FATIGUE-RELATED ASYMMETRY AND INSTABILITY DURING A 3200-M TIME-TRIAL PERFORMANCE IN HEALTHY RUNNERS.

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The purpose of this study was to examine fatigue effects on symmetry and stability during a maximal effort running time-trial (TT). Recreational runners had continuous recordings of 3D trunk acceleration parameters (spatio-temporal, RMS vector ratio, step symmetry, and stride regularity) during the TT. Statistical analysis was carried out using generalised estimating equations (GEE) to investigate longitudinal changes (laps two to eight) compared to baseline (lap one), while statistically adjusting for running speed. Runners had significantly longer contact times (4th lap onwards), higher mediolateral root mean square (RMS) ratio (3rd lap onwards), lower vertical symmetry and vertical RMS ratio (final lap). Coaches could use these results to recognize, minimize, and delay fatigue-related onset of asymmetries and instabilities possibly through training strategies.

KEY WORDS: 3D accelerometer, self-paced, fatigue, asymmetry, instability.

INTRODUCTION: Running is characterised as a cyclic motion. The body is rhythmically geared to copy patterns of motion continuously, with previous stride patterns having a great influence on the stride patterns that follow (Bosch & Klomp, 2005). However, this process may be disrupted when a runner is fatigued: when exhausted, the body may become less-geared to copy motions or stride patterns effectively as stride asymmetries and irregularities begin to emerge. Consequently, performance could be hampered due to unnecessary increases in energy expenditure (Le Bris et al., 2006) as well as enhanced risk of overuse injury (Meardon, Hamill, & Derrick, 2011; Miller, Lowry, Meardon, & Gillette, 2007). Therefore, strategies to identify and minimize such fatigue-related compensations in real-time could have potential to enhance performance and minimize injury risk.

Fatigue resulting from a fast paced 3200-m TT has shown to cause deficits in post-race postural stability (Pendergrass, Moore, & Gerber, 2003). However, limited attention has been given to fatigue during, rather than after such an event. Some evidence has been provided whereby a single 3D trunk-mounted accelerometer could detect whole-body asymmetries irregularities, and increased variability of movement linked to running fatigue (Le Bris et al., 2006; McGregor, Busa, Yaggie, & Bollt, 2009; Schütte, Maas, Exadaktylos, Berckmans, & Vanwanseele, 2015). In these studies running velocity was experimentally imposed either using fixed treadmill speeds or fixed timing between cones. While this approach delineates changes in running gait parameters that are due to variable running velocity, it doesn't reflect real-life race-pace strategies and could cause unnatural control of gait characteristics.

The purpose of this study was therefore to examine fatigue effects on symmetry and stability during an exhaustive, self-paced, middle-distance running time-trial. We hypothesized that after statistical adjustment for running velocity, 3D trunk accelerometry parameters could be used to detect fatigue related asymmetries and instabilities in center of mass (CoM) motion.

METHODS: Fifteen recreational endurance runners aged 19 to 21 years of mixed gender (40 % women) were recruited for this study, with a mean (SD) age 20.07 (0.70); height 1.74 m (0.07), weight 62.33 kg (9.30); and BMI 20.47 (2.22). All participants were screened to have no history of lower extremity injury within the past three months. Written informed consent was received from all runners prior to participation in accordance with the Declaration of Helsinki. The study was approved by the local ethics committee.

Runners performed a maximal effort 3200-m TT on an outdoor 400-m track. Split times per lap were recorded using a hand-held chronometer. Participants verbally communicated their lap-for-lap rating of perceived exertion (RPE) on BORG scale of 6 – 20 (Borg GAV., 1982). Participants were verbally encouraged to promote maximal effort. Each participant's heart rate was continuously recorded and percentage of maximal heart was calculated using the formula: HR max = 208 - 0.7 x age (Tanaka et al., 2001). A tri-axial accelerometer (X50-2 wireless accelerometer, range ± 50g, sampling at 1024 Hz, 13-bit resolution, 33g weight, Gulf Coast Data Concepts, MS) was securely mounted in a custom-designed neoprene pocket in a waist strap, at the L3 spinous process level of the lower back to approximate the CoM (Moe-Nilssen & Helbostad, 2004).

All signal processing of acceleration curves was performed using customized software in MATLAB version 8.3 (The Mathworks Inc., Natick, MA, USA). 3D trunk accelerations were trigonometrically tilt-corrected and filtered using a zero-lag 4th order low-pass Butterworth filter (cut-off frequency 50 Hz) prior to parameter extraction. Accelerometry parameters were computed in windows consisting of ten consecutive strides, and the number of windows was normalized from 0% to 100% duration of the TT, and finally segmented into eight equal duration intervals (laps).

