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Section I – Kinesiology

Reproducibility of the Evolution of Stride Biomechanics During Exhaustive Runs

by

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Running biomechanics and its evolution that occurs over intensive trials are widely studied, but few studies have focused on the reproducibility of stride evolution in these runs. The purpose of this investigation was to assess the reproducibility of changes in eight biomechanical variables during exhaustive runs, using three-dimensional analysis. Ten male athletes (age: 23 ± 4 years; maximal oxygen uptake: 57.5 ± 4.4 $ml0_2 \cdot min^{-1} \cdot kg^{-1}$; maximal aerobic speed: 19.3 ± 0.8 $km \cdot h^{-1}$) performed a maximal treadmill test. Between 3 to 10 days later, they started a series of three time-to-exhaustion trials at 90% of the individual maximal aerobic speed, seven days apart. During these trials eight biomechanical variables were recorded over a 20-s period every 4 min until exhaustion. The evolution of a variable over a trial was represented as the slope of the linear regression of these variables over time. Reproducibility was assessed with intraclass correlation coefficients and variability was quantified as standard error of measurement. Changes in five variables (swing duration, stride frequency, step length, centre of gravity vertical and lateral amplitude) showed moderate to good reproducibility ($0.48 \leq ICC \leq 0.72$), while changes in stance duration, reactivity and foot orientation showed poor reproducibility ($-0.71 \leq ICC \leq 0.04$). Fatigue-induced changes in stride biomechanics do not follow a reproducible course across the board; however, several variables do show satisfactory stability: swing duration, stride frequency, step length and centre of gravity shift.

Key words: *kinematics, 3D, treadmill, exhaustion, running, evolution.*

Introduction

Running is an increasingly widespread form of exercise due to the naturalness of the movements required and health benefits (Dugan and Bhat, 2005). The growing interest in this sport has been mirrored by technical improvements in research facilities and diversification of research into running biomechanics. As the number of recreational and competitive runners increases, professionals such as sports physicians, physical therapists and trainers have a key role to play in improving our understanding of the mechanisms underlying sports injuries as well as in developing performance enhancement strategies.

To this end a lot of equipment for recording temporal, spatial and angular variables has been developed in recent decades and is used for both clinical and practical purposes. These devices include force platforms, pressure sensors, electromyography, accelerometers, electrogoniometers and motion analysis systems (Higginson, 2009). Motion analysis systems are used mainly by the research community due to their cost and weight. All these tools have their pros and cons; three-dimensional (3D) motion

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capture is powerful and is extensively used by investigators (although the validity of the data is sometimes questionable due to skin movement artefacts) (Leardini et al., 2005; Reinschmidt et al., 1997). It is suited to assess biomechanical patterns of the normal gait (Deflandre et al., 2016; Pietraszewski et al., 2012), to investigate abnormal movements that cause injuries (Bruderer-Hofstetter et al., 2015) and to estimate the success of interventions intended to correct gait anomalies (Ferber et al., 2005) or enhance performance (Snyder et al., 2009).

There are many features that distinguish running from walking (e.g. increased velocity, float phase, decreased centre of gravity (CG) and variation in initial foot contact) (Dugan and Bhat, 2005) and this is why stride biomechanics are often described in terms of variables that are sensitive to an increase in velocity, such as stride frequency (Avogadro et al., 2003; Schache et al., 2014), step length (Cho, 2015; Hayes et al., 2014), stance and swing duration (Kivi et al., 2002; Ogueta-Alday et al., 2013) as well as running economy (Gruber et al., 2013; Lacour and Bourdin, 2015) (i.e. oxygen uptake at a given velocity; Anderson, 1996). Some patterns are known to alter running economy, for example an increase in the vertical or lateral shift in the CG during running (Dugan and Bhat, 2005; Saunders et al., 2004). Some authors focus on the foot (initial contact location and toe-off position for instance) (Delgado et al., 2013; Lieberman et al., 2010) or the knee pattern (leg stiffness or range of motion) (Abt et al., 2011; Hayes et al., 2014), whereas others take a holistic approach to the running gait. The latter group has described various patterns of stride biomechanics, but under differing conditions. Some have focused on the evolution of kinematic variables during long runs at constant speed (Hunter and Smith, 2007), whereas others have compared the evolution of variables across runs at different speeds (Dorn et al., 2012) or over the course of an accelerating run (Schache et al., 2014). Other studies have investigated elite athletes running at high intensities or until exhaustion (Fourchet et al., 2014). Interesting biomechanical changes emerge during these exhaustive runs: swing duration reduces and stance duration increases, peak vertical ground reaction force decreases and so does leg stiffness (Gazeau et al., 1997; Rabita et al., 2013). Although the evolution of these kinematic variables during an exhaustive run seems to have been widely investigated, there is a lack of knowledge about the reproducibility of the pattern of changes over repeated exhaustive runs.

