Reduced oxygen cost of running is related to alignment of the resultant GRF and leg axis vector: A pilot study

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Abstract

Purpose: This pilot study investigated whether a ten-week running programme (10wkRP), which reduced the oxygen cost of running, affected resultant ground reaction force (GRF), leg axis alignment, joint moment characteristics and gear ratios. **Methods:** Ten novice, female runners completed a 10wkRP. Running kinematics and kinetics, in addition to oxygen consumption ($\dot{V}O_2$) during steady-state running, were recorded pre- and post-10wkRP. **Results:** $\dot{V}O_2$ decreased (8%) from pre-10wkRP to post-10wkRP. There was a better alignment of the resultant GRF and leg axis at peak propulsion post-10wkRP compared to pre-10wkRP (10.8 ± 4.9 vs. 1.6 ± 1.2°), as the resultant GRF vector was applied 7 ± 0.6° (p=0.008) more horizontally. There were shorter external ankle moment arms (24%) and smaller knee extensor moments (23%) at peak braking post-10wkRP. 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=0.003). **Conclusion:** As runners became more economical they exhibited a more aligned resultant GRF vector and leg axis at peak propulsion. This appears to be a self-optimisation strategy that may improve performance. Additionally, changes to external ankle moment arms indicated beneficial low gear ratios were achieved at the time of peak braking force.

Key words: Running economy, joint moments, gear ratio, running gait

Introduction

Lowering the oxygen cost of running has been associated with improved running performance (Conley and Krahenbuhl, 1980). It is well known that generating muscular force requires energy, and therefore incurs an oxygen cost (Kram and Taylor, 1990; Taylor, Heglund, McMahon and Looney, 1980). Thus, alterations to lower limb running mechanics that affect muscular force-generating requirements are likely to influence the oxygen cost of running and running performance.

Studies have identified certain mechanical characteristics of running that are associated with the oxygen cost of running (Moore, Jones and Dixon, 2012; Moore, Jones and Dixon, 2014; Scholz, Bobbert, Van Soest, Clark and Van Heerden, 2008; Williams and Cavanagh, 1987). Several running characteristics identified can be described as unmodifiable, such as muscle moment arms (Scholz et al., 2008). Some are modifiable and therefore can be changed, such as kinetics (Moore et al., 2012), and others are an interaction of both, such as ‘gear ratios’ (Carrier, Heglund and Earls, 1994). Minimising the muscular force needed during running by altering the mechanical characteristics of running, that are either modifiable or an interaction of modifiable and unmodifiable characteristics, to lower the oxygen cost of running is known as self-optimisation (Moore et al., 2012; Moore et al., 2014; Williams and Cavanagh, 1987).

A high oxygen cost of running has been associated with the following kinetic parameters; a high medio-lateral force (Williams and Cavanagh, 1987), high total and net vertical impulse (Heise and Martin, 2001), high vertical impact peak force (Williams and Cavanagh, 1987), high anterior-posterior braking force (Kyrolainen, Belli and Komi, 2001), and low anterior-posterior propulsive force (Moore et al., 2012). Yet many have reported no associations between individual ground reaction force (GRF) components and the oxygen cost of running

(Heise and Martin, 2001; Nummela, Keranen and Mikkelsson, 2007). Researchers have argued that considering the GRF as separate, independent components is not realistic to how runners are likely to operate. Supporting this argument, Storen and colleagues (2011) found a significant relationship between the sum of peak vertical and anterior-posterior forces and the oxygen cost of running, but no such relationship was evident when considering the peak forces separately. Furthermore, it is metabolically expensive to generate horizontal force (Chang and Kram, 1999), even though it is not acting against gravity (Chang, Huang, Hamerski and Kram, 2000). This led Chang and colleagues (2000) 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 (Alexander, 1991; Chang et al., 2000).