Spatio-temporal parameters were quantified by step frequency and stance time. The former was acquired using the time lag of the first dominant peak of the vertical acceleration's unbiased autocorrelation (Moe-Nilssen & Helbostad, 2004). The latter was acquired using zero crossings of vertical accelerations that identified periods where the vertical acceleration was positive and accelerating upwards (initial contact to final contact) (Gaudino, Gaudino, Alberti, & Minetti, 2013).

Dynamic stability parameters were quantified from tri-axial (vertical, mediolateral, anteroposterior) accelerations firstly using the ratio of each linear acceleration axis root mean square (RMS) relative to the vector RMS to capture variability (McGregor et al., 2009); and secondly using step and stride regularity (unbiased autocorrelations procedure) to capture symmetry and consistency of running steps and strides respectively, with perfect values equivalent to one (Moe-Nilssen & Helbostad, 2004).

All 3D accelerometry parameters showed to be normally distributed (-1 < accepted skewness <1), and were analyzed by means of linear regression, using linear generalized estimating equations (GEE). GEE analysis is more sophisticated than linear regression because it takes into account that measures within one subject are correlated with repeated observations (exchangeable correlation structure). The effect of fatigue on accelerometry parameters was evaluated by comparing lap's two-to-eight vs. lap one (baseline reference category control). Running velocity was included in the model as a time-dependent covariate given its potential to confound accelerometry parameters. Alpha level was set to 0.05.

RESULTS: On average, participants completed the 3200-m TT in 13:40 (min: s) (CI_{95} = 12:37 to 14:44) and all achieved criteria for maximum effort at completion (RPE ≥ 19; and mean percentage of age-predicted maximum heart rate 98% (CI_{95} = 94 to 101). The total number of running steps included for analysis per participant was 2236 (CI_{95} = 2087 to 2384).

Running velocity (m/s) decreased significantly from lap two to seven (-0.24; -0.27; -0.28; -0.26; -0.26; -0.23; all $p < 0.01$) (**Figure 1 A**). After adjusting for velocity, step frequency (steps/min) decreased significantly from lap two to six (-2; -3; -3; -3; -2; all $p < 0.05$) (**Figure 1 B**); contact time (ms) significantly increased from lap four to eight (2; 3; 3; 4; 3, all $p < 0.05$) (**Figure 1 C**). After adjusting for velocity, vertical RMS ratio decreased (trend only) in lap seven (-0.02; $p = 0.058$) and significantly decreased in lap eight (-0.04; $p < 0.01$) (**Figure 1 D**); similarly, vertical step symmetry decreased (trend only) in lap seven (-0.015, $p = 0.08$) and significantly decreased in lap eight (-0.02; $p < 0.01$) (**Figure 1 E**). After adjusting for velocity, mediolateral RMS ratio increased significantly from lap three to lap eight (0.02; 0.02; 0.03; 0.04; 0.05; 0.05; all $p < 0.05$) (**Figure 1 F**). Mediolateral and anteroposterior step symmetry, and stride regularity from any axis did not change significantly from lap one ($p > 0.05$).

