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Spring-mass characteristics during human locomotion: Running experience and physiological considerations of blood lactate accumulation

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Abstract

The aim of this study was to examine how running experience affects leg stiffness ($K_{leg}$) and spring-mass characteristics during running stages associated with the onset of blood lactate accumulation (OBLA). Seven trained (66.9 ± 4.8 kg; 182 ± 4.0 cm; 23.1 ± 3.1 years) and 13 untrained (78.5 ± 7.6 kg; 182 ± 3.0 cm; 20.3 ± 1.5 years) runners completed an incremental treadmill run. Running velocity was increased by 1 km·h$^{-1}$ every four minutes and blood lactate samples were taken at every stage, in addition to a 10 s video recording using ‘Runmatic’. Once 4 mmol L$^{-1}$ (OBLA; the second lactate turn point) had been reached one more stage was completed. Spring-mass characteristics across groups and at pre-OBLA, OBLA and post-OBLA were compared. The velocity at OBLA was higher for the trained runners compared to the untrained runners (18 ± 0.7 vs 11 ± 1.3 km·h$^{-1}$, $p<0.001$). $K_{leg}$ was similar between untrained and trained runners across each stage (15.8 ± 0.3 vs 14.3 ± 0.3 kN·m) and did not change between stages, yet spring-mass characteristics differed between groups. Vertical stiffness increased in the trained runners from pre-OBLA to post-OBLA (45.5 ± 3.35 – 51.9 ± 3.61 kN$^{-1}$), but not in untrained runners (35.0 ± 5.2 – 39.6 ± 5.7 kN$^{-1}$). $K_{leg}$ was strongly related to $F_{peak}$ for trained runners only ($r=0.79$; untrained runners, $r=0.34$). $K_{leg}$ was unaffected by physiological training status and was maintained across all OBLA stages. Trained runners appear to have optimised their spring-mass system in a homogenous manner, whilst less consistent spring-mass characteristics were observed in untrained runners.

Keywords: Physiology, kinesiology, biomechanics, exercise, performance

Highlights

• Trained runners exhibit increases in vertical stiffness during running after the onset of blood lactate accumulation, predominantly due to decreases in vertical oscillation rather than increases in vertical force production.
• Leg stiffness was unaffected by physiological training status and maintained at running speeds associated with before, at and after the onset of blood lactate accumulation.
• Untrained runners appear to use less consistent strategies to maintain leg stiffness than trained runners, which may be due to a lack of experience and limited time to self-optimise.

Introduction

During running the spring-like compression of the leg and forward movement during rebound provides a challenge for the accurate measure of stiffness (Butler, Crowell, & Davis, 2003; Hobara et al., 2008). Subsequently, two components have been established that contribute to the spring-mass model during running, namely vertical stiffness which describes the linear vertical movement (Butler et al., 2003) and leg stiffness which incorporates the horizontal centre of mass (CoM) movement (Morin, Jeannin, Chevallier, & Belli, 2006).

Previous research has identified that training status influences mechanical factors associated with stiffness in hopping tasks, with faster hopping frequencies resulting in greater leg stiffness in trained individuals. Such individuals increase their leg stiffness by reducing their vertical displacement of the CoM during ground contact time (Hobara et al., 2008; Hobara et al., 2010). Changes in velocity have also been
found to influence stiffness in running tasks, where trained individuals demonstrated increases in both leg stiffness and vertical stiffness with increasing running speed (Arampatzis et al., 1999; Kuitunen et al., 2010; Hayes & Caplan, 2014; Rabita et al., 2011). Differences between trained and untrained runners have been identified, with trained runners employing more adaptive strategies to control biomechanical factors associated with running at and above the anaerobic threshold (Mo & Chow, 2018).