Mathematical modelling of the lower limb during running has demonstrated that aligning the resultant GRF with the leg axis would shorten external GRF moment arms and reduce joint moments (Alexander, 1991). This would lower the oxygen cost of locomotion, as the muscular force needed to counteract such moments would also be reduced (Alexander, 1991; Chang et al., 2000). Modifying the external GRF moment arms through greater alignment will affect the ratio of external GRF moment arms to internal muscle-tendon unit moment arms. This is known as the ‘gear ratio’ or effective mechanical advantage of the muscle (Biewener, Farley, Roberts and Temaner, 2004; Carrier et al., 1994; Lee and Piazza, 2009; Willwacher, König, Braunstein, Goldmann and Brüggemann, 2014).

A modifiable mechanical characteristic, GRF moment arm, and an unmodifiable mechanical characteristic, muscle moment arm, therefore affect gear ratio. Research has traditionally focused on statically measuring the unmodifiable characteristic, with findings showing shorter Achilles tendon moment arms are associated with lower oxygen costs of running, implying high gear ratios are beneficial for running economy (Barnes, McGuigan and Kilding, 2014; Raichlen, Armstrong and Lieberman, 2011; Scholz et al., 2008). However, Carrier and colleagues (1994) proposed a dynamic understanding of gear ratios during running. They suggested that a low gear ratio during braking increases the stretch of the triceps surae muscle-tendon unit, potentially enhancing the force output during propulsion, whereas a high gear ratio during propulsion (push-off) when the foot is moving rapidly allows the muscles to operate at lower velocities according to the force-velocity relationship (Carrier et al., 1994). Consequently, shorter external GRF moment arms would lower the gear ratio and potentially be beneficial during braking, in addition to contributing to the alignment of the GRF and the leg axis. However during propulsion, longer external GRF moment arms would increase the gear ratio and potentially be beneficial, but may be detrimental for the alignment of the GRF and the leg axis. Currently, there is limited direct empirical evidence to support the alignment hypothesis during running, as Chang et al. (2000) did not measure the leg axis orientation or oxygen cost of running. Furthermore, it is not known whether changes in alignment are also directly associated with changes in external GRF moment arms, and thus, alterations to gear ratios. Additionally, greater understanding regarding alignment and external GRF moment arms during propulsion is needed given the possible conflicting effects on the oxygen cost of running.

To the authors’ knowledge, assessing whether runners change their alignment and external GRF moment arms when optimising their running gait, over a training period that lowers their oxygen cost of running, has not been investigated. We have previously shown mechanical characteristics of running to explain the majority (94%) of the variance of the change in running economy in beginner runners (Moore et al., 2012). However, what is not known is whether improved alignment and decreased external moment arm length occurs as runners become more economical. Therefore, the aim of this pilot study was to investigate whether a ten-week running programme (10wkRP), which reduced the oxygen cost of running, also altered resultant GRF and leg axis alignment and joint moment characteristics. 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 external moment arms would also be observed and thirdly, that such changes would correlate with reductions in the oxygen cost of running.

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 have been presented elsewhere (Moore et al., 2012). Participants were classified as a novice runner if they were not involved in sporting activity at the time of testing and had not received any previous running-related training. 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 undertake physiological and biomechanical testing. These testing sessions were performed on separate days and the exact timescales have been previously presented (Moore et al., 2012). Participants were tested post-10wkRP at a similar time of day as their pre-10wkRP testing. Additionally, they were given a minimum of six minutes to become familiarised with treadmill running during physiological testing to enable a natural running style to be achieved (Lavcanska, Taylor and Schache, 2005). Only ten participants completed the 10wkRP, with the other four participants withdrawing as they could not commit to the weekly running sessions.

Gait analysis

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 (AMTI, 960 Hz, Advanced Mechanical Technology, Inc., Massachussetts) 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. All raw kinematic data were smoothed with a fifth order quintic spline filter within the Vicon system. Smoothed coordinates and raw GRF data were exported to MATLAB for further processing.

A standardised neutral trainer (Adidas Performance Galaxy) was used by all participants during the gait assessment. Participants performed their own warm-up and were then fitted with eleven reflective markers using a modified Soutas-Little and colleagues (1987) model, to denote the thigh, shank and foot: proximal greater trochanter (hip), medial and lateral condyles (knee), midline of the posterior shank, the musculotendious junction where the medial and lateral belly of the gastrocnemius meet the Achilles tendon, the mid tibia below the belly of the tibialis anterior, lateral malleolus (ankle), superior and inferior calcaneus, the proximal head of the third metatarsal and the distal head of the fifth metatarsal joint.

