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# Detrended fluctuation analysis detects altered coordination of running gait in athletes following a heavy period of training

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ABSTRACT

*Objectives:* To investigate whether functional overreaching affects locomotor system behaviour when running at fixed relative intensities and if any effects were associated with changes in running performance.
*Design:* Prospective intervention study.
*Methods:* Ten trained male runners completed three training blocks in a fixed order. Training consisted of one week of light training (baseline), two weeks of heavy training designed to induce functional overreaching, and ten days of light taper training designed to allow athletes to recover from, and adapt to, the heavy training. Locomotor behaviour, 5-km time trial performance, and subjective reports of training status (Daily Analysis of Life Demands for Athletes (DALDA) questionnaire) were assessed at the completion of each training block. Locomotor behaviour was assessed using detrended fluctuation analysis of stride intervals during running at speeds corresponding to 65% and 85% of maximum heart rate ($HR_{max}$) at baseline.
*Results:* Time trial performance (effect size ±95% confidence interval (ES): 0.16 ± 0.06; $p < 0.001$), locomotor behaviour at 65% $HR_{max}$ (ES: −1.12 ± 0.95; $p = 0.026$), and DALDA (ES: 2.55 ± 0.80; $p < 0.001$) were all detrimentally affected by the heavy training. Time trial performance improved relative to baseline after the taper (ES: −0.16 ± 0.10; $p = 0.003$) but locomotor behaviour at 65% $HR_{max}$ (ES: −1.18 ± 1.17; $p = 0.048$) and DALDA (ES: 0.92 ± 0.90; $p = 0.045$) remained impaired.
*Conclusions:* Locomotor behaviour during running at 65% $HR_{max}$ was impaired by functional overreaching and remained impaired after a 10-day taper, despite improved running performance. Locomotor changes may increase injury risk and should be considered within athlete monitoring programs independently of performance changes.


## 1. Introduction

Athletes commonly complete deliberate periods of sustained heavy training in preparation for competition.[1,2] This heavy training is characterised by high training workloads and minimal recovery time between training efforts.[1] The process of intensifying training can cause athletes to experience fatigue and short-term decrements in performance, known as overreaching.[1,2] Functional overreaching is achieved if periods of heavy training are followed by adequate recovery (tapering), which facilitates positive training adaptations and improved performance.[1] Non-functional overreaching is associated with stagnation or decreased performance and occurs if heavy training is continued for too long or tapering is inadequate.[1] In extreme circumstances, athletes may experience overtraining syndrome, which is associated with chronically supressed performance, and physiological and psychological signs and symptoms of maladaptation.[1,2]

Overreaching can cause changes to bodily functions that are observed through measurement of heart rate,[3–5] hormone levels,[6,7] physical performance,[8] and psychological wellbeing.[9–11] Closely

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monitoring these markers can help identify overreaching early and allow for modification of training load to avoid the onset of non-functional overreaching or overtraining syndrome. There is currently no gold-standard marker for identifying overreaching and coaches commonly use a combination of physiological, psychological and performance measures to monitor athletes.[1] Recently, our laboratory demonstrated altered control of running gait in runners who experienced functional overreaching (i.e. performance decrements after 2 weeks of heavy training followed by supercompensatory performance improvements following taper).[12] Impaired locomotor function may increase injury risk,[13] and thus have implications for athlete monitoring during periods of heavy training. However, little else is known about the effects of overreaching on running gait.