Fatigue produces the opposite effect to increasing running speed, with leg stiffness decreasing during fatigue-inducing running tasks (Girard et al., 2010; Hayes & Caplan, 2014; Rabita et al., 2011). When running speed is increased from steady-state, the aerobic energy system is insufficient in providing enough oxygen for the exercising muscles, therefore increasing the demand on the anaerobic energy system and resulting in the production of blood lactate (Davis, 1985). The point at which aerobic energy production is insufficient is often deemed the ‘anaerobic threshold’ and is consequently followed by the onset of blood lactate accumulation (OBLA) which distinguishes the velocity above which individuals can no longer achieve a steady-state (Binder et al., 2008). Although blood lactate has not directly been linked to fatigue during running, the discomfort associated with increased lactate concentration in the blood often leads to decrements in performance (Westerblad et al., 2002). Differences between trained and untrained athletes at the anaerobic threshold have been identified, with trained runners reaching the threshold at significantly higher speeds (Mo & Chow, 2018); however, differences in spring-mass characteristics associated with the anaerobic threshold are yet to be identified. Evidence shows that runners exhibit adaptations in spring-mass characteristics when performing at higher velocities or under increasing fatigue (Arampatzis et al., 1999; Girard et al., 2010; Hayes & Caplan, 2014; Kuitunen et al., 2002; Rabita et al., 2011). However, the relationship between changes in velocity and blood lactate accumulation is yet to be addressed within the literature. Exploring the effects of lactate accumulation on biomechanical running performance in trained and untrained runners could provide a greater understanding of how different fatiguing factors contribute to changes during intensities used during running training.

Therefore, the aim of this study was to examine how running experience affects leg stiffness and spring-mass characteristics during running stages associated with OBLA. It was hypothesised that leg stiffness would reduce in both trained and untrained runners with the accumulation of lactate, yet the associated changes in spring-mass characteristics may differ. Additionally, it was hypothesised that spring-mass characteristic differences would exist between trained and untrained runners at each stage associated with OBLA.

Methods

Participants

Seven trained (mass: 66.9 ± 4.8 kg; height: 182 ± 4.0 cm; 23.1 ± 3.1 years) and 13 (mass: 78.5 ± 7.6 kg; height: 182 ± 3.0 cm; 20.3 ± 1.5 years) untrained, injury-free runners volunteered for the study. To be included in the study the trained runners had to have run 5000 m in less than 15 min 30 s in the previous 12 months and be currently undertaking between 50 and 70 miles of running training each week. The untrained runners were required to be physically active and engaging in at least 150 min of endurance or light-resistant exercise per week. All participants were familiar with treadmill running and required to visit the laboratory once. Ethical approval was obtained by the institutional ethics committee and all participants provided written informed consent.

Procedure

On arrival to the laboratory, each participant’s height was measured using a stadiometer (Holtain Fixed Stadiometer, Crymych, UK) and body mass measured using electronic scales (SECA, 770, Hamburg, Germany). Prior to submaximal incremental test, participants completed a 10-min self-selected paced warm-up on the treadmill. The
initial treadmill velocity for the lactate threshold test was different for each group to ensure the appropriate lactate turn point could be identified following a suitable number of completed stages. For the untrained runners the velocity was initially set to 9 km h\(^{-1}\), whilst to accommodate the trained runners’ superior fitness levels the velocity was initially set to 14 km h\(^{-1}\). The treadmill velocity was increased by 1 km h\(^{-1}\) every four minutes with 30 s ‘rest’ periods between stages to allow a capillary fingertip blood lactate sample to be taken. Each blood sample was run through a lactate analyser (Biosen, C-Line Sport, EKF-Diagnostic, Barleban, Magdeburg, Germany) and blood lactate values were recorded. Once 4 mmol L\(^{-1}\) (OBLA; the second lactate turn point) had been reached one more stage was completed. The gradient was set to 1% for all participants during each stage of the test to reflect the metabolic cost of outdoor running (Jones & Doust, 1996). Each run was filmed using a Certified iPhone app ‘Runmatic’ (Balsalobre-Fernandez et al., 2017), at a frequency of 250 Hz from behind the participant. During each stage of the lactate threshold test, a 10 s video was taken during the third minute to allow a minimum of six full gait cycles to be recorded.