Participants performed as many familiarisation trials as were needed for them to feel comfortable performing the running trials. Ten successful running trials at 2.53 $m \cdot s^{-1}$ were recorded for each participant. For a trial to be deemed successful participants had to satisfy the following requirements: be running at the test speed (± 5%); and have their whole foot make contact with the force plate without targeting the force plate or making obvious gait adjustments to hit the force plate. 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.

Three-dimensional joint moments were calculated using an inverse dynamics approach. Subject specific segmental parameters were derived using regression equations, which take into account the height and mass of each participant (Shan and Bohn, 2003). Segmental density data were taken from cadavers (Dempster, 1955). A Butterworth, 4th order, recursive filter (cut-off frequency, 20 Hz) was used to process the raw GRF data before it was used within the joint moments calculation. The centre of pressure and free torque were taken from the force plate data. To calculate the ankle joint centre the ankle width was measured using callipers and the relative position was determined using the lateral malleolus marker during dynamic trials. The knee joint centre was computed as the mid-point between the lateral and medial knee markers. All parameters used for the inverse dynamics calculation were transformed from the global coordinate system to the local coordinate system (LCS) of each segment (Hof, 1992). For the external ankle joint moments the origin of the LCS was set as the foot centre of mass, whereas for external knee joint moments the LCS origin was set as the shank centre of mass. The orientation of the foot LCS axes were as follows: vertical (z) axis was the vector from the inferior to superior calcaneus; medial-lateral (x) axis was the cross product of the foot z axis and vector from inferior calcaneus to third metatarsal and; anterior-posterior (y) axis was the cross product of the foot z and foot x axes. The orientation of the shank LCS axes were as follows: vertical (z) axis was the vector from mid ankle to mid knee; medial-lateral (x) axis was the vector between medial and lateral condyles and;

anterior-posterior (y) axis was the cross product of the shank z and shank x axes. Joint moments (M_{joint}) were calculated using the equations defined by Hof (1992) and Hamill and Selbie (2004), specifically:

$$M_{joint} = - T_{FP} - M_{GRF} - M_{weight} + M_{eff} + M_{rot}$$

Where T_{FP} represents the free torque between the foot and the force plate; M_{GRF} is the moment applied by the GRF; M_{weight} is the moment applied by the weight of the segments; M_{eff} is the moment applied by the effective, acceleration forces acting on the segment centre of mass and; M_{rot} is the moment due to rotational acceleration.

The minimum and maximum of the anterior-posterior force (horizontal Fy) represented the peak braking and peak propulsive force respectively (Figure 1). Based on similar work by Chang and colleagues (2000), the time that these peaks occurred after initial contact was used in further calculations. The **sagittal plane** moment arm, **perpendicular to the GRF** (sum of the **y and z** components) was calculated for each joint by multiplying the GRF by the distance between the joint centre and centre of pressure and then dividing it by the resultant GRF (Carrier et al., 1994; Karamanidis and Arampatzis, 2005; Willwacher et al., 2014). The **sagittal plane** moment arm for each joint is referred to as the ‘external ankle moment arm’ and ‘external knee moment arm’. Net resultant moment arm represents the sum of both the external knee moment arm and the external ankle moment arm. The external ankle and knee moment arms were calculated at the time of peak braking and peak propulsive force (Figure 1). Braking (negative Fy) and propulsive (positive Fy) impulses were also calculated and normalised to body weight impulse as described by Munro, Miller and Fuglevand (1987).

Additionally, net anterior-posterior impulse (braking impulse + propulsive impulse) was normalised to body mass to assess the change in horizontal velocity during ground contact.

