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The effect of attentional cues on mechanical efficiency and movement smoothness in running gait: An interdisciplinary investigation

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ABSTRACT

The aim was to examine the effect of focus of attention cues on foot angle for retraining movement purposes. Twenty (females: 8) rearfoot-striking recreational runners (mass: 72.5 ± 11.8 kg; height: 1.73 ± 0.09 m; age: 32.9 ± 11.3 years) were randomly assigned to an internal focus (IF) ($n = 10$) or external focus (EF) ($n = 10$) verbal cue group. Participants performed 5 × 6 minute blocks of treadmill running (control run, 3 × cued running, retention run) at a self-selected running velocity (9.4 ± 1.1 km·h^{-1}) during a single laboratory visit. Touchdown foot angle, mechanical efficiency, internal and external work were calculated and, centre of mass (COM) and foot movement smoothness was quantified. Linear-mixed effect models showed an interaction for foot angle ($p < 0.001$, $\eta_p^2 = 0.35$) and mechanical efficiency ($p < 0.001$, $\eta_p^2 = 0.40$) when comparing the control to the cued running. Only the IF group reduced foot angle and mechanical efficiency during cued running, but not during the retention run. The IF group produced less external work during the 1st cued run than the control run. COM and foot smoothness were unaffected by cueing. Only an IF produced desired technique changes but at the cost of reduced mechanical efficiency. Movement smoothness was unaffected by cue provision. Changes to foot angle can be achieved within 6 minutes of gait retraining.

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Focus of attention; gait retraining; conscious control; running gait; external work

Introduction

Running gait retraining is used in the prevention and rehabilitation of various common lower limb injuries, particularly anterior knee pain (Diss et al., 2018; Noehren et al., 2011; Willy et al., 2012), tibial stress fractures (Crowell & Davis, 2011) and chronic exertional compartment syndrome (Breen et al., 2015). More specifically, it typically employs visual (Crowell & Davis, 2011) and/or auditory (Bramah et al., 2019; Diss et al., 2018) instructions or feedback strategies to elicit specific biomechanical changes whilst running. Several studies have compared the effectiveness of different feedback methods (Creaby & Franettovich Smith, 2016; Phanpho et al., 2019); however, few have considered the type and content of instructions provided. This is of particular importance as studies emanating from the performance domain routinely demonstrate that even very subtle changes in instructional language that manipulate one's focus of attention, can have significant performance implications (Schücker et al., 2014).

The constrained action hypothesis (Wulf & Lewthwaite, 2016) states that if an individual uses an internal focus of attention (IF; a focus on an aspect of bodily movement), this will affect their movement and reduce performance compared to an external focus of attention (EF; a focus on the effect of the movement). Many researchers have reported data supporting this hypothesis using a variety of tasks and outcome measures, showing that adopting an EF (e.g., run quietly) is superior to an IF (e.g., knee displacement; see review by Wulf and Lewthwaite (Wulf & Lewthwaite, 2016)). The effect that these different foci have resides in the promotion or disruption of automatic skill execution. Specifically, cues that stimulate an IF interrupt habituated, automatic motor coordination by promoting the conscious control of movement. Conversely, cues that promote an EF serve to facilitate fluent and efficient skill execution by directing attention away from bodily movement and preventing or minimising conscious control or monitoring (Wulf & Lewthwaite, 2016).

Despite widespread support for the constrained action hypothesis, a small number of recent studies conducted within the gait retraining context have demonstrated that IF cues are more effective in promoting desired technique changes (Moore, Phillips, et al., 2019; Noehren et al., 2011) and that EF cues are actually ineffective (Moore, Phillips, et al., 2019) in this setting. Further, challenges to the constrained action hypothesis perspective have been levied with researchers advocating the importance of critical self-attention in order to change or refine habitual movement patterns (Shusterman, 2009; Toner & Moran, 2015). Aside from these conflicting findings, many of the studies in this domain refer to movement efficiency and movement smoothness or automaticity, yet use outcome measures to establish causation (e.g., improved jump height (Wulf & Dufek, 2009)) rather than actually assessing these aspects of task execution. Given that the premise of running gait retraining (or indeed any retraining paradigm) is to change technique, quantifying efficiency and smoothness is essential to

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understanding task execution when applying the constrained action hypothesis (Moore, Phillips, et al., 2019). However, efficiency and smoothness are typically more challenging to quantify than simple outcome measures.