**Data analysis**

Data were normalised to the OBLA threshold rather than to speed, with only data from three stages per participant being used for analysis. Data were categorised as pre-OBLA, OBLA and post-OBLA to represent the velocities immediately before the lactate level had reached OBLA, at or the closest lactate level to OBLA and when OBLA has been surpassed respectively. The biomechanical data for each stage (pre-OBLA, OBLA and post-OBLA) were derived from the video recording. Five gait cycles (10 foot contacts) per stage were manually digitised within Runmatic, allowing calculation of contact time (\(T_c\)) and aerial time (\(T_a\)). Additionally, running velocity was inputted to determine step frequency and each participant’s body mass and height were entered to allow peak vertical force, vertical oscillation and leg stiffness (\(K_{leg}\)) to be estimated. Specifically, the estimated peak vertical force (N) was determined using the sine wave method:

\[
F_{\text{peak}} = mg \left( \frac{T_a}{T_c} \right) + 1
\]

where \(m\) represents body mass (kg) and \(g\) represents gravity (m s\(^{-2}\)). In all further calculations below absolute (N) \(F_{\text{peak}}\) was used, however, \(F_{\text{peak}}\) was normalised to body weight (BW; \(m \cdot g\)) when used in the statistical analysis. Vertical oscillation was derived from the modelled change in the vertical centre of mass position (\(\Delta\text{CoM}\); m):

\[
\Delta\text{CoM} = \frac{F_{\text{peak}} T_c^2}{m \pi^2} + g \frac{T_c^2}{8}
\]

To determine \(K_{leg}\) (kN m\(^{-1}\)) each participant’s leg length (\(L\)) was quantified using Winter’s (1979) anthropometric equation: \(L = 0.53 h\) where \(h\) represents height (m), to allow comparison to modelled \(K_{leg}\) values derived previously (Morin, Dalleau, Kyröläinen, Jeannin, & Belli, 2005). Additionally, estimating leg length in this way has been shown to have only a small mean error bias of 1.94% and explains 89% of the variance in measured leg length (Morin et al., 2005). To derive \(K_{leg}\), the following equation was used:

\[
K_{leg} = F_{\text{peak}} \cdot \Delta L^{-1}
\]

where \(\Delta L\) represents a change in \(L\) (m) as determined by:

\[
\Delta L = L - \sqrt{L^2 - \left( \frac{v T_c}{2} \right)^2} + \Delta\text{CoM}
\]

where \(v\) represents the running velocity (m s\(^{-1}\)) of the individual. All of the above calculations were performed within the Runmatic app. Data were then exported to Microsoft Excel for the calculation of stride frequency (step frequency \(\frac{2}{T_a} \)) and flight time \([2(T_a) + T_c]\). Finally, \(K_{vert}\) (kN m\(^{-1}\)) was calculated as the ratio between \(F_{\text{peak}}\) and \(\Delta\text{CoM}\).

**Statistical analysis**

Mean and standard deviations for ground contact time, peak vertical force (\(F_{\text{peak}}\)), flight time, normalised leg stiffness (\(h_{leg}\)), stride frequency, stride length (using stride frequency and seconds per strides), vertical oscillation and vertical stiffness (\(k_{vert}\)) during each stage were calculated using the left and right leg data from five gait cycles. The mean of left and right leg data was calculated and used in the analysis. Due to multiple blood lactate measurements being taken throughout the running task, only spring-mass characteristics associated with three distinguishable OBLA stage were taken: pre-OBLA (stage prior to OBLA), OBLA (the stage at OBLA) and post-OBLA (the stage immediately after OBLA). All data were analysed using the R language (R core team, 2018) and was tested for...
normal distribution. The differences between biomechanical variables at each OBLA stage were analysed using the Kruskal–Wallis test. Differences between the trained and untrained runners were analysed using the Wilcox test. The relationship between $F_{\text{peak}}$ and $K_{\text{leg}}$ was analysed using the Spearman rank correlation, with the following thresholds used to denote weak, moderate and strong relationships: 0.2, 0.5 and 0.8. Significance was accepted at 0.05.