The leg axis was defined in the global coordinate system as the vector between the hip (greater trochanter) and the lateral malleolus markers. The leg axis angle was defined as an angle between the leg axis and the vertical. A positive angle denotes that the leg axis vector was directed in front of the vertical, with the hip being in front of the lateral malleolus. A negative angle denotes that the leg axis vector was directed behind the vertical. The angle of the resultant GRF vector was also defined in the global coordinate system and computed as relative to the vertical, thus a resultant GRF perpendicular to the ground had an angle of 0°. Similar to the leg axis angle, a positive angle represents the resultant GRF being directed in front of the vertical and a negative angle represents the resultant GRF being directed behind the vertical. Both the leg axis and GRF vector were three-dimensional vectors. The difference between the leg axis angle and the resultant GRF vector angle was determined throughout stance **as the smallest angle between the two vectors in three-dimensional space**. One participant's data had to be excluded due to incomplete data resulting from marker drop-out.

Physiological assessment

Participants performed a 6-minute familiarisation run on the treadmill prior to the physiological assessment, which served as their warm-up. The oxygen cost of running 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 following the recommendations that test speeds should be representative of training speeds for the assessment of the oxygen cost of running (Daniels and Daniels, 1992; Jones and Carter, 2000). Although not a randomised protocol, fatigue effects were minimised by progressing from the slowest to the fastest speed. Each speed was sustained for six minutes, with 9-minute rest periods between consecutive running bouts.

Oxygen consumption ($\dot{V}O_2$) was measured during the final two minutes of each bout of running. A steady-state was assumed if there was <10% change in $\dot{V}O_2$ over the final two minutes (Gruber, Umberger, Braun and Hamill, 2013). All tests met this criterion. The mean $\dot{V}O_2$ over the final two minutes was then calculated. All three mean $\dot{V}O_2$ values were used to calculate the oxygen cost of running.

Statistical Analysis

Means (SD) of each variable were calculated. Due to the small sample size two statistical methods were used to test for normality. Firstly, kurtosis and skewness values were converted to z-scores to assess for significant deviations from normal (Ghasemi and Zahediasl, 2012). Significant deviations were defined as absolute z-scores > 1.28, with significance set at $p \leq 0.10$ (Supplementary Tables 1-3). Secondly, boxplots were used to identify outliers, defined as >1.5 times the interquartile range away from the end of the boxes (Supplementary Figures 1-2) (Ghasemi and Zahediasl, 2012; Milner, Ferber, Pollard, Hamill and Davis, 2006). If significant deviations and outliers were present non-parametric Wilcoxon Signed Rank tests were used to compare pre and post measurements. Conversely, paired T-tests were used when there was no significant deviations or outliers. If significant changes were found, Pearson's product-moment correlations or Spearman's Rank correlations were used depending on the normality and deviation of the changes. For Spearman's Rank correlations, 95% confidence intervals (CI) were calculated using Fisher's Z transformations. 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 the oxygen cost of running from pre-10wkRP to post-10wkRP (224 ± 24 vs. 205 ± 27 $mL\cdot kg^{-1}\cdot km^{-1}$ respectively) ($p = 0.029$). Additionally, there was a decrease in the alignment angle between the leg axis and the resultant GRF during peak propulsive force post-10wkRP compared to pre-10wkRP ($p = 0.008$) (Table 1). This was predominantly due to an increase in the resultant GRF angle during propulsion ($p = 0.008$), which led to runners applying their resultant GRF 65% flatter (more horizontal). There was a small, but non-significant ($p = 0.201$), increase in the leg axis angle at peak braking force, resulting in a near perfect alignment angle (Table 1).

At the time of peak braking, external ankle moment arms shortened by 24% and resultant knee extensor moment decreased by 23% post-10wkRP compared to pre-10wkRP (Table 2). Furthermore, post-10wkRP there was an 11% shorter net moment arm at the time of peak propulsion than pre-10wkRP. However, there were no significant changes in external ankle and knee moment arms at the time of peak propulsion. Compared to pre to post-10wkRP, stance time was similar (302 ± 37 vs. 290 ± 38 ms, $p = 0.500$), as was net anterior-posterior impulse (-0.02 ± 0.07 vs. -0.02 ± 0.09 N·s, $p = 0.880$).