This may be partly explained by the difficulty to assess the reproducibility of various types of efforts through 3D analysis, given the complexity of marker placement on the anatomical landmarks. Inter-investigator variability in marker placement is a major issue; it appears to be high and dependent on the investigator’s familiarity with the procedures (Sinclair et al., 2014). It is therefore recommended that the markers should always be placed by the same person throughout an investigation. Several other variables must also be kept constant to ensure the reproducibility of the measurements including time of day (Saunders et al., 2004), shoes (Nigg et al., 2003; Rose et al., 2011), sportswear (Zhang et al., 2002) and the treadmill slope (Jones and Doust, 1996). To determine whether a given runner’s biomechanical pattern always evolves in the same way during an exhaustive effort, it needs to be measured repeatedly under the same conditions and, to the authors’ knowledge, this kind of study has never been carried out with respect to long, exhaustive runs. We would like to fill the gap in the existing literature regarding the repetition of exhaustion-induced biomechanical events to see whether the potential adaptations of the running gait are reproducible from one run to another.

The aim of this study was, therefore, to investigate whether the evolution of the main biomechanical variables used to describe a running gait is reproducible.

Methods

Participants

Ten well-trained male runners (age: 23 ± 4 years; body mass: 69 ± 7 kg; body height: 181 ± 5 cm; maximal oxygen uptake (VO_{2max}): 57.5 ± 4.4 $ml0_2 \cdot min^{-1} \cdot kg^{-1}$; maximal aerobic speed (MAS): 19.3 ± 0.8 $km \cdot h^{-1}$) were recruited for this study. The inclusion criteria were (1) being an active, male runner training at least three times a week; (2) $VO_{2max} > 55\ ml \cdot min^{-1} \cdot kg^{-1}$; (3) MAS > 18 $km \cdot h^{-1}$. All participants were healthy and pain-free during the testing period. None of them reported any musculoskeletal injury or dysfunction in the lower limbs over the six weeks preceding the study. All runners participated on a voluntary basis and were fully informed about the nature of the experimental protocol. An institutional ethical committee approved the study.

Measures

We chose to monitor eight biomechanical variables which have been extensively studied and/or are sensitive to gait adjustments over time: stance duration, swing duration, reactivity, step length (Lienhard et al., 2013), stride frequency (Dorn et al., 2012), foot orientation at impact (Rooney and Derrick, 2013), and variations in vertical (Morin et al., 2006) and lateral amplitude of the CG (Table 1).

In every trial, all biomechanical variables were recorded over a 20 s period every 4 min. Sessions lasted until exhaustion was reached.