**Results**

Both groups completed three stages of running which were grouped into three blood lactate stages (pre-OBLA, OBLA, post-OBLA) for analysis, with speeds ranging from 16 to 20 km h$^{-1}$ for trained runners and nine to 13 km h$^{-1}$ for untrained runners. The velocity at OBLA was higher for the trained runner compared to the untrained runners (18 ± 0.7 km h$^{-1}$ vs 11 ± 1.3 km h$^{-1}$, respectively, $p = 0.00, \ W^2 = 0$). The mean values for ground contact time, $F_{\text{peak}}$, flight time, $K_{\text{leg}}$, stride frequency, vertical oscillation and $K_{\text{vert}}$ for both groups are shown in Figure 1.

**Changes between blood lactate stages**

There was an increase in $K_{\text{vert}}$ in the trained runners from pre-OBLA to post-OBLA (45.5 ± 3.35 – 51.9 ± 3.61 k N$^{-1}$; $df = 2$, $p = 0.03$, Cohen’s $d = 1.8$). Yet, all other biomechanical variables remain unchanged across stages. In addition, all biomechanical variables were unchanged across the stages in the untrained runners.

**Differences between trained and untrained runners**

The mean values for the biomechanical measures of both groups across OBLA stages are shown in Table 1. There were significant differences between groups at each stage of OBLA in ground contact time, stride frequency, vertical oscillation, $F_{\text{peak}}$ and $K_{\text{vert}}$. Untrained runners had a 19-26% longer
ground contact time \((p = 0.00, W = 87/82/86)\) and 17–20% larger vertical oscillation \((p = 0.01/0.02, W = 79/76.5)\) at each stage compared to the trained runners. The trained runners demonstrated 9–11% higher \(F_{\text{peak}}\) \((p = 0.02/0.01, W = 16/17/12)\), 23–24% higher \(K_{\text{vert}}\) \((p = 0.00, W = 5/10)\) and 6–8% higher stride frequency \((p = 0.005/<0.001, W = 6/11/3)\) than untrained runners at each stage.

### Relationship between leg stiffness and spring-mass characteristics

Trained runners demonstrated a strong, positive relationship between \(F_{\text{peak}}\) and \(K_{\text{leg}}\) \((r = 0.79, p < 0.001)\), yet a weak relationship was found in the untrained runners \((r = 0.34, p = 0.04)\). There was also a strong negative relationship between ground contact time and \(K_{\text{leg}}\) in the trained runners \((r = -0.71, p < 0.001)\), with the untrained runners showing only a moderate negative relationship \((r = -0.47, p < 0.001)\).

### Discussion

The main findings of this study were that trained runners exhibited a significant increase in \(K_{\text{vert}}\) from the pre-OBLA to the post-OBLA stages of the running task, while the untrained runners showed no differences. The changes demonstrated in \(K_{\text{vert}}\) in the trained runners was dominated by a decrease in the vertical oscillation, with minimal changes in maximal force production. Differences between the trained and untrained runners were also identified, where the untrained group showed significantly longer contact time and larger vertical oscillation than the trained runners at each OBLA stage. The trained runners demonstrated significantly higher maximum force and higher \(K_{\text{vert}}\) at each OBLA stage during the running task. Yet, \(K_{\text{leg}}\) was similar between groups. Furthermore, trained runners also demonstrated a strong positive relationship between maximum force and \(K_{\text{leg}}\), whereas untrained runners demonstrated a weak relationship.

