OPTIMISING RUNNING MECHANICS FOR LONG-DISTANCE RUNNING: ALIGNING GROUND REACTION FORCE AND LONGITUDINAL LEG AXIS VECTORS

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This study examined whether changes in running economy were associated with changes in alignment of the resultant ground reaction force (GRF) and leg axis and consequent changes in joint moment arms after a ten-week running programme (10wkRP). Ten novice, female runners completed a 10wkRP with biomechanical and physiological testing occurring both pre- and post-10wkRP. Oxygen consumption ($\dot{V}O_2$) decreased (8%) and the resultant GRF and leg axis at peak propulsion was better aligned post-10wkRP compared to pre-10wkRP (10.8 vs. 1.6°, respectively). The change in $\dot{V}O_2$ was associated with the change in alignment of the resultant GRF and leg axis (r_s = 0.88, p = 0.02). Aligning the resultant GRF vector with the leg axis at peak propulsion appears to be a self-optimisation strategy that may improve performance.

KEY WORDS: running gait; oxygen consumption; performance;

INTRODUCTION: Running economy (RE), the rate of oxygen consumption ($\dot{V}O_2$) during steady-state running, is a major determinant of running performance. Poor RE, or high $\dot{V}O_2$, has been associated with many kinetic parameters such as, high total and net vertical impulse (Heise & Martin, 2001), high anterio-posterior (horizontal) braking force (Kyrolainen, Belli, & Komi, 2001), and low anterio-posterior (horizontal) propulsive force (Moore, Jones, & Dixon, 2012). Yet others have reported no associations between individual ground reaction force (GRF) components and RE (Nummela, Keranen, & Mikkelsson, 2007).
It has been argued that considering the GRF as separate, independent components is not realistic to how runners are likely to operate. Storen and colleagues (2011) supported this argument by finding a significant relationship between the sum of peak vertical and anterio-posterior forces and RE, but no such relationship when considering the peak forces separately. Furthermore, Chang and colleagues (2000; 1999) found that generating both vertical and horizontal forces was metabolically expensive. This led them to propose that horizontal forces are modified in proportion to changes in vertical force in an attempt to maintain the alignment of the resultant GRF with the long axis of the leg. Such alignment is postulated to have important mechanical and metabolic consequences, possibly resulting in an improved RE (Chang et al., 2000). However, there is limited empirical evidence to support the alignment hypothesis, as Chang et al. (2000) did not measure RE or leg axis orientation.
The ratio of external, joint moment arms to internal, muscle moment arms is termed 'gear ratio'. During braking a low gear ratio is believed to be associated with enhancing the storage of elastic energy due to increased stretch of the triceps surae muscle-tendon unit (Carrier, Heglund, & Earls, 1994). During propulsion a higher gear ratio is advocated as beneficial and may explain why shorter Achilles tendon moment arms have been related to better RE (Scholz, Bobbert, Van Soest, Clark, & Van Heerden, 2008). Yet, joint moment arms have received limited research attention in comparison to muscle moment arms.
The aim of the study was to investigate whether a ten-week running programme (10wkRP), which improved RE, affected resultant GRF and leg axis alignment and joint moment arms. It was hypothesised that, post-10wkRP, the leg axis would be more aligned with the resultant GRF. Additionally, if better alignment was found, it was hypothesised that shorter joint moment arms would also be observed.

METHODS: Fourteen novice female runners (mass: 69.1 ± 10.8 kg; height: 1.64 ± 0.09 m; age: 34.1 ± 8.8 yr) volunteered for the study through a 10wkRP, which aimed to have them running continuously for 30 minutes at week ten. Details regarding the 10-week training program and the precise timescales for testing have been presented elsewhere (Moore et al., 2012). To be classified as a novice runner participants must have not received any previous running training or be currently involved in sporting activities. All participants provided written informed consent and were free from injury and cardiac abnormalities prior to testing. The University's Ethics Committee gave ethical approval for this study. The participants visited the laboratory both pre- and post-10wkRP, to undergo both physiological and biomechanical testing. Only ten participants completed the 10wkRP. The other four participants withdrew, as they could not commit to the weekly running sessions.

A three-dimensional gait assessment of the left leg was performed using an eight camera motion capture system (Vicon Peak, 120 Hz, automatic, opto-electronic system; Peak Performance Technologies, Inc., Englewood, CO). Synchronised force plate data were also recorded during the gait assessment. The force plate, situated in the centre of the eight cameras, was located half-way down a 12 m run-way and sat flush with the floor. A standardised neutral trainer (Moore et al., 2012) was used by all participants during the gait assessment. Participants performed their own warm-up and were then fitted with eleven reflective markers on the left leg.