In healthy running gait, the locomotor system moves the body forward using consistent strides that fluctuate only slightly in duration and length, from one stride to the next.[14] These small fluctuations occur in a predictable, non-random fashion that is thought to result from the complex coordination of motor control processes operating on different time scales.[15] These motor control processes become less predictable and more random in the presence of acute fatigue,[13] functional overreaching,[12] and recent injury.[13] The sensitivity of these processes to fatigue and injury suggests that measurement of running gait could provide coaches with useful information about athlete training status. Additionally, recent improvements in the quality and cost of wearable technologies provides readily available means for monitoring running gait in sports settings.[16]

Our previous investigation of running gait in functionally overreached athletes used fixed running speeds to assess locomotor system behaviour and observed inconsistent changes across athletes and speeds.[12] Using fixed running speeds may not be appropriate for athletes of varying fitness levels because each speed will represent a different relative intensity. Increasing and decreasing relative running intensity is known to influence locomotor system behaviour.[14,17] Therefore, the aims of the present study were to investigate if functional overreaching affects locomotor system behaviour when running at fixed relative intensities and if any effects were associated with changes in athlete performance. We hypothesised that (1) locomotor behaviour and athlete performance would be impaired after heavy training relative to baseline training and improved after tapering relative to heavy training, (2) locomotor behaviour would be unchanged and athlete performance would be improved after tapering relative to baseline training, and (3) changes in locomotor behaviour and athlete performance would be linearly associated.

## 2. Methods

Ethical approval was obtained from the Human Research Ethics Committee of the University of South Australia. Ten trained male runners (age: 35.8 ± 10.0 years; mass: 77.3 ± 10.0 kg; running distance: 46 ± 17 km/week) provided written informed consent and completed the study. Runners were included if they had no current injuries. Sample size was based on a previous study that detected a relationship between changes in locomotor behaviour and athlete performance in runners completing an overreaching protocol.[12]

The study used a repeated measures design that required participants to complete three training blocks in a fixed order. The training blocks consisted of 1-week of light training (baseline), 2 weeks of heavy training designed to induce functional overreaching, and a 10-day taper designed to allow recovery from the effects of heavy training. Running gait and athlete performance were assessed after each training block. Deficits in athlete performance and subjective reports of training status were used to confirm overreaching. Participants completed two practice sessions before starting the study to minimise learning effects. All testing was performed at the same time of day. Participants were instructed to maintain (and standardise) their typical diet and levels of hydration in preparation for testing, not to consume caffeine and alcohol 24 h before testing, not to complete any training on testing days, and to wear the same running shoes for all assessments.

**Table 1**
Running training intervention.

| Training phase | Training day | Daily training description[a] |
|---|---|---|
| Light | Day 1–5 | 30 min at 65–75% |
| Light | Day 6 | Rest day |
| Light | Day 7 | 30 min at 65–75% |
| Baseline test | Day 8 | Testing only |
| Heavy | Day 9–22 | 5 min warm-up at <69%<br>4 sets of the following progression:<br>4 min at 69–81%, 4 min at 82–87%,<br>4 min at 88–94% and 2 min at >94%<br>5 min cool-down at <69% |
| Post-heavy test | Day 23 | Testing only |
| Taper | Day 24 | Rest day |
| Taper | Day 25–26 | 30 min at 65–75% |
| Taper | Day 27 | 25 min at 75–85% |
| Taper | Day 28–29 | 30 min at 65–75% |
| Taper | Day 30 | 4 sets of the following progression:<br>3 min at 69–81% and 2 min at 88–94% |
| Taper | Day 31 | 30 min at 65–75% |
| Taper | Day 32 | Rest day |
| Taper | Day 33 | 30 min at 65–75% |
| Post-taper test | Day 34 | Testing only |

[a] Percentages indicated the training intensity as a percentage of maximum heart rate.

All training was prescribed relative to the maximum heart rate ($HR_{max}$) achieved across two 5-km treadmill time trials that were performed during the practice sessions. Training was prescribed in five heart rate zones: <69%, 69–81%, 82–87%, 88–94%, and >94% $HR_{max}$.[8] All training sessions were programmed into heart rate monitors (RS800CX, Polar Electro Oy, Kempele, Finland) that alerted participants whenever their heart rate was outside the prescribed training zone. Table 1 provides a detailed overview of the training program. Training load was considered the product of $\%HR_{max}$ and training duration (TRIMP). Training Block 1 involved light training on 6 of 7 days (mean daily TRIMP: 1800 arbitrary units (AU)), Training Block 2 involved heavy training on 14 consecutive days (mean daily TRIMP: 5226 AU), and Training Block 3 involved taper training on 8 of 10 days (mean daily TRIMP: 1622 AU).