The term *efficiency* is often not defined in the motor-learning literature. This has led to efficiency being represented in a number of ways during cyclical activities, such as running (Hill et al., 2017; Moore, Phillips, et al., 2019; Schücker et al., 2014). During running, the volume of oxygen consumed ($\dot{V}O_2$) at a given speed has been used to denote changes in movement efficiency (Schücker et al., 2014). Yet, to calculate efficiency, a measure of work done and energy expended is required (Winter, 2009). As a result, *efficiency* cannot be inferred from $\dot{V}O_2$. One type of efficiency relevant for running is mechanical efficiency, which is defined as the amount of external and internal work done relative to the net energy consumed (metabolic cost whilst running minus resting metabolic cost) (Winter, 2009). It is therefore possible to improve or reduce mechanical efficiency without altering $\dot{V}O_2$, as shown with barefoot compared to shod running increasing mechanical efficiency by producing greater work done but no changes in $\dot{V}O_2$ (Divert et al., 2008). While, within the context of running, it has been demonstrated that the provision of IF cues can lead to higher $\dot{V}O_2$ compared to EF cues (Hill et al., 2017; Schücker et al., 2014), the cues provided were generalised to overall movement or feelings (e.g., IF: focus on your running movement or bodily signals such as heart rate or exertion) or the environment (e.g., EF: video of a running course). In contrast, IF and EF cues designed specifically for gait retraining purposes did not alter $\dot{V}O_2$ compared to habitual running, yet mechanical efficiency may have increased with the EF cues as the associated biomechanical changes suggested greater external work was being performed against gravity (Moore, Phillips, et al., 2019). Considering the importance of understanding these functional changes for both the individual and their performance and practitioners providing retraining services, it is surprising that very few running-related studies exploring focus of attention have assessed biomechanical variables, and to-date none have quantified mechanical efficiency. Therefore, it is not known whether the predictions of the constrained action hypothesis can be supported, that is, whether an EF elicits enhanced mechanical efficiency and an IF reduces efficiency during running.

Studies have quantified automaticity using the first-time derivative of acceleration, known as jerk (Hreljac, 2000). This has been termed fluency (Seifert et al., 2014) and smoothness (Hreljac, 2000). Theoretically, it is suggested that individuals try to minimise the magnitude of jerk of a specified end point jerk trajectory to promote smoothness (Flash & Hogan, 1985). Yet, there is limited understanding about smoothness as a control feature in running and in response to attentional cues (Kiely et al., 2019). Using the constrained action hypothesis, movement smoothness would be predicted to improve or be maintained with an EF cue in experienced runners, whilst an IF cue would be predicted to disrupt it. Modifying smoothness may be important for gait retraining as greater jerk represents greater changes in acceleration and therefore, greater changes in force being produced. Assuming mass is unchanged, from a biomedical perspective, this variation in exposure to force and acceleration may be too demanding for a runner's tissue tolerance and subsequently negatively affect injury rehabilitation. Consequently, understanding the impact an individual's focus of attention can have on movement smoothness appears important for gait retraining, both from a theoretical and practical perspective.