Design and Procedures

The experimental design consisted of four sessions: the first one was used to determine the participant's MAS and the remaining three to assess reproducibility of the evolution of the stride at 90% of this intensity. Participants were instructed to keep their usual training pace between sessions and to avoid major competitions during the study period. The first test consisted of an incremental run to exhaustion on a calibrated treadmill (SportsArt T650, SportsArt, Taiwan) comparable to the Bruce protocol (McDonough and Bruce, 1969) to assess VO_{2max}. Briefly, participants started exercising at a treadmill speed of 8 $km \cdot h^{-1}$. Speed was subsequently increased by 2 $km \cdot h^{-1}$ every 3 min until exhaustion was reached. Oxygen uptake (VO_2), minute ventilation (VE), respiratory exchange ratio (RER) (Ergostick, Geratherm Respiratory, Germany), heart rate (Polar Belt, Polar, USA) and lactataemia (1500 Sport L-Lactate, YSI, USA) were measured. The test was stopped when the participant could not maintain the required pace or had reached voluntary exhaustion. The criteria used to assess VO_{2max} were a RER ≥ 1.10, a heart rate in excess of 90% of the age-predicted maximum (i.e. 220 - age) and identification of a VO_{2max} plateau (< 150 ml/min increase despite a further velocity increase). In all tests two of the three criteria were met. MAS was defined as the lowest speed that elicited VO_{2max} and was used in the next three sessions, which were carried out 3 to 15 days later, as shown in Figure 1.

Each session consisted of running to exhaustion on an equivalent treadmill with a 1% gradient. The running speed was set at 90% of the individual's MAS (90% MAS). Cardiac frequency was monitored with a Polar® belt. All the subjects ran in the same model of shoes (Neutral Asics shoes, Asics Corporation, Japan) wearing just their underwear. A three-dimensional optoelectronic system (CX1, Codamotion™, Charnwood Dynamics, Rothley, UK) was used to track four active markers fixed to the traditional anatomical landmarks (i.e, right and left anterosuperior iliac spine and posterosuperior iliac spine) and four attached directly to the shoe (i.e. right and left heel and great toe distal end) as described by Fellin et al. (2010) and Pohl et al. (2010); the marker locations are depicted in Figure 2. Data were acquired over 20-s periods every 4 min at a rate of 200 Hz. Markers were always attached by the same investigator, with the subject in an upright position. The three tests were performed at the same time of the day at 7-day intervals.

Statistical Analysis

Mean values were calculated for all 20-s recordings. At the end of a session, the 20-s means were averaged and their standard deviation (*SD*) computed. A linear regression line was fitted to the means and its slope estimated to assess any within-trial time effect. The coefficient of determination (R^2) was also calculated to assess the fit of the regression. Reproducibility was assessed using the intraclass correlation coefficient (ICC – two-way random model) and its 95% confidence interval (95%CI), using SAS software (SAS© Institute Inc., Cary, NC, USA). Reliability was expressed as standard error of measurement (*SEM*) using ICC values ($SEM = SD \times \sqrt{[1 - ICC]}$). Reproducibility refers to the proportion of variance attributable to the true variation (Shrout et al., 1979; Maszczyk et al, 2012), whereas variation due to measurement error was evaluated as reliability (De Vet et al., 2011; Maszczyk et al., 2014).

We assessed the reproducibility and reliability of the biomechanical variables and their time courses (slopes). We also evaluated the reproducibility of the athletes' performance (expressed as running time and distance). We used the standard Fleiss criteria (Fleiss, 2011) to categorise reproducibility (i.e. poor: ICC < .4;

moderate to good: .41 < ICC < .74; excellent ICC > .75). *SEM* values were interpreted in relation to the mean values of each variable; the lower the *SEM*, the better.

Results

Physiological Data

The first incremental exercise to exhaustion session was used to obtain physiological data for the whole sample, VO_{2max}: 57.5 ± 4.4 mL/kg/min; MAS: 19.3 ± 0.8 km/h; lactate thresholds: 15.3 ± 2.2 and 17.6 ± 1.4 km/h; maximal lactataemia: 7.5 ± 1.3 mmol/L; maximal heart rate: 191 ± 8 bpm. Table 2 shows the 10 runners' performance during the three runs to exhaustion at 90% MAS (17.3 ± 0.7 km/h). The ICC values suggest that both running time and distance had excellent reproducibility.