Subjective measurement of athlete training status was undertaken using the Daily Analysis of Life Demands for Athletes (DALDA) questionnaire.[11] Each day, participants were required to score 34 training and life stressors on a scale of "worse than normal," "normal," or "better than normal." The total number of "worse than normal" scores was calculated each day and the seven-day rolling average at the completion of each training phase was used for analysis (i.e. the average value from the previous 7 days). Total number of "worse than normal" scores is sensitive to the effects of overreaching.[8]

Performance was assessed with a 5-km time trial test that has been previously shown to be reliable (coefficient of variation (CV): 1.3%)[18] and sensitive to the effects of overreaching.[5,12] The trial was completed on a calibrated motorized treadmill (Trackmaster TMX425CP, Full Vision Inc, KS, USA) set at 0% incline. Participants selected the starting speed that would allow them to complete the trial in the fastest possible time. This selection was based on two practice sessions and the same starting speed was used at each assessment. Treadmill speed could be adjusted up or down by participants during the assessment (after starting). Treadmill speed and time were concealed from participants throughout the trial, but participants could monitor distance using the treadmill display. Participants reported their perceived exertion after completing the trial using 0-to-10 rating of perceived exertion (RPE) scales.

Locomotor behaviour was assessed during five minutes of sub-maximal treadmill running at speeds that corresponded to 65% and 85% $HR_{max}$ at baseline. This assessment was completed before the time trial during each testing session. Force-sensitive resistors positioned under the heel and forefoot recorded foot contacts wirelessly at 2000 Hz (Trigno™, Delsys Inc, MA, USA). This system has been previously used to reliably measure spatiotemporal stride parameters (CV < 2.2%).[18] Foot-ground contacts were identified using the findpeaks function in MATLAB (R2013a, MathWorks, MA, USA) and stride intervals were calculated as the time between successive peaks.[19] The initial 30 s of running was excluded to avoid start-up effects and the following 300 stride intervals were included.[12]

Locomotor behaviour was analysed by detrended fluctuation analysis (DFA)[20] using PhysioNet software.[21] This analysis measures the extent to which each stride interval is correlated with previous and subsequent stride intervals over different time scales.[20] First, the PhysioNet algorithm divided the integrated time series of 300 strides into bins of length $N$. In each bin, a least squares line was used to represent the local trend. The integrated times series was then detrended by subtracting the local trend in each bin. Finally, the root-mean-square fluctuation of this integrated and detrended time series was calculated across all bin lengths from $N = 4$ to $N = 75$ strides. The coefficient ($\alpha$) relating fluctuations to bin length on a log-log plot determined the degree of long-range correlations. Strides with perfect correlations across all times scales are represented by $\alpha = 1.00$ while strides that are completely uncorrelated with previous and subsequent strides are represented by $\alpha = 0.50$.[14] Cohorts with impaired locomotor behaviour have $\alpha$ values that are below that of controls.[13,20] DFA $\alpha$ values have demonstrated good intra- and inter-day reliability during treadmill walking (intraclass correlation coefficient: 0.91 and 0.77, respectively).[22] To the authors' knowledge, the reliability of DFA $\alpha$ values during running has not been investigated.