Ten successful running trials at 2.53 $m \cdot s^{-1}$ were recorded for each participant. A single standing trial was also recorded with the participants in the anatomic position. The dynamic angles were then adjusted to the standing trial to provide anatomically meaningful values.

The length of the joint moment arm during running was calculated as the distance between the centre of pressure and joint centre of either the knee or ankle. The minimum (negative) and maximum (positive) of the anterior-propulsive horizontal force represented the peak braking and peak propulsive force respectively. Similar to Chang et al. (2000), the time that these peaks occurred after initial contact was used in further calculations. The leg axis vector was defined as the vector between the hip and the lateral malleolus relative to the vertical. The resultant GRF vector was also calculated relative to the vertical.

RE was measured on a level treadmill over three test speeds in the following order: 2.08, 2.31, and 2.53 $m \cdot s^{-1}$. These speeds were chosen as test speeds should be representative of training speeds when assessing RE (Jones & Carter, 2000). Each speed was sustained for 6 minutes, with 9 minute rest periods between consecutive running bouts. $\dot{V}O_2$ was measured during the final 2 minutes of each bout of running. The mean $\dot{V}O_2$ over the final 2 minutes was then calculated. All three $\dot{V}O_2$ values were used to calculate RE.

Means ± SD of each variable were calculated. Where normality was present parametric tests were used, however, where normality was violated non-parametric tests were used. To determine whether there were any significant changes between pre and post measurements paired T-tests of the Wilcoxon signed-rank test was used. If significant changes were found, Pearson's Product Moment correlations or Spearman's Rank correlations were used to assess the relationships between changes. All statistical analysis was performed using SPSS version 22 (SPSS Inc., Chicago, Il) with significance set as $p \leq 0.05$.

RESULTS: There was an 8% decrease in $\dot{V}O_2$ from pre-10wkRP to post-10wkRP (224 ± 24 vs. 205 ± 27 $mL \cdot kg^{-1} \cdot km^{-1}$ respectively) ($p = 0.027$). Additionally, there was an improvement in the alignment angle between the leg axis and the resultant GRF during peak propulsive force post-10wkRP compared to pre-10wkRP ($p = 0.001$) (Table 1). This was predominantly due to a mean increase of 7° ± 0.6° ($p = 0.008$) in the resultant GRF angle during propulsion, as runners applied their resultant GRF 65% flatter (more horizontal). Joint moment arms were shorter during braking post-10wkRP. Stance time was unchanged from pre (302 ± 37 ms) to post (290 ± 38 ms). There was a positive relationship between the change in $\dot{V}O_2$ and the change in alignment of the resultant GRF and leg axis at peak propulsive force ($r_s = 0.88$, $p = 0.02$), indicating larger improvements in RE were associated with larger improvements in alignment (Figure 1a). It was evident that two participants appeared to have large changes to $\dot{V}O_2$ and alignment. Therefore a secondary correlation was performed with these participants removed. This also showed a significant relationship ($r_s = 0.82$, $p = 0.03$) (Figure 1b).

Table 1 Mean ± SD and (95% CI) of the resultant GRF and leg axis vector angles, alignment difference, peak forces and moment arms at the time of peak braking and propulsive force both pre- and post-10wkRP

Variables	Time of peak braking force		Time of peak propulsive force	
	Pre	Post	Pre	Post
Resultant GRF vector (°)	-10.4 ± 0.9 (-11.0 to -9.8)	-10.8 ± 0.8 (-11.3 to -10.3)	10.9 ± 6.5 (6.7 to 15.1)	18.0 ± 0.6* (17.6 to 13.4)
Leg axis vector (°)	-13.4 ± 1.0 (-14.1 to -12.7)	-10.6 ± 0.8 (-11.1 to -10.1)	21.7 ± 4.9 (18.5 to 24.9)	19.6 ± 1.2 (18.8 to 20.4)
Alignment difference (°)	-3.0 ± 6.5 (-7.2 to 1.2)	0.1 ± 0.6 (-0.3 to 0.5)	10.8 ± 4.9 (7.6 to 14.0)	1.6 ± 1.2* (0.8 to 2.4)
Ankle moment arm (cm)	9.6 ± 2.6 (7.9 to 11.3)	7.3 ± 2.3 (5.8 to 8.8)	18.3 ± 2.3 (16.8 to 19.8)	17.2 ± 0.7 (16.7 to 17.7)
Knee moment arm (cm)	4.7 ± 4.2 (2.0 to 7.4)	3.8 ± 3.5 (1.5 to 6.1)	5.0 ± 3.6 (2.6 to 7.4)	3.5 ± 1.8 (2.3 to 4.7)
Time of peak force (% of stance)	20 ± 4 (17 to 23)	19 ± 6 (15 to 23)	67 ± 8 (62 to 72)	67 ± 10 (60 to 74)

* Significantly different to pre-10wkRP ($p \leq 0.05$). Positive degrees represent when the vector was angled in the direction of the run, in front of the vertical. Negative degrees represent when the vector was angled behind the vertical.