Biomechanical Variables

Table 3 shows the grand averages over the three runs to exhaustion for all variables. The mean running time for the 30 runs (30 ± 10minutes) yielded 8 ± 3 recordings/session from which the slope of the regression line was estimated. Based on the ICCs all variables showed excellent reproducibility. The *SEM* was low for all variables except for foot orientation at impact.

Reproducibility of Evolution of Parameters

Table 4 displays, for each biomechanical variable and each trial, the means and *SD*s of the slopes calculated from the 10 athletes. The corresponding mean coefficients of determination (r^2), ICCs (95%CI) and *SEM*s are also given. Five out of the eight variables evolved in a way that showed moderate to good reproducibility across the three trials (swing duration; stride frequency; step length; vertical amplitude of CG; lateral amplitude of CG), but the time courses of the remaining three (stance duration; reactivity; foot orientation at impact) had poor reproducibility. All *SEM*s were high relative to the corresponding mean.

Table 1

Biomechanical variables considered

Variable	Units	Definition	Determination
Stance duration	Seconds	Interval between foot landing and take-off	Interval between the vertical negative velocity peak for the centre of the foot (computed as the barycentre of the big toe and heel markers) and the point of minimal big toe contact
Swing duration	Seconds	Take-off duration of one foot and landing of the other	Interval between minimal big toe contact with one foot and vertical negative velocity peak for the centre of the other foot
Reactivity	None	Ratio between swing duration and stance duration	
Stride frequency	Hertz	Number of strides executed in 1 s	
Step length	Metres	Ratio between distance covered and total number of steps	
Foot orientation at impact	Degrees	Angle between the vector linking the heel marker to the 5th metatarsal marker and the horizontal axis in the sagittal plane. Positive angles represent dorsiflexion	
Vertical amplitude of CG	Metres	Vertical motion of the CG during one whole stride	CG defined as the barycentre of the four pelvic markers
Lateral amplitude of CG	Metres	Lateral of the CG during one whole stride	CG defined as the barycentre of the four pelvic markers

Table 2

Mean values, standard deviations, intraclass correlation coefficients with 95% confidence intervals and standard errors of measurement for performance over the three 90% MAS trials

Variable	**Mean± *SD***	**ICC**	**95%CI**	***SEM***
Running time (min)	30 ± 10	0.80	0.58 – 0.91	4.5
Covered distance (km)	8.7 ± 2.9	0.81	0.59 – 0.92	1.3

Table 3

Mean values and standard deviations for each trial, intraclass correlation coefficient with 95% confidence interval and standard error of measurement of 8 biomechanical variables over the three trials at 90% MAS

Variable	Trial 1	Trial 2	Trial 3	ICC	95%CI	*SEM*
Stance duration (s)	0.23 ± 0.01	0.23 ± 0.01	0.23 ± 0.01	0.99	0.99-0.99	0.001
Swing duration (s)	0.48 ± 0.02	0.48 ± 0.02	0.48 ± 0.01	0.99	0.99-0.99	0.002
Reactivity	2.13 ± 0.17	2.07 ± 0.11	2.08 ± 0.11	0.99	0.99-0.99	0.013
Stride frequency (Hz)	1.41 ± 0.04	1.40 ± 0.04	1.41 ± 0.05	0.99	0.99-0.99	0.004
Step length (m)	1.71 ± 0.08	1.72 ± 0.08	1.72 ± 0.08	0.99	0.99-0.99	0.008
CG vertical amplitude (m)	0.10 ± 0.01	0.10 ± 0.01	0.10 ± 0.01	0.99	0.99-0.99	0.001
CG lateral amplitude (m)	0.06 ± 0.02	0.06 ± 0.02	0.06 ± 0.02	0.99	0.99-0.99	0.002
Foot orientation at impact (°)	11.9 ± 5.0	13.0 ± 4.3	12.3 ± 3.7	0.99	0.98-0.99	0.425

Table 4

Means and standard deviations of the slopes with mean coefficient of determination (r^2) for each trial, intraclass correlation coefficient with 95% confidence interval and standard error of measurement for eight biomechanical variables over the three trials at 90% MAS.