### Changes between blood lactate stages

Contrary to our hypothesis \(K_{\text{leg}}\) did not reduce with the accumulation of lactate. However, there was an increase in \(K_{\text{vert}}\) from the pre-OBLA stage to the post-OBLA stage in the trained runners, which is similar to previous research investigating stiffness in sprint running (Kuitunen et al., 2002). In contrast, Girard et al. (2010) identified reductions in \(K_{\text{vert}}\) in trained runners during a fatigue-induced run, with an associated reduction in \(F_{\text{peak}}\). Although there is a contrast in the findings between these studies, the difference between the dominating contributor to changes in \(K_{\text{vert}}\), namely vertical oscillation in the current study, provides an explanation for the differences identified. One of the suggested contributing factors to a decrease in vertical oscillation is the increasing running speed from the pre-OBLA to the post-OBLA stage, which has been suggested to result in adaptations to the stride frequency coupled with decreasing ground contact time (Kuitunen et al., 2002).
Although these differences were not significant in the current study, based on the findings of Kuitunen et al. (2002) it can be suggested that the trained runners in the current study demonstrated adaptations to increasing speed demands throughout the running task, by making minor changes to their spring-mass characteristics associated with their stride to ensure \( K_{\text{leg}} \) was maintained. In contrast to this, the untrained runners showed no significant difference between OBLA stages, possibly due to the comparatively lower running velocity. It could therefore be suggested that as the untrained runners were running at lower speeds throughout the task, the mechanical demand on running performance was lower, meaning that the untrained runners were able to sustain consistent running mechanics throughout.

**Differences between trained and untrained runners**

In support of our hypothesis, there were several biomechanical differences evident between trained and untrained runners, yet \( K_{\text{leg}} \) was similar between groups. Given the lower running velocities performed by the untrained runners, the longer ground contact times, lower stride frequencies and lower \( F_{\text{peak}} \) values were to be expected. However, for the range of running velocities used, the trained runners produced similar \( K_{\text{vert}} \) as previous work, but the untrained runners produced higher \( K_{\text{vert}} \) (Morin et al., 2005). Interestingly, the relative difference between the groups in \( K_{\text{vert}} \) was similar to the relative difference in ground contact time rather than \( F_{\text{peak}} \). This could reflect the untrained runners disproportionately producing longer ground contact times at slower speeds, trained runners disproportionately producing shorter ground contact times at faster speeds or a combination of the two. Based on the inverse relationship between energy cost of running and ground contact time (Kram & Taylor, 1990), the potential strategy used by untrained runners would be metabolically beneficial, whilst the potential strategy for the trained runners would be metabolically detrimental. It is conceivable that the trained runners were closer to their mathematically optimal stride characteristics due to the greater exposure to running they will have acquired over time (de Ruiter, Verdijk, Werker, Zuidema, & de Haan, 2014). Coaches working with beginner runners and implementing training intensities near an individual’s anaerobic threshold could target increases in ground contact time, which may be metabolically beneficial. However, such a training approach requires further examination.

Trained runners maintaining a similar level of \( K_{\text{leg}} \) at higher running velocities compared with untrained runners at lower running velocities supports previous work involving intra-individual comparisons with increasing velocity, whereby \( K_{\text{leg}} \) was unchanged over a range of velocities (3–7 m s\(^{-1}\); Morin et al., 2006). Additionally, the \( K_{\text{leg}} \) produced by both the trained and untrained runners were within the range of stiffness values previously reported by Morin et al. (2005) at similar running velocities. Furthermore, this is the first study to identify that \( K_{\text{leg}} \) during running appears to be unaffected by physiological training status and the stages of OBLA. In contrast, Hobara et al. (2010) found trained athletes had higher \( K_{\text{leg}} \) during hopping than untrained athletes. Yet, the untrained runners produced longer ground contact times at the same hopping frequency (2.2 Hz), which may explain a large part of the variation in \( K_{\text{leg}} \) (Morin et al., 2006). In the current study, the fact trained and untrained runners produced similar \( K_{\text{leg}} \) even with running-related mechanical differences suggests that the underlying intrinsic muscle properties may differ between the groups which influence the \( K_{\text{leg}} \) produced. For example, Hobara et al. (2010) previously hypothesised that trained endurance runners possessing more slow-twitch muscle fibres than untrained runners may explain their ability to produce greater \( K_{\text{leg}} \) during a hopping task. However, both trained and untrained runners hopped at 2.2 Hz and were given the cue ‘hop with as short a contact time as possible’. It is possible that setting the hopping frequency based on a preferred frequency and without an encouraged shortening of ground contact time may produce similar \( K_{\text{leg}} \) between groups of different training statuses. However, this has yet to be tested.