Few studies have investigated how to perform running gait retraining and the optimal exposure time required to modify gait. Typically, previous work assessing acute gait retraining with consistent cues in asymptomatic runners has used one short block of cue exposure during one visit (≤10 minutes) (Creaby & Franettovich Smith, 2016; Moore, Phillips, et al., 2019; Townshend et al., 2017). In addition, retention conditions in these studies are typically confounded by participants receiving instructions and/or reminders to alter their gait in line with the cued running prior to their retention run (Creaby & Franettovich Smith, 2016; Townshend et al., 2017). In contrast, research on symptomatic runners employing feedback to modify gait and reduce pain with short-term gait retraining has used multiple visits over two to 3 weeks (Chan et al., 2018; Futrell et al., 2020; Noehren et al., 2011; Willy et al., 2012). The feedback incorporates visual kinematic information as well as IF cues, but none have reported if technique changes were evident after a single visit or whether fewer visits could have achieved similar technique changes (Chan et al., 2018; Futrell et al., 2020; Noehren et al., 2011; Willy et al., 2012). Recently, van den Berghe and colleagues (Van den Berghe et al., 2020) observed greater reductions in tibial acceleration in asymptomatic runners as a result of auditory feedback after 8 minutes of exposure compared to 3 minutes. However, no retention condition was included in the study design. Given that running gait retraining increases the perceived effort associated with breathing and lower limb muscular work (Moore, Phillips, et al., 2019) and that practitioners may only see a client on a limited number of occasions, finding the minimum time required to change running technique with attentional cues has the potential to facilitate adherence to, and effectiveness of, the gait retraining programme being prescribed.

The aim of this study was to examine the effect of attentional cues on foot angle for the purposes of retraining movement. Using the constrained action hypothesis, we predicted that an EF cue would enhance mechanical efficiency by increasing the external work done, produced for the same metabolic cost and improving movement smoothness. In contrast, we predicted that the IF cue would reduce mechanical efficiency by increasing metabolic cost disproportionately to increasing the internal work done and reducing movement smoothness, and that perceived exertion would increase in line with metabolic cost. We also examined the potential application of the constrained action hypothesis for retraining movement and hypothesised that greater biomechanical changes would occur with accumulated exposure to the EF cue. Finally, we sought to explore the impact of accumulated exposure to both cues on levels of perceived exertion.

Methods

Participants

Twenty-four recreational runners volunteered for this repeated-measures experimental study and provided written, informed consent to participate. All runners were screened to ascertain their habitual foot angle at initial contact with the ground, with those demonstrating a non-rearfoot striking pattern excluded from the study. Participants were injury-free for at least the previous 6 months, undertook at least 150 minutes of moderate-to-vigorous activity a week and completed a Physical Activity Readiness questionnaire. Following screening, 20 rearfoot striking participants (females = 8; males = 12; body mass: 72.5 ± 11.8 kg; height: 1.73 ± 0.09 m; age: 32.9 ± 11.3 years) were included and randomly assigned to either an IF group or an EF group. Power analysis using our previous work ($\eta^2 = 0.251$ for foot angle at initial contact (Moore, Phillips, et al., 2019)) demonstrated that only a small number of participants were required ($n = 6$). Ethical approval for the study was obtained from the University's ethics committee.

Experimental conditions

Based on our previous work (Moore, Phillips, et al., 2019), two task-specific attentional cues designed to elicit a flatter foot at initial ground contact were developed; The IF verbal cue was "run with a flat foot" and the EF verbal cue was "run quietly". To explore participants' perceptions of conscious control of movement during each block of running (control, cued, and retention – see below for details) a questionnaire was given to participants following the completion of each block. Open and closed-ended questions were used to understand what participants focused on during each block of running, to what extent participants believed they changed their technique (5-point Likert scale) and what technique changes they perceived they had made. In addition, to ensure attention was allocated appropriately during the cued conditions, participants responded to the following question: "To what extent were you focused on the [verbal cue] when you were running?" (5-point Likert scale), and to assess focus during retention participants were asked "To what extent did you use the [verbal cue] that was provided in the three training sessions?" (5-point Likert scale). All 5-point Likert scales were anchored with: 1 "Not at all" to 5 "Very much so".

