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Changes in leg spring behaviour, plantar loading and foot mobility magnitude induced by an exhaustive treadmill run in adolescent middle-distance runners

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ABSTRACT

Objectives: This study aimed to determine adjustments in spring–mass model characteristics, plantar loading and foot mobility induced by an exhaustive run.
Design: Within-participants repeated measures.
Methods: Eleven highly-trained adolescent middle-distance runners ran to exhaustion on a treadmill at a constant velocity corresponding to 95% of velocity associated with VO_{2max} (17.8 ± 1.4 km h^{-1}, time to exhaustion = 8.8 ± 3.4 min). Contact time obtained from plantar pressure sensors was used to estimate spring–mass model characteristics, which were recorded (during 30 s) 1 min after the start and prior to exhaustion using pressure insoles. Foot mobility magnitude (a composite measure of vertical and medial–lateral mobility of the midfoot) was measured before and after the run.
Results: Mean contact area (foot to ground), contact time, peak vertical ground reaction force, centre of mass vertical displacement and leg compression increased significantly with fatigue, while flight time, leg stiffness and mean pressure decreased. Leg stiffness decreased because leg compression increased to a larger extent than peak vertical ground reaction forces. Step length, step frequency and foot mobility magnitude did not change at exhaustion.
Conclusions: The stride pattern of adolescents when running on a treadmill at high constant velocity deteriorates near exhaustion, as evidenced by impaired leg-spring behaviour (leg stiffness) and altered plantar loading.

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1. Introduction

From a mechanical point of view, running is a typical human movement where the musculo-tendinous structures of the lower limbs alternately store and return elastic energy during the so-called stretch-shortening cycle.[1] Accordingly, the lower limbs can be considered as springs loaded by the weight and inertia of the body mass. This paradigm refers to the "spring–mass model" (SMM) and has been applied increasingly in recent years to describe the lower limb neuromuscular behaviour (stiffness regulation) during fatiguing runs.[2–4] Studies examining changes in SMM characteristics during ultra-long distance events have reported increased leg and/or vertical stiffness and step frequency with fatigue development.[5–7] Conversely unchanged peak vertical forces and constant or decreased step frequency and vertical stiffness over multiple running sprints have been observed.[2,8,9]

Part way between ultra-long distance and sprint events, studies of SMM characteristics during middle-distance running trials have reported contrasting results.[3,10,11] Slawinski et al. failed to observe any modification of the main SMM parameters after a 2000 m time trial on a running track, which lasted approximately 7 min.[11] Other authors have explored SMM changes during constant-pace exhaustive runs,[3,4,10] but to the best of our knowledge, the study by Rabita et al. is the only one that assessed changes in SMM parameters during a severe intensity run performed at a constant velocity (i.e., 95% of the velocity associated with the maximal oxygen uptake) on an indoor athletic track.[4] These authors reported that peak vertical ground reaction forces are reduced under fatigue, as also mentioned by Slawinski et al.[11] but added that higher step frequencies, constant vertical stiffness and decreased leg stiffness values are developed near exhaustion. These latter findings were in conflict with former studies.[3,10] This most likely resulted from the higher running velocity achieved by the subjects in the study of Rabita

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et al. when compared with the protocols used by Hunter et al. and Dutto et al.[3,4,10]

Studies reporting fatigue-induced alterations of stride characteristics in adolescent runners are scarce. In one study, Ratel et al. compared changes in stride patterns during intermittent runs between adults and children.[12] Under fatigue, a lower decline in step frequency was reported in children compared to adults, while the underlying mechanisms remained unclear.[12] Reportedly, adult runners adopt a “smoother” running pattern (e.g. reductions in peak vertical ground reaction force and stride frequency) as a safer running strategy in order to attenuate the load imposed on their musculoskeletal system at each foot strike.[6,13] It has been proposed that these changes may impair performance by increasing metabolic costs during the latter stages of an exhaustive run, yet whether it is a conscious phenomenon and whether adolescent runners display similar adjustments remain answered.[14]

Foot alignment during the stance phase (e.g. the sole interface with the ground)[15] may influence an athlete’s leg spring behaviour. Any foot malalignments/weaknesses that negatively affect foot mobility may disturb the absorption or propulsion phases when running.[15] For example, excessive pronation resulting in a medial longitudinal arch flattening impairs the resupination of the foot at toe-off.[15] This phenomenon is likely to be exacerbated by fatigue affecting the medial arch supporting muscles, as manifested by an increased navicular drop.[16] The fatigued lower limb muscles would also reduce their shock-absorbing capacities with an increased loading of the second and third metatarsal and medial midfoot.[17–19] This would modify the “foot roll-over” and result in potential structural overload. This may in turn influence injury risk.[20] Especially in immature adolescents involved in middle distance running.[21] Of importance the foot mobility measurement (FMM, a composite measure of vertical and medial–lateral mobility of the midfoot) has been described as reliable technique in order to clinically assess foot mobility changes between non-weight bearing and weight bearing conditions.[22] It is also worth noting that pedobarography has recently been used to characterize the pressure distribution patterns under the feet of pathological and non-pathological subjects.[23,24] Although a direct link between plantar pressure and joint motion has yet to be firmly established, it is a common belief that changes in plantar pressure distribution – e.g. excessive peak plantar pressure under the medial forefoot and midfoot and/or a decrease of the peak plantar pressure under the lateral forefoot and midfoot – reflect an excessive pronation. Overall, changes in subtalar alignment during the stance phase (i.e., excessive pronation) are considered as linked to subsequent changes in plantar pressure distribution.[23,24]

So, the question of the effects of running-induced fatigue on foot and leg spring behaviour warrants further attention.