**Relationship between force and leg stiffness**

Trained runners demonstrated a strong positive relationship between \( K_{\text{leg}} \) and maximal force production, but only a weak relationship was observed for untrained runners. The trained runners also showed a strong negative relationship between \( K_{\text{leg}} \) and contact time, but only a moderate relationship was observed in untrained runners. Previous research in spring-mass behaviour during fatigue-inducing running tasks identified that \( K_{\text{leg}} \) decreases due to an inability to maintain force production (Rabita et al., 2011; Slawinski, Heubert, Quevire, Ronique Billat, & Hannon, 2008). Our findings suggest trained runners respond to increasing velocities by adapting their force production to maintain \( K_{\text{leg}} \) whilst simultaneously reducing ground contact duration. Morin and colleagues (2007) demonstrated that variations in \( K_{\text{leg}} \) during running were dominated by contact time alterations, which others have
identified as a contributing factor to less economical running and subsequent reductions in $K_{\text{leg}}$ (Hayes & Caplan, 2014; Rabita et al., 2011). Trained runners appear to have optimised their spring-mass system in a consistent, homogenous manner as evident by the group level relationships, yet untrained runners appear to have less consistent strategies to maintain $K_{\text{leg}}$. Consequently, a lack of experience and limited time to self-optimise may have led to untrained runners using less optimal strategies to produce $K_{\text{leg}}$ during a running task than trained runners (de Ruiter et al., 2014; Moore, 2016; Moore, Jones, & Dixon, 2012).

**Limitations**

One limitation in the current study is the limited number of trained runners utilised in the study, primarily due to participants being excluded when the blood lactate criteria were not met. Including a larger number of trained runners would provide further opportunity to analyse and compare biomechanical measures at different stages of blood lactate concentration across groups. Secondly, once the second lactate turn point (OBLA; 4 mmol L$^{-1}$) had been reached during the running task, only one more three-minute stage of running was completed. The singular stage following the lactate turn point in the current study may not have elicited large changes to running mechanics as would be experienced during faster velocities, where concentrations can reach as high as 12–13 mmol L$^{-1}$ during interval running tasks (Nurmekivi, Karu, Phil, Jurimae, & Lemberg, 2001). However, velocities associated with OBLA are often used to inform training programmes and the data provides a useful mechanistic understanding of this physiological turn point. Further work could identify whether significant increases in blood lactate concentration affect running mechanics differently or to a larger degree than identified in the current study.

In conclusion, the current study provides support that the trained runners exhibit changes in $K_{\text{vert}}$ during a running task, primarily due to decreases in vertical oscillation. Furthermore, $K_{\text{leg}}$ was unaffected by physiological training status and maintained across all OBLA stages. However, only trained runners demonstrated a strong positive relationship between $K_{\text{leg}}$ and maximal force production, suggesting they have optimised their spring-mass system in a homogenous manner. The untrained runners appeared to use less consistent strategies to maintain $K_{\text{leg}}$ which may be due to a lack of experience and limited time to self-optimise. Further work is warranted to understand whether targeting alterations in spring-mass characteristics in untrained runners provides beneficial physiological and mechanical changes, such as reduced metabolic cost and consistent strategies to maintain $K_{\text{leg}}$ with velocity changes.

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