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 ($r_s = 0.88$, $p = 0.003$, 95% CI 0.52 to 0.97), indicating larger decreases in the oxygen cost of running were associated with larger improvements in alignment (Figure 2a). There were two participants with large reductions in $\dot{V}O_2$, when these participants were removed from the dataset the positive relationship was still identifiable ($r_s = 0.82$, $p = 0.030$, 95% CI 0.17 to 0.97) (Figure 2b).

Discussion

This pilot study examined whether changes in running economy were associated with changes in alignment of the resultant GRF and leg axis and consequent changes in joint moment characteristics after a 10wkRP. In support of our first and third hypotheses, runners were more economical post-10wkRP and the leg axis and resultant GRF were more aligned. 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.

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 by reducing joint moments. Our pilot study provides the first evidence to support this hypothesis. The original hypothesis was proposed when Chang and colleagues (2000) investigated the resultant GRF and other mechanical characteristics of running during different gravity and inertia conditions. However, data relating to the leg axis angle and oxygen cost of running were not gathered. Our findings show that, as novice runners acquired greater running experience, they self-optimised their running mechanics by altering their resultant GRF vector to align with their leg axis.

The runners decreased their external knee extensor moment and external ankle moment arm when exerting their peak braking force. As there were no changes in external knee moment arm during braking, the lower knee extensor moment represents a reduction in force production, possibly by the dominant knee extensor muscles the quadriceps. Minimising muscular activity has been mathematically modelled as being able to produce representative lower limb joint moments (Gopalakrishnan, Modenese and Phillips, 2014) and a control strategy for economical running (Miller, Umberger, Hamill and Caldwell, 2012). Additionally, low thigh coactivation is associated with a lower oxygen cost of running (Moore, Jones and Dixon, 2013). Therefore, it is likely that the reduced external knee moments were accompanied by lower muscular activation and force production, which could facilitate a lower oxygen cost of running (Kram and Taylor, 1990; Taylor et al., 1980). However, the changes in external knee extensor moment were not directly related to the changes in oxygen cost. Further work incorporating muscle activity measures, in addition to joint moment characteristics, could provide greater understanding.

The shorter external ankle moment arms during braking post-10wkRP indicate lower gear ratios were achieved, in addition to the occurrence of near perfect alignment of the GRF and leg axis. Carrier and colleagues (1994) argued that a low gear ratio when braking optimises the triceps surae muscle-tendon unit’s function. Further, Karamandis and colleagues (2005; 2006) state that the mechanical characteristics of running may be modified to accommodate changes in muscle-tendon unit force capacities. Specifically, they refer to a low gear ratio observed in older runners relating to decreases in plantarflexor isometric strength. However, it could also conceivably relate to novice runners self-optimising their running gait, as Karamandis and colleagues (2005; 2006) argued that a modified gear ratio was a result of proprioceptive feedback from repeated running exposure. Consequently, it is suggested that the increase in effective mechanical advantage due to a lower gear ratio may have improved the muscular force production of their triceps surae muscle-tendon unit (Biewener et al., 2004) and required less muscular activity (Kunimasa, Sano, Oda, Nicol, Komi, Locatelli, Ito and Ishikawa, 2014).

The unchanged external ankle moment arm post-10wkRP at peak propulsion, when the external moment arm is longest, means a high gear ratio was maintained during late stance. It has been suggested that a high gear ratio at this time is optimal for forward propulsion (Baxter et al., 2012; Lee and Piazza, 2009) as it allows the triceps surae muscle-tendon unit to shorten more slowly and maintain force production (Carrier et al., 1994). However this does contradict our second hypothesis, as greater alignment at peak propulsion was not accompanied with individual changes in external moment arms, even though there was a decrease in the net moment arm length at this time. It is possible that the small changes in individual external moment arms were harder to detect due to measurement error and the sample size of this pilot study, but the summation of moment arms was able to identify the differences. The subsequent change in net moment arm suggests there was a tendency for the resultant GRF vector to move closer to the lower limb joint centres, whilst high gear ratios were maintained. However, further investigations are required to examine the relationship between alignment and external moment arms in more detail. Additionally, quantifying the standard error of measurement for external moment arms is advised.