Statistical analysis was performed using SPSS (v24, IBM, NY, USA). The effects of training on TRIMP, DALDA "worse than normal" scores, time trial performance and RPE were investigated using mixed effects models. Participant was a random effect and training was a fixed effect with repeated observations. DFA $\alpha$ values were investigated using a similar mixed effects model that included additional fixed effects for speed and training*speed, with speed treated as a repeated observation. Residual plots were used to assess normality, homoscedasticity and independence of residuals. Statistical significance was set at alpha equals 0.05. Effects sizes (ES) were calculated using standardised mean differences and considered small (<0.50), moderate (0.50–0.79) and large (>0.80).[23]

Changes in time trial performance and DFA $\alpha$ values were calculated for each pairwise comparison (heavy vs. baseline, taper vs. baseline, and taper vs. heavy). Analysis of covariance was then used to investigate correlations between changes in these variables.[24] Participant was considered a fixed effect to account for the repeated observations on each participant.[24] Correlation coefficients (r) were considered small (<0.30), moderate (0.30–0.49) and large (>0.50).[25]

## 3. Results

There was a main effect of training on TRIMP and DALDA scores ($p < 0.001$; Table 2). Participants achieved higher mean daily TRIMP values during heavy training compared to baseline (ES: 5.36; 95% CI: 4.57, 6.15; $p < 0.001$) and tapering (ES: 6.92; 95% CI: 6.13, 7.71; $p < 0.001$). Mean daily TRIMP was lower during tapering compared to baseline (ES: −1.56; 95% CI: −2.44, −0.68; $p = 0.001$). There were large increases in mean daily DALDA "worse than normal" scores during heavy training compared to baseline (ES: 2.55; 95% CI: 1.75, 3.34; $p < 0.001$) and tapering (ES: 1.62; 95% CI: 0.83, 2.41; $p < 0.001$). Mean daily DALDA "worse than normal" scores were higher during tapering compared to baseline (ES: 0.92; 95% CI: 0.02, 1.83; $p = 0.045$).

**Table 2**
Mean and standard deviation for outcome measures after baseline, heavy and taper training.

| Outcome | Baseline | Heavy | Taper |
|---|---|---|---|
| Daily TRIMP (AU) | 2745 ± 317 | 5290 ± 635[a] | 2003 ± 434[a,b] |
| Daily DALDA scores | 1.3 ± 1.0 | 6.0 ± 2.2[a] | 3.0 ± 2.1[a,b] |
| 5 km time trial | | | |
| Time (s) | 1165 ± 144 | 1187 ± 145[a] | 1143 ± 139[a,b] |
| RPE | 9.3 ± 1.1 | 9.3 ± 0.8 | 9.6 ± 0.6 |
| DFA $\alpha$ values | | | |
| 65% $HR_{max}$ | 0.80 ± 0.09 | 0.68 ± 0.13[a] | 0.68 ± 0.12[a] |
| 85% $HR_{max}$ | 0.74 ± 0.09 | 0.71 ± 0.22 | 0.69 ± 0.15 |

AU, arbitrary units; DALDA, Daily Analysis of Life Demands for Athletes; DFA, detrended fluctuation analysis; $HR_{max}$, maximum heart rate; RPE, rating of perceived exertion; TRIMP, training impulse.
[a] Different from baseline ($p < 0.05$).
[b] Different from heavy ($p < 0.05$).

There was a main effect of training on time trial performance ($p < 0.001$; Table 2). Time taken to complete the trial increased after heavy training relative to baseline (ES: 0.16; 95% CI: 0.09, 0.22; $p < 0.001$) and decreased after tapering relative to baseline (ES: −0.16; 95% CI: −0.25, −0.06; $p = 0.003$). There was no main effect of training on time trial RPE (P = 0.313; Table 2).

There was a main effect of training on DFA $\alpha$ values ($p = 0.031$; Table 2) but no main effect of speed ($p = 0.848$) and no training*speed interaction ($p = 0.527$). There was a large decrease in DFA $\alpha$ values after heavy training relative to baseline when running at 65% $HR_{max}$ (ES: −1.12; 95% CI: −2.09, −0.15; $p = 0.026$) but not 85% $HR_{max}$ (ES: −0.22; 95% CI: −0.87, 0.43; $p = 0.134$). This decrease relative to baseline for the 65% $HR_{max}$ running speed persisted after tapering (ES: −1.18; 95% CI: −2.35, −0.01; $p = 0.048$).

