodalen® scores and their corresponding objective measures, and simplify the use of the scale.

Hierarchical importance of Volodalen® criteria

Multiple linear regressions were used to assess the relative contribution of the 3D parameters to the $V^{®}_{\text{score}}$ at the different speeds. The vertical head oscillation explained the variance in the $V^{®}_{\text{score}}$ the most, and the horizontal distance from the heel to the pelvis at ground contact the least (Table II). However, the relative contribution of each objective parameter to the $V^{®}_{\text{score}}$ changed with running speed. For instance, the contribution of the vertical head oscillation to the $V^{®}_{\text{score}}$ decreased from 29.5% to 22.1% with the increase in speed. On the contrary, the relative importance of footstrike angle increased from 9.5% to 31.9% as speed increased. The explanation could be attributed to the effect of running speed on kinematics. For instance, we observed a decrease in the vertical oscillation of the centre of mass as speed increased, in agreement with previous running research findings (Brughelli, Cronin, & Chaouachi, 2011). As such, one could expect greater variance in certain biomechanical parameters with an increase in speed, but a reduction in variance in other parameters. Furthermore, using cluster analysis, Forrester and Townend (2015) have reported that footstrike angle remains constant in particular individuals, but decreases in others as running speed increases, indicating individual-specific responses to changes in running speed. Here, we found interaction effects between running pattern and speed for footstrike angle, horizontal displacement of the elbows, and heel-to-pelvis horizontal distance at ground contact. These parameters increased more in terrestrial than aerial runners as speed increased (footstrike angle: +8.9 vs. 5.0°, horizontal displacement of the elbows normalized to upper arm length: +0.286 vs. 0.187, and heel-to-pelvis horizontal distance at ground contact normalized to lower extremity length: +0.122 vs. 0.114), while the change in the vertical head oscillation normalized to its position in stance with speed was similar between groups (−0.012 vs. 0.013), decreasing the relative contribution of this parameter to the $V^{®}_{\text{score}}$. Thus, the shift in the relative contributions of the different variables to $V^{®}_{\text{score}}$ may be partly explained by the difference in the change of these parameters across speeds between groups. Nonetheless, despite changes in the relative contribution of 3D parameters with speed, noteworthy is the maintenance of the overall classification of runners across the different speeds examined.

Considerations

One limitation of the current study was the differing proportions of females in the terrestrial (65%) and aerial (14%) groups. However, given that normalization to body segment lengths or static positions was undertaken to account for differences in anthropometric characteristics, we believe that the differing sex proportions should not impact our main findings. Furthermore, it is to be noted that we used a sampling frequency of 25 Hz to collect our 2D video footage. This sampling frequency served our purpose of classifying runners into aerial and terrestrial groups using the Volodalen® scale; however, using a sampling rate of 120 Hz or higher is recommended when conducting objective biomechanical assessment of running kinematics (Souza, 2016).

Conclusions

As the subjective assessment of running parameters was clearly and largely related to objectively measured parameters, we suggest that the Volodalen® method is a valid tool for classifying runners into aerial and terrestrial subgroups. Coaches, clinicians, and researchers experienced in visually observing movement patterns should be able to use the Volodalen® method to assess running patterns without the need for advance technologies or statistical processes. The Volodalen® method could become useful in designing intervention programs as it easily identifies runners into different functional subgroups that use different movement strategies.

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Disclosure statement

C.G. is the originator of the Volodalen® method. However, this paper does not constitute endorsement of the method by the other author and stems completely from a PhD research project undertaken at the Bourgogne Franche-ComtComté University by T.L.

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