The generation of horizontal force during running incurs a high oxygen cost (Chang and Kram, 1999). Yet, the braking and acceleration behaviour of the runners was similar pre- and post-10wkRP, as shown by the anterior-posterior impulses. Additionally, the magnitude of the impulses was also slightly lower than previous reports, probably due to a slower running velocity (Heise and Martin, 2001; Karamanidis and Arampatzis, 2005; Munro et al., 1987). It appears therefore, that anterior-posterior impulses may be more resistant to change in novice runners than external moment arms or alignment. Nevertheless, findings show that during long-term habituation to running anterior-posterior impulses decrease, with older runners having lower impulses than younger runners (Karamanidis and Arampatzis, 2005). Thus, the short-term training programme investigated in this study may not have been long enough to induce changes.

The small sample size used in this pilot study affects the statistical power of the analyses conducted and limits the generalisation of the findings. However, this could not be overcome due the training programme under investigation. It is advised that future studies look to assess larger sample sizes, as the results presented in this pilot study provide encouraging links between running economy and running technique. Whilst it may be argued that measuring GRF moment arms rather than muscle moment arms limits our interpretation of the gear ratio, it does provide the greatest information with regards to self-optimisation strategies implemented. This is because self-optimisation refers to ‘fine-tuning’ running mechanics that are either modifiable, such as external moment arms, or an interaction of both modifiable and unmodifiable mechanics, such as gear ratio (Moore et al., 2012; Williams and Cavanagh, 1987). Contrastingly internal (muscle) moment arms are considered unmodifiable characteristics and are often measured statically (Barnes, McGuigan and Kilding, 2014; Raichlen, Armstrong and Lieberman, 2011; Scholz et al., 2008). Additionally, previous evidence shows internal moment arms exhibit negligible changes in length (< 1cm) during the range of motion expected during ground contact (Rugg, Gregor, Mandelbaum and Chiu, 1990).

In conclusion, as 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 oxygen cost of lower limb muscular force-generation during steady-state running and thus has the potential to improve running performance. Additionally, changes to external ankle moment arms indicate beneficial gear ratios were achieved at the time of peak braking force. During propulsion a high gear ratio was maintained, even with improved alignment.

Perspectives

Based on the current study’s findings, aligning the direction of the resultant GRF vector with the direction of the leg axis appears to be an economical self-optimisation strategy, which may improve running performance. Novice runners with no previous running experience can make such modifications in ten weeks. This study also highlights the importance of trying to minimise the muscular force-generating requirements during steady-state running through alterations to joint moment characteristics. Our research suggests that large changes in the mechanical characteristics of running occur during a runner’s initial training period. Therefore, extrapolating these results to trained runners is difficult, although it is expected that all runners do aim to minimise muscular forces and lower their oxygen cost of running. Further investigations using trained runners are warranted to identify whether the most economical trained runners also align their resultant GRF and leg axis. Additionally, as it is likely that acute changes to running technique will increase the oxygen cost of running and decrease performance, examining whether such an alignment can be taught to trained runners over several weeks warrants investigation.

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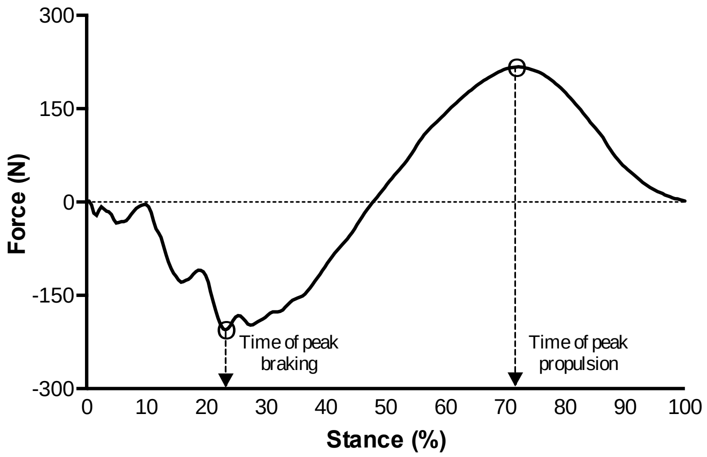

Figure 1. Typical anterior-posterior force (horizontal Fy) during stance, with the timing of peak braking and propulsion identified.