Changes in DFA $\alpha$ values at 85% $HR_{max}$ were not correlated with changes in performance (r: −0.08; $p = 0.722$) or DALDA scores (r: 0.16; $p = 0.517$). Changes in DFA $\alpha$ values at 65% $HR_{max}$ were correlated with changes in DALDA scores (r: −0.52; $p = 0.021$) and tended to be moderately correlated with changes in time trial performance (r: −0.41; $p = 0.066$). Seven participants demonstrated negative correlations (Fig. 1A and C ), indicating that greater decreases in DFA $\alpha$ values at 65% $HR_{max}$ were associated with greater decreases in time trial performance (increased time taken to complete time trial) and greater increases in "worse than normal" scores. Three participants demonstrated the opposite relationship (Fig. 1B and D) i.e. DFA $\alpha$ values at 65% $HR_{max}$ increased when performance decreased and "worse than normal" scores increased. However, 1 of these 3 participants did not return the DALDA questionnaires so could not be analysed for that outcome. Notably, the mean daily TRIMP values for these participants during heavy training (3785, 5031, and 5143 AU) were lower than the other participants (mean ± standard deviation: 5563 ± 355 AU; range: 5145–6216 AU).

## 4. Discussion

The purpose of the present study was to investigate if functional overreaching affects locomotor behaviour when running at fixed relative intensities and if any effects were associated with changes in running performance. Consistent with our hypothesis, locomotor behaviour, assessed using DFA, was altered after 2 weeks of heavy training and tended to be associated with changes in running performance. Locomotor behaviour had not recovered after a 10-day taper, despite improvements in running performance.