DISCUSSION: This study examined whether changes in RE were associated with changes in alignment oft he resultant GRF and leg axis and consequent changes in joint moment arms after a 10wkRP. In support of our first hypothesis, runners were more economical post-10wkRP and the leg axis and resultant GRF were more aligned (Figure 2). Specifically, results showed that larger decreases in $\dot{V}O_2$ were associated with greater improvements in alignment of the resultant GRF and leg axis during propulsion. This was primarily due to runners applying their resultant GRF more horizontally. Therefore, such an alignment can be described as a self-optimisation strategy, as runners fine-tuned their running mechanics to minimise their $\dot{V}O_2$ during running.

Chang and colleagues (2000) proposed that aligning the resultant GRF vector with the leg axis would be metabolically beneficial, as it would minimise the muscular forces. Our study provides the first evidence to support this hypothesis. Furthermore, the traditional approach of assessing the magnitudes of individual GRF components in associated with RE would have failed to identify the GRF as a contributory factor to economical running. However, our results suggest it is not the magnitudes that are important, as they remained unchanged, but the angle of force application.

Partially contradicting our second hypothesis, there was no change in individual moment arm lengths at the time of peak propulsion. However, our previous data has shown that the same runners flexed their leg more at toe-off through less knee extension and less plantarflexion (Moore et al., 2012). It is therefore conceivable that runners were able to re-direct their resultant GRF through greater leg flexion, but unaltered joint moment arms. There were however, changes in ankle moment arms during peak braking. Assuming that internal, muscle moment arms remained similar pre to post-10wkRP, the shorter ankle moment arms would have led to a lower gear ratio. Producing a low gear ratio during the braking, absorption phase of stance is reported as beneficial for the triceps surae muscle-tendon unit's storage of elastic energy (Carrier et al., 1994). Therefore, the muscular force production of the triceps surae muscle-tendon unit may have improved (Biewener, Farley, Roberts, & Temaner, 2004).

The novel approach to assess running mechanics and RE first described by Chang and colleagues (2000) and adopted in this study could have wider applications to running mechanics associated with fatigue and altered running mechanics due to changes in surface and footwear. It is possible that such a self-optimisation strategy could be implemented by trained runners in unfamiliar conditions.

A limitation is that the magnitude of, and variation in, moment arm lengths means that the small sample size led to a lack of power in the statistical analysis. Unfortunately due to the nature of the training programme a larger sample size could not be obtained. Nevertheless, future work should look to build on these preliminary findings by investigating larger running populations or by quantifying the moment arm measurement error.

CONCLUSION: In conclusion, as novice runners became more economical they exhibited a more aligned resultant GRF vector and leg axis at the time of peak propulsion. This is believed to be a self-optimisation strategy that minimises the metabolic cost of lower limb muscular force-generation during steady-state running and thus has the potential to improve running performance. Additionally, alterations to ankle moment arms indicate beneficial gear ratios were achieved during peak braking.

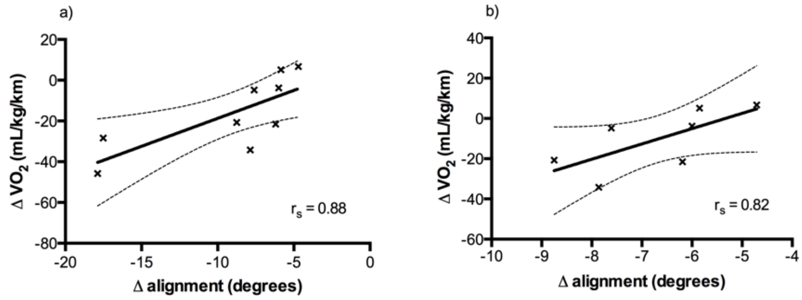

Figure 1: Relationship between the change in oxygen consumption ($\dot{V}O_2$) and alignment of the resultant GRF and leg axis with a) all participants and b) participants minus the two extreme values. Dotted lines represent 95% confidence intervals.

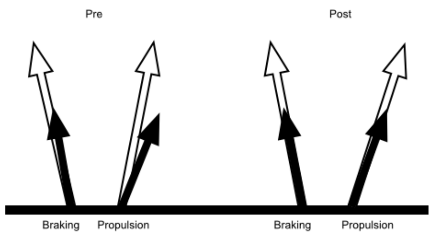

Figure 2. Resultant GRF (black arrows) and leg axis (white arrows) vectors at time of peak braking and peak propulsive force, pre- and post-10wkRP.

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