Variable slope	Test 1	Test 2	Test 3	r^2	ICC	95% CI	*SEM*
Stance duration (s·rec^{-1}[a]·10^3)	1.5 ± 0.8	- 1.9 ± 8.7	0.7 ± 1	0.55	-0.18	-0.56-0.25	5.4
Swing duration (s·rec^{-1}·10^3)	0.8 ± 4.7	1.3 ± 1.5	0.5 ± 3	0.38	0.57	0.2-0.8	2.4
Reactivity (s·rec^{-1}·10^3)	-12 ± 23	13 ± 47	-3.5 ± 27	0.33	-0.71	-0.87--0.41	40.0
Stride frequency (s·Hz^{-1}·10^3)	-4.5 ± 9.7	-0.3 ± 13.3	-2.5. ± 4.3	0.49	0.67	0.35-0.85	6.4
Step length (m·rec^{-1}·10^3)	5.3 ± 11.6	-0.1 ± 17.4	3.0 ± 5.2	0.49	0.65	0.31-0.84	8.4
vertical ampl· CG [b] (m·rec^{-1}·10^3)	0.4 ± 1.0	0.2 ± 0.9	0.4 ± 0.5	0.37	0.72	0.44-0.88	0.5
lateral ampl· CG (m·rec^{-1}·10^3)	1.1 ± 1.1	1.3 ± 1.5	0.8 ± 0.9	0.54	0.48	0.084-0.75	0.9
Foot orientation at impact (°·rec^{-1}·10^3)	27.6 ± 263	88.4 ± 542	-102 ± 177	0.31	0.04	-0.38-0.45	354.0