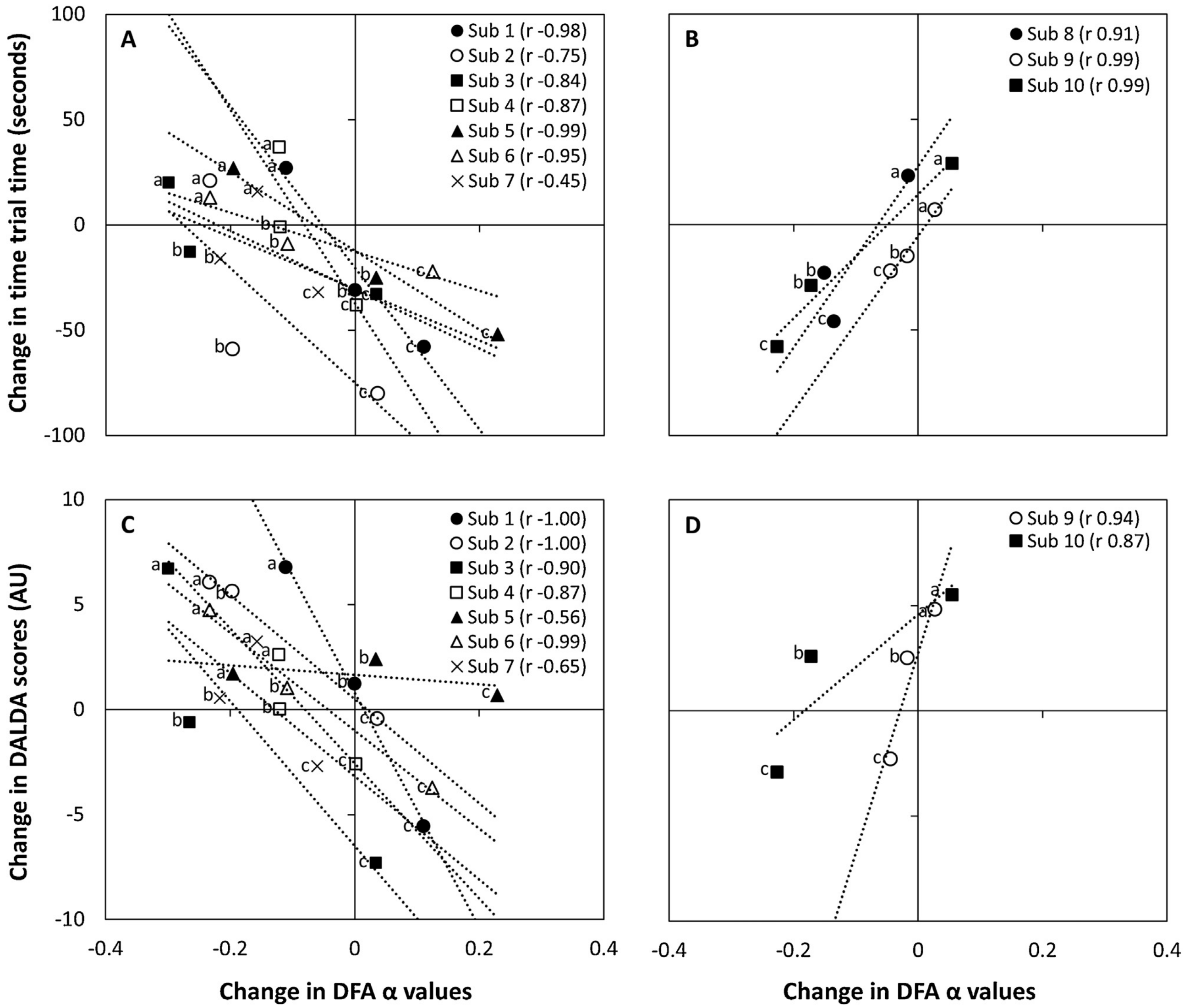


**Fig. 1.** Relationship between changes in time trial performance (Panel A and B) and Daily Analysis of Life Demands for Athletes (DALDA) scores (Panel C and D) with changes in detrended fluctuation analysis (DFA) $\alpha$ values at 65% maximum heart rate. Panels A and C present data for participants with a negative association. Panels B and D present data for participants with a positive association. Change values were calculated from each pairwise comparison: (a) post-heavy training minus baseline, (b) post-taper minus baseline, and (c) post-taper minus post-heavy training. Positive values on the y-axis indicate a reduction in time trial performance (longer time to complete trial) and an increase in number of "worse than normal" training and life stressors. Positive values on the x-axis indicate an increase in DFA $\alpha$ values. AU, arbitrary units. *Note:* DALDA data for Sub 8 were missing so could not be presented in Panel D.

Numerous physiological and psychological markers have been monitored during periods of overreaching in an attempt to determine reliable pre-cursors to overtraining.[1] Most markers of training status have demonstrated inconsistent responses to training interventions[1,2,26] so a combination of markers is often used to better identify true maladaptation. Changes to locomotor system behaviour during periods of overreaching have received much less research attention when compared to physiological and psychological outcome measures.[12] Measurements of locomotor behaviour might capture aspects of functional overreaching that are not adequately assessed by conventional physiological and psychological markers of training status.