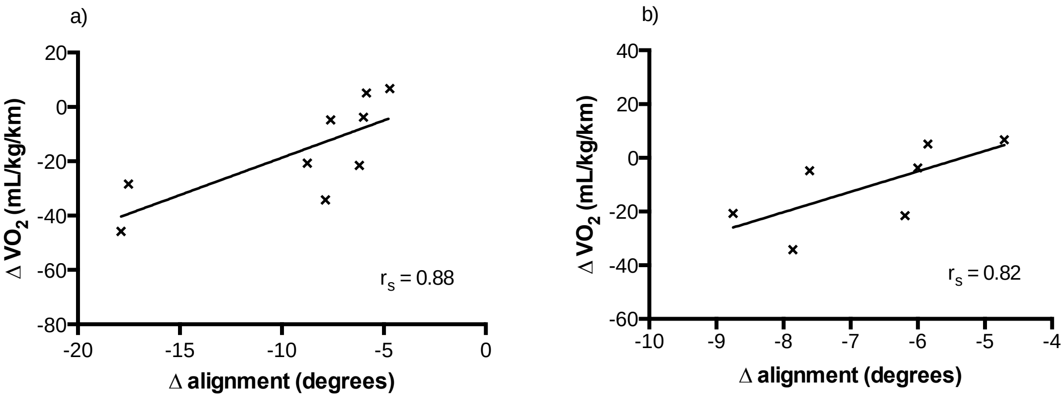

Figure 2. Relationship between the change in oxygen consumption ($\dot{V}O_2$) and alignment of the resultant GRF and leg axis for a) all participants and b) seven participants (extreme changes removed).

Table 1 Mean (SD) resultant GRF vector and leg axis angles relative to the vertical, and alignment difference at the time of peak braking and propulsive force pre-10wkRP, post-10wkRP and the change over time.

Angles (°)	Time of peak braking force			Time of peak propulsive force		
	Pre	Post	Change (95% CI)	Pre	Post	Change (95% CI)
Resultant GRF	-10.4 (0.9)	-10.8 (0.8)	0.4 (-0.5 to 1.4)	10.9 (6.5)	18.0 (0.6)*	6.9 (6.5 to 7.3)
Leg axis	-13.4 (1.0)	-10.6 (0.8)	-2.8 (-8.0 to 2.4)	21.7 (4.9)	19.6 (1.2)	2.1 (-1.7 to 5.9)
Alignment difference	-3.0 (6.5)	0.1 (0.6)	3.1 (-1.0 to 8.2)	10.8 (4.9)	1.6 (1.2)*	-9.2 (-13.0 to -5.3)

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

Table 2 Mean (SD) joint moment characteristics at the time of peak braking and propulsive force pre-10wkRP, post-10wkRP and the change over time.

Variables	Time of peak braking force			Time of peak propulsive force		
	Pre	Post	Change (95% CI)	Pre	Post	Change (95% CI)
Ankle moment arm (cm)	9.6 (2.6)	7.3 (2.3)*	2.3 (0.5 to 4.1)	18.3 (2.3)	17.2 (0.7)	1.1 (-0.6 to 2.7)
Knee moment arm (cm)	4.7 (4.2)	3.8 (3.5)	0.8 (-1.1 to 2.8)	5.0 (3.6)	3.5 (1.8)	1.5 (-0.2 to 3.1)
Net moment arm (cm)	14.2 (5.0)	11.1 (4.8)	3.2 (-0.1 to 6.2)	23.3 (3.5)	20.7 (2.1)*	2.6 (0.5 to 4.6)
Ankle resultant moment (N·m)	75.7 (44.4)	53.2 (23.1)	22.5 (-17.8 to 62.8)	119.5 (32.2)	111.7 (10.8)	7.7 (-13.9 to 29.4)
Knee resultant moment (N·m)	134.2 (44.1)	103.3 (47.2)*	31.1 (1.5 to 60.6)	30.6 (16.3)	40.1 (18.8)	-9.5 (-31.0 to 12.0)

* Significantly lower than pre-10wkRP ($p \leq 0.05$).