a: recordings; b: centre of gravity

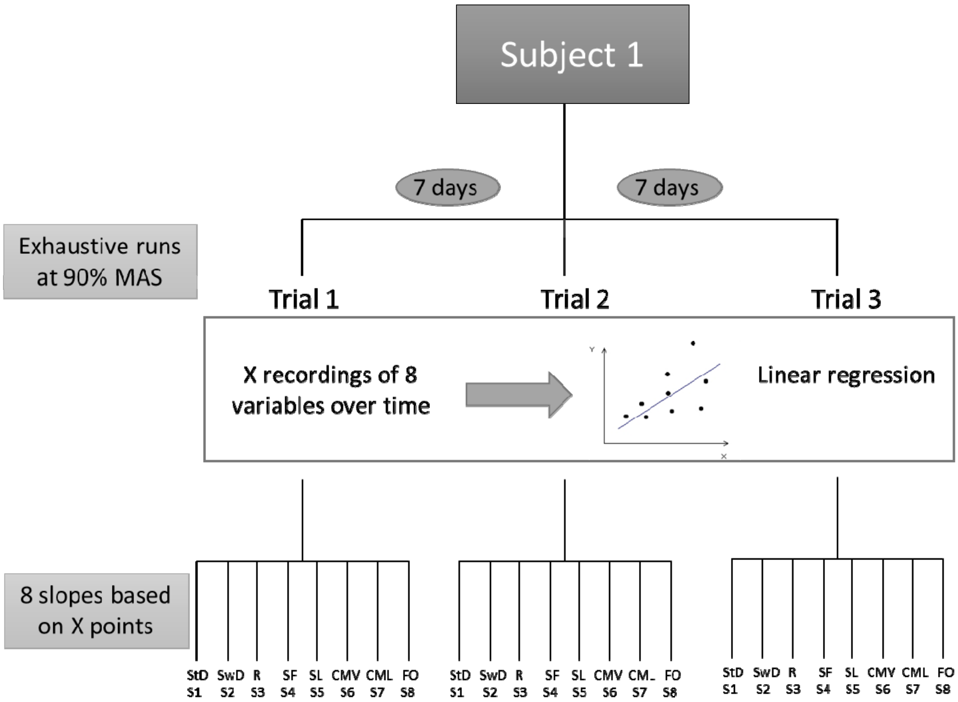

Figure 1

Study design

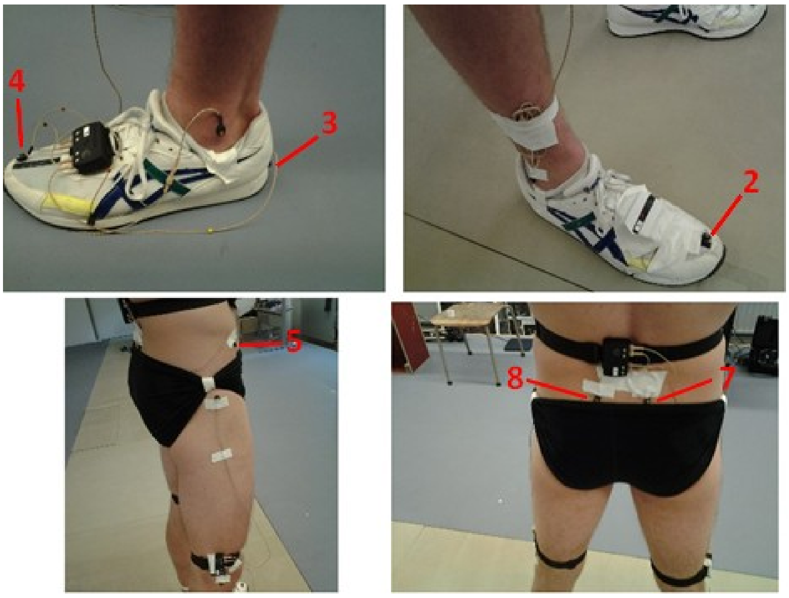

Figure 2

Marker placement

Discussion

The aim of this study was to investigate whether changes in the biomechanical pattern, as described by eight variables (related to foot strike, movement of CG or stride), during performance were similar from one 90% MAS trial to another in a sample of 10 regular runners. Well-trained runners are known to have a more stable running pattern than novice runners (Hopkins et al., 2001; Pollock et al., 1976) and hence are better subjects for investigations into reproducibility.

The selected intensity (90% of the individual's MAS) had to be high enough to induce fatigue-related changes yet allow us a recording period long enough to observe biomechanical adjustments to the running gait before exhaustion was reached. Several earlier studies had shown that major biomechanical alterations tended to appear shortly before exhaustion (Derrick et al., 2002; Gazeau et al., 1997; Rabita et al., 2013). The time course of changes over higher intensity runs to exhaustion (100% of the MAS) appears to be reproducible, but this is based on assessments of a relatively small number of recordings per trial, since running times at this speed are rather short, ranging from 5 (Gazeau et al., 1997) to 7 minutes (Billat et al., 1994) and do not allow high volumes of biomechanical data to be recorded.

We chose to use 3D analysis as it provides a precise record of the runner's kinematics (Deflandre et al., 2016) and we needed accurate data on biomechanics of the entire stride. This method of analysis requires the subject to run on a treadmill; however, running reliability should be similar in the field and on a treadmill (Hopkins et al., 2001).

Since the volume of 3D data collected depended directly on the duration of effort (which varied between participants), the main analytical challenge was to find an appropriate way of quantifying the evolution of the variables of interest. For this purpose, we drew on research by Bosquet et al. (2010) and Pincivero et al. (2001). These scientists studied the reproducibility of muscle fatigue using the slope of the linear regression of the performance on the amount of contractions to track its course. This method allows one to maximise use of data obtained between the first and last recordings. The reproducibility and reliability of the regression slopes were assessed using the ICC and SEM, in accordance with the work of the above-mentioned groups and existing sports science literature on reproducibility (Ford et al., 2007; Karamanidis et al., 2003; Lienhard et al., 2013; Schabort et al., 1998; Sinclair et al., 2014; Wilken et al., 2011).