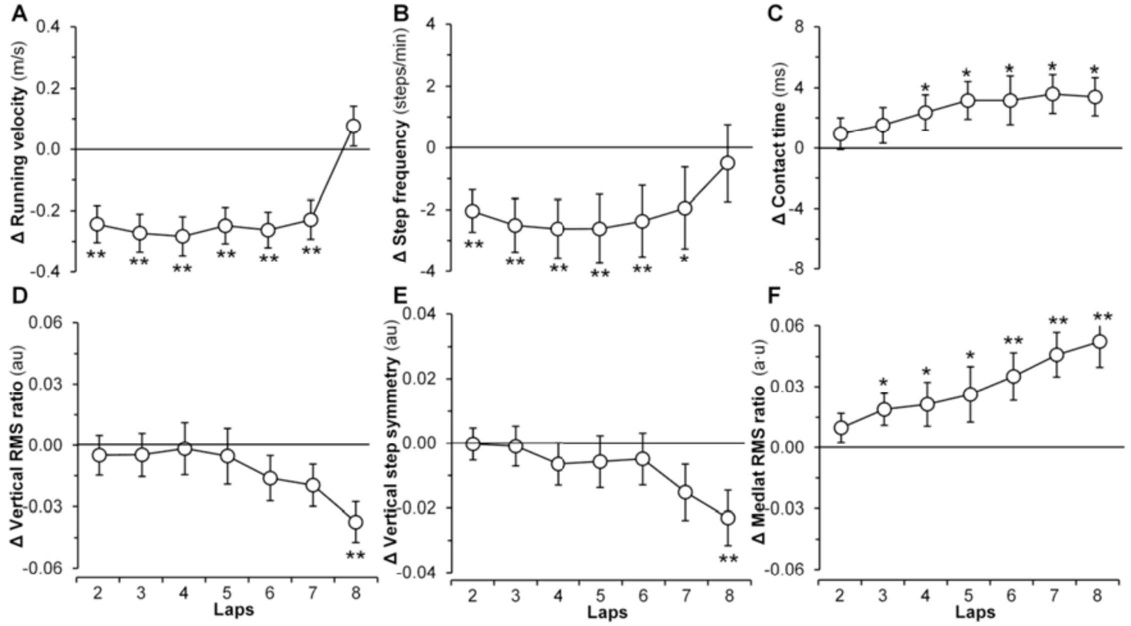

Figure 1. Lap changes in running parameters, represented as average regression coefficients (β) ± standard error bars (significantly different from lap one */ ** $p < 0.05$/ $p < 0.01$).

DISCUSSION: In support of our hypothesis, the current study shows that 3D trunk accelerometry parameters could be used to detect fatigue-related asymmetries and instabilities in CoM motion during an exhaustive, self-paced running TT. The analysis technique used in this study required only a single 3D accelerometer placed at the lower back, which enabled quantification of a large amount of consecutive running steps (> 2000) during an entire running test. This study appears to be the first to evaluate fatigue related changes during a 3200-m TT, a running test that is commonly used by coaches and athletes when formulating training or racing practices, and that is relatively easy to perform with respect to equipment and time needed. The main findings of this study were that runners had significantly longer contact times (fourth lap onwards), higher mediolateral RMS ratio (third lap onwards), and lower vertical symmetry and vertical RMS ratio in the final lap. These findings may be related to the different postural compensations utilised by runners in response to running-related fatigue.

Previous investigations on accelerometry related compensations due to running fatigue have experimentally standardised/imposed velocity on their runners either during treadmill running (Schütte et al., 2015) or track running (Le Bris et al., 2006). However, this could result in unnatural control of gait characteristics. The current study therefore differs principally in that we allowed runners to self-select their pacing strategy and statistically adjusted for confounding running velocity. Indeed, adjustments were appropriate since the running velocity was significantly faster in the first and final laps compared to well-regulated middle lap velocities, a phenomenon showing a 'bath-tub' curve response that has similarly occurred in elite 5000-m and 10000-m TT performances (Tucker, Lambert, & Noakes, 2006). Furthermore, several accelerometry parameters showed dependency on running velocity (data not shown).

Significant changes in accelerometry parameters showed different responses with temporally different turning points. For example, step frequency, and contact time (when inverted) tended to follow the velocity's 'bath-tub' curve response, even after statistically normalizing to velocity. Nummela, Stray-Gundersen, and Rusko (1996) have speculated that spurts of longer contact times observed during the 400-m TT were ‘thresholds’ physiologically connected with the depletion of creatine phosphate and the increased contribution of glycolysis to the energy production. This is because following creatine phosphate depletion, adenosine triphosphate (ATP) turnover rate decreases rapidly.

Mediolateral RMS ratio showed a gradual positive linear response with each consecutive lap. Increases in mediolateral RMS ratio (Schütte et al., 2015) and mediolateral signal energy (Le Bris et al., 2006) with running fatigue has been reported previously, with the notion that a loss of mediolateral coordination induces an increase in energy expenditure that is not useful for propulsion (Le Bris et al., 2006).

Vertical symmetry and vertical RMS ratio appeared to show a typical “hockey-stick’ response, whereby changes were relatively constant until a sharper turning point in the final two-to-three laps. It seems that increased variability or instability of the CoM occurring vertically occurs at a later onset than mediolaterally. Moreover, it has previously been shown that anteroposterior accelerations became more asymmetrical during a treadmill fatigue run (Schütte et al., 2015), which was not the case during the current experiment. This would suggest that mechanisms of fatigue-induced asymmetries are different between overground and treadmill surfaces.

CONCLUSION: The current study demonstrates that changes in 3D trunk accelerometry parameters can be used to determine onsets of instability or loss of coordination with fatigue that occurs during a 3200-m TT. Coaches could use these results as a means to recognize, minimize or delay fatigue-related onset of asymmetries and instabilities. This could be achieved by implementing wireless 3D trunk accelerometers with a real-time feedback driven mobile app. Such a mobile system may well be incorporated with fatigue-resistance training strategies i.e. technique, strength or stability training, with the long term aim of improving endurance running performance times and preventing overuse injury.

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