Therefore the purpose of this study was to determine to what extent running to exhaustion at severe, constant velocity on a treadmill modifies SMM parameters, plantar loading, and FMM measurement in highly-trained adolescent athletes. We first hypothesised that exhaustion is associated with significant adjustments in running mechanics as manifested by reductions in step frequency, leg stiffness and peak vertical ground reaction forces. We further hypothesised that this is associated with concomitant alterations in the foot roll-over process at stance phase affecting plantar pressure parameters and foot mobility magnitude.

2. Methods

Based on the results of a previous study,[11] a priori analyses were used to determine sample sizes. Assuming a difference in means of 10 $\mathrm{kN\,m^{-1}}$ in vertical stiffness measurements, required sample size was 11 for $\alpha = 0.05$ and statistical power = 0.8. Therefore eleven male adolescent distance runners (age: 16.9 ± 2.0, body mass: 54.6 ± 8.6 kg, height: 170.6 ± 10.9 cm) completed the study. They were free of lower limb injury in the two months preceding testing. Informed consent was sought and obtained from all participants. The study was accepted by the local scientific research ethics committee (Aspire Academy, Doha, Qatar/697019). The ethical guidelines followed by the investigators conformed to the recommendations of the Declaration of Helsinki about human investigations.

Two runs performed on a treadmill (h/p/Cosmos, Nussdorf-Traunstein, Germany) at 5–7 days apart were required. Each participant first completed an incremental test to exhaustion in order to determine maximal oxygen uptake and its associated velocity. It consisted of an initial 1 min workload of 8 $\mathrm{km\,h^{-1}}$ followed by increases of 1 $\mathrm{km\,h^{-1}}$ every minute (1% slope). Gas exchange was measured using a breath-by-breath analyser (Oxycon Pro, Jaeger, Hoechberg, Germany). The second run was a constant velocity run until exhaustion performed at 95% of velocity associated with their maximal oxygen uptake (Fig. 1). During exercise, RPE (6-20 Borg scale) was recorded every minute. Running pattern was assessed by determining SMM and plantar pressure data over a 30 s period at two occasions: (i) 1 min after the exercise start (ONSET) and then (ii) as soon as the participant reported 18 as RPE (ENDPOINT) corresponding to 78–84 steps (Fig. 1). This 30 s window ended in a range of 25–45 s prior to exhaustion. A blood sample was collected for lactate measurement (Lactate Pro, Arkray Inc., Japan) 3 min following ENDPOINT.

Insole plantar loading of both feet was recorded using the X-Pedar Mobile insole (Novel GmbH, Munich, Germany) consisting of a 2-mm-thick array of 99 capacitive pressure sensors. All the participants wore the same type of universal shoes (Adidas, Supernova sequence). Plantar loadings were sampled at 50 Hz. An excellent reliability has been reported for this device.[25] Contact time (T_c in s), mean area (cm^2), contact area (cm^2), mean force (N), maximum force (N), mean pressure (kPa), peak pressure (kPa) were determined for the whole foot. Data from the left and right foot were averaged for subsequent analysis.

In terms of stride parameters, flight (T_f, in s) and contact (T_c, in s) times were determined from the X-Pedar mobile software (Novel Win, Novel GmbH, Munich, Germany).[26] Step frequency ($S_F = 1/(T_c + T_f)$ in Hz) and step length ($S_L = V_{\mathrm{forward}}/S_F$ in m) were calculated.

From these measurements of T_c, T_f, forward running velocity (V_{forward}; i.e., 4.94 ± 0.40 $\mathrm{m\,s^{-1}}$) and from participants’ body mass (m in kg) and lower limb length (in m), measured as the great trochanter-to-ground distance in a standing position, spring–mass parameters were calculated using the computation method proposed by Morin et al.[1] This method is based on a modelling of the ground reaction force signal during the contact phase by a sine function and allows computation of vertical stiffness (K_{vert}, $\mathrm{kN\,m^{-1}}$) as the ratio of the peak vertical ground reaction force ($Fz_{\max}$ in N) to the maximal downward displacement of centre of mass (CM) during contact (Δz in m). This method was recently shown to provide reasonable estimates when compared with direct kinetic–kinematic analysis.[27] In this study, intra-class correlation coefficient based on model leg stiffness calculation between direct kinematic–kinetic measures vs. only force platform derived and anthropometric measures was higher than 0.90.[28,29]

$$K_{\mathrm{vert}} = \frac{Fz_{\max}}{\Delta z}$$

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