Reproducibility of Changes in Physiological and Biomechanical Variables

Running time and distance covered showed excellent reproducibility; in other words, the participants performed similarly in their three high-intensity trials to exhaustion. In contrast the SEMs were quite high. In the case of running time the mean was 30 min and the SEM 4.5 min, meaning that only changes of at least 9 min can be attributed to factors other than random measurement error (Gouttebarge et al., 2015).

It was not the primary focus of this study, but we observed that the means for all biomechanical variables showed excellent reproducibility (all ICCs were .99), indicating that at this intensity an individual running style appears to be stable. Several authors have already demonstrated that many biomechanical variables (stance duration, swing duration, step length, vertical CG amplitude) have satisfactory reproducibility at velocities ranging from 9 to 14 km·h-1 (Diss, 2001; Karamanidis et al., 2003; Morgan et al., 1991). The average speed of our sample was 17.3 ± 0.7 km·h-1 and to our knowledge reproducibility has not been investigated at this velocity. The SEMs were small relative to the means in the case of all variables, indicating relatively little random measurement error. We can therefore assume that the position of the markers and the recording technology were both highly reliable. However, the reproducibility of a mean value only provides an estimate of where the markers are placed but lacks specificity regarding the evolution of their location with exercise.

Reproducibility of Evolution

We therefore analysed the reproducibility of the evolution of biomechanical variables during one exhaustion trial. Evolution was estimated as the slope of the recorded values of a given variable (8 ± 3 recordings per trial) over time. First, inspection of the SEMs for the slopes made it clear that not all were acceptably small relative to the mean. The worst example was the evolution of foot orientation at impact for which the mean was -0.29 and the SEM 0.351; this indicates that the reliability of these measurements was extremely poor; in effect, they lack precision. This may be partly because the raw data were converted into slopes based on linear regressions that sometimes had very small coefficients of determination in the case of time courses that were not in fact linear. Nevertheless, as explained above, we chose this method to retain as much of the recorded data as possible for analysis. Further studies of the reproducibility of temporal changes in biomechanical variables should tackle this issue.

Nonetheless our results showed that the time course of changes in the following variables had moderate to good reproducibility: swing duration, stride frequency, step length and both CG amplitudes; the reliability of vertical CG amplitude approached excellence (ICC = .72). Stance duration, reactivity (calculated on basis of stance duration) and foot orientation at impact showed poor reproducibility. The evolution of these stride-related variables thus appears to be rather steady with the significant exception of stance duration (ICC = -.18).

The sign of the slope for stance duration indicated that in all participants, stance duration increased over the course of the first and third trials (positive slope) but decreased during the second trial (negative slope), which suggests that there is high variability in the evolution of stance duration over time. This is not that surprising, since the literature on evolution of stance duration during a single session is not consistent. Some authors have reported that stance duration increases over time at high intensities, i.e. between 90% and 100% MAS (Avogadro et al., 2003; Gazeau et al., 1997; Hobara et al., 2010; Slawinski et al., 2008). Several explanations for this increase have been proposed namely that it decreases the energetic cost of running as fewer muscle fibres are recruited and that it reduces leg stiffness and the decline in muscular propulsion capacity (Fourchet et al., 2013). However, other authors have reported the opposite pattern, namely a decrease in stance duration. Borrani et al. (2003) reported that stance duration decreased over time in a 95% MAS trial, attributing this result to activation of fast twitch fibres to prevent loss of strength. Stance duration also seems to decrease over long (several hours) runs (Degache et al., 2013; Morin et al., 2011a).