Reduced DFA $\alpha$ values have been associated with acute fatigue,[13] injury status,[13] and declining physical function.[20] Therefore, the large reductions in DFA $\alpha$ values at 65% $HR_{max}$ amongst functionally overreached athletes in the present study are likely to indicate impaired locomotor system behaviour and might have important implications for injury risk and prevention of overtraining. Notably, DFA $\alpha$ values at 65% $HR_{max}$ remained low relative to baseline at completion of the 10-day taper, despite participants demonstrating improved time trial performance. DALDA scores were also not completely recovered following the 10-day taper and changes in DALDA scores and DFA $\alpha$ values at 65% $HR_{max}$ were correlated. Participants were still reporting three times as many "worse than normal" training and life stressors at the end of the 10-day taper compared to the baseline. Each of the training and life stressors are thought to be associated with overreaching.[11] Thus, the persistent elevation in DALDA scores combined with the persistent reduction in DFA $\alpha$ values at 65% $HR_{max}$ at the end of the taper suggests that participants had not completely recovered from overreaching, despite their improved time trial performance. We speculate that the ill-effects of this residual fatigue were outbalanced by beneficial cardiovascular and local muscular adaptations to the heavy training, which allowed participants to run faster post-taper. If correct, the impaired locomotor control associated with the residual fatigue might increase injury risk when combined with the higher forces experienced by athletes who are able to run faster after a successful taper. However, we are not aware of any research investigating whether the mismatch between recovery of performance and locomotor behaviour has any implications for injury risk. Future research should investigate whether monitoring the recovery of DALDA scores and DFA $\alpha$ values following a successful period of overreaching is a useful method for determining when to commence a subsequent overreaching training block.

The decreased DFA $\alpha$ values measured at 65% $HR_{max}$ in the present study were larger and more consistent than reductions in DFA $\alpha$ values measured at a fixed running speed of 10.5 km/h in a previous overreaching study.[12] The consistent low relative running intensity appears to be more sensitive to the effects of overreaching on locomotor system behaviour than fixed running speeds, which represent different relative intensities to different athletes. This suggests that when using DFA $\alpha$ values in athlete monitoring programs, assessments should be performed at the same relative exercise intensity, and preferably a lower intensity. It is possible that higher relative intensities (i.e. 85% $HR_{max}$) place greater constraints on the running movement (i.e. reduce available degrees of freedom)[17] and limit the ability to observe changes in locomotor behaviour.

Three participants in this study demonstrated strong correlations between DFA $\alpha$ values at 65% $HR_{max}$, time trial performance and DALDA scores that were in the opposite direction to most of the cohort i.e. performance and DALDA scores indicated functional overreaching but DFA $\alpha$ values at 65% $HR_{max}$ did not. TRIMP values suggested that these three participants completed less heavy training than the other participants and this might explain why their locomotor behaviour was not impaired. We speculate that higher training loads are required to negatively effect locomotor behaviour in comparison to physical performance and subjective reporting from athletes. If correct, impaired locomotor behaviour during heavy training should be considered a late sign rather than an early sign of overreaching. Monitoring DFA $\alpha$ values in combination with other markers of training status that respond earlier to the effects of heavy training may provide a clearer indication of athlete training status and lead to more effective decisions about athlete training load. DFA $\alpha$ values provide a means for assessing the effects of functional overreaching on the locomotor system that can complement physiological and psychological measures that assess the effects of functional overreaching on other bodily systems and functions. The improved quality of the accelerometers that are currently being integrated into athlete wearable technologies[16] provide readily accessible instruments for monitoring DFA $\alpha$ values in sports settings. Future research should seek to replicate the present study using accelerometer-based wearable technology and field-based running tests. The ability to translate the present findings is limited because laboratory-based testing protocols were used.

## 5. Conclusion

Locomotor system behaviour during running was altered by functional overreaching and remained altered after a 10-day taper, despite improved running performance. Changes in locomotor behaviour were associated with changes in subjective assessments of training and life stressors, which were also not recovered after the taper. Low relative running intensities were more sensitive to the effects of functional overreaching on locomotor behaviour. Multiple methods should be used to monitor athlete training status during overreaching training and help coaches prevent the onset of overtraining.

## Practical implications

- Locomotor behaviour, assessed using DFA of stride intervals during running, was altered after 2 weeks of heavy training in a manner that has previously been associated with injury.
- Locomotor behaviour had not recovered after a 10-day taper period, despite improvements in running performance.
- These changes to locomotor behaviour could have detrimental effects on injury risk.
- The assessment of locomotor behaviour used in this study could be incorporated into athlete monitoring programs.


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