The stance phase is actually the only stride phase in which the runner is able to adjust his or her running pattern. Our results suggest that the time courses of all the variables directly related to this phase (i.e. stance duration, reactivity and foot orientation at impact) have poor reproducibility, which suggests that adjustments to the gait vary considerably from one similar effort to another, perhaps partly due to use of multiple strategies to tackle fatigue onset (e.g. reduction in stride frequency (Hunter and Smith, 2007), reduction in stance duration (Degache et al., 2013) and increase in knee flexion at impact (Kellis and Liassou, 2009; Mizrahi et al., 2000)). It has previously been shown that foot location at impact varies considerably between individuals (Delgado et al., 2013; Lieberman et al., 2010); for instance, a distinction has been drawn between heel-striking and toe-striking runners (Deflandre et al., 2016; Gruber et al., 2013). Our results suggest that the evolution of impact location is also highly individually variable and does not follow the same pattern in each trial (ICC = .04; positive slopes for the first and second trials and a negative slope for the third trial).

On the other hand, the evolution of the other stride-related variables (swing duration, stride frequency and step length) showed satisfactory reproducibility (ICCs of .57, .67 and .65, respectively), indicating that the evolution of the flight phase followed a consistent pattern across trials involving similar effort. The extant evidence on changes in swing duration during a single session suggests that it depends on effort, with reports that it remains constant (Gazeau et al., 1997; Hobara et al., 2010; Slawinski et al., 2008), increases (Avogadro et al., 2003) or decreases (Fourchet et al., 2013; Morin et al., 2011b) depending on the type of effort. We found that although inter-subject variability in the evolution of swing duration was high, over three trials intra-subject variation was low.

The same applies to the evolution of stride frequency, which is generally reported to decrease over time (Borrani et al., 2003; Dutto and Smith, 2002; Hobara et al., 2010; Hunter and Smith, 2007). This gradual decrease appears to follow a similar course in similar runs. Step length is directly related to stride frequency for a given velocity, so it is not surprising that the reproducibility of their evolution appears to be similar. There is a consensus that step length is constant over both exhaustive (Fourchet et al., 2014; Derrick et al., 2002) and endurance (Degache et al., 2013; Morin et al., 2011b) runs. Based on our results (ICC = .65), we assume that this regularity is reproducible from one effort to another.

Turning to CG amplitudes, the reproducibility of the evolution of vertical amplitude of CG was close to excellent (ICC = .72) and that of lateral amplitude of CG was moderate (ICC = .48). The incremental increase in vertical amplitude over an effort (Borrani et al., 2003; Fourchet et al., 2013) is known to have a deleterious effect on running economy (Anderson, 1996). Anderson (1996) also reported that the vertical amplitude of CG was negatively related to stride frequency. Unsurprisingly the reproducibility of the evolution of both stride frequency and CM vertical amplitude was, therefore, satisfactory. The lateral amplitude of CG has been much less widely studied, but its evolution appeared to be consistent over three trials (ICC = .48).

In summary, five out of the eight biomechanical variables studied evolved in a way that showed moderate to good reproducibility, with ICCs ranging from .48 to .72 despite poor reliability indicated by relatively large SEMs. This means that the overall reproducibility of the evolution of stride biomechanics is not homogeneous, even in experienced runners. Although variables linked to the stance phase (i.e. stance duration, reactivity and foot orientation at impact) seem to evolve differently across trials, those related to the swing phase (i.e. swing duration, stride frequency and step length) and the vertical and lateral amplitude of CG appear to evolve consistently across trials; in other words, the evolution of these variables over an exhaustive trial is consistent in regular runners. The poor reproducibility of the variables linked to the stance phase suggests that this critical period when the foot is in contact with the treadmill is highly sensitive to changes regarding the biomechanical pattern. These changes may be the results of the runner’s progressive adaptation in his stride along with the apparition of fatigue and might affect running economy.

In this study the variables which evolved in the most reproducible way were vertical amplitude of the CG and stride frequency. Hence several individual strategies to adapt the stride incrementally during this stance phase could be identified in further studies.

Conclusion

Temporal evolution of the running gait appears to be consistent in well-trained runners performing an extended, high-intensity effort; nevertheless, there are intra-individual fluctuations especially with respect to stance duration and reactivity. This shows the holistic approach of running biomechanics is reductive and that each recorded variable should be considered separately.

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