Procedures

Participants were informed that the aim of the study was to assess how individuals respond to verbal instructions; they were not provided with any indication that they should be altering their foot strike. One laboratory visit per participant was used to obtain all experimental data. Before the experiment began, participants completed a self-determined warm-up for at least 6 minutes to give them time to familiarise themselves with running on the treadmill (Life fitness, Activate series, Cambridgeshire, UK) in the laboratory (Lavcanska et al., 2005). Each participant then performed five blocks of treadmill running (control run, 3 × cued running, retention run) at a self-selected running velocity (9.4 ± 1.1 km·h^{-1}) in their own running shoes. Running blocks were 6 minutes in length with a 5-minute rest period between consecutive bouts, with the exception of the final rest period (between the final cued run and the retention), which was 20 minutes; thus, total running time equated to 30 minutes. A longer rest period was used prior to the retention run compared to between cued running blocks to act as a washout period. During the control run no verbal cues were provided allowing a participant's habitual running gait, metabolic cost and perceived exertion to be quantified. During the cued running blocks, verbal cues were provided every 30 seconds (Moore, Phillips, et al., 2019). Previous research in asymptomatic runners has typically used one cued running condition and not quantified kinematic changes across different time points (Creaby & Franettovich Smith, 2016; Moore, Phillips, et al., 2019; Townshend et al., 2017). Providing participants with multiple cued runs within the same session and measuring biomechanics during each cued run allowed us to determine the effect of accumulated time.

Metabolic measurements

Throughout each run, breath-by-breath respiratory data were recorded in 5 second epochs using an online gas analysis system (OxyconPro, Jaeger at Viasys Healthcare, Warwick, UK) and heart rate was measured using a wireless chest strap (Polar H30; Kempele, Finland). Steady-state was verified using the control run's respiratory exchange ratio (RER), which was required to be <1.0. The physiological data ($\dot{V}O_2$, RER, and HR) for the entire 6 minutes were exported and filtered with a low-pass, recursive, second-order Butterworth filter (cut-off frequencies determined using residual analysis ranged between 0.33 and 1 Hz (Moore, Ashford, et al., 2019)). The mean of each physiological measure for each participant during the final 2 minutes was calculated and any within-participant outliers (±2 SDs) for each block of running were removed; the mean was then re-calculated to represent steady-state. To determine net $\dot{V}O_2$ and volume of carbon dioxide expired ($\dot{V}CO_2$), two-minutes of quiet standing data were recorded by breath-by-breath gas analysis prior to the onset of exercise and then subtracted from all dynamic trials. Metabolic cost per unit body mass per unit distance ($ml \cdot kg^{-1} \cdot km^{-1}$) was calculated from $\dot{V}O_2$ per unit body mass per unit time ($ml \cdot kg^{-1} \cdot min^{-1}$) and running velocity to standardise across participants running at different velocities. Energy cost per unit distance ($J \cdot kg^{-1} \cdot m^{-1}$) during the final 2 minutes was computed using net $\dot{V}O_2$ and $\dot{V}CO_2$ and Brockway (Brockway, 1987) coefficients. In order to assess the sensations of central and local fatigue that may arise due to cardiopulmonary and peripheral muscular strain (e.g., lower limb) sensations, respectively, ratings of perceived central (cRPE) and peripheral (pREP) were used. Both cRPE and pRPE were recorded during the final 10 seconds of each running condition using Borg's 6–20 scale.

Kinematic measurements

Full-body three-dimensional coordinate data were recorded (Vicon, Oxford Metrics, UK; 200 Hz) during the final 2 minutes of each treadmill run and filtered using a fourth-order, low-pass Butterworth filter (14 Hz cut-off frequency determined using residual analysis). The Plug-in Gait full-body marker set (39 markers) was used to create 15 body segments: head, thorax, pelvis, thigh, shank, foot, upper arm, lower arm and hand. For limb-based data, both the left and right sides were used. The whole body's centre of mass (COM_{wb}) and segmental centre of mass positions were outputted directly from the motion analysis system. Segment masses (m_i) and gyrations (K_i) were determined according to Dempster (Dempster, 1955) inertial parameters. The total work of the whole body (W_{tot}) was computed by summing the external work (W_{ext}) and internal work (W_{int}) as outlined by Willems and colleagues (Willems et al., 1995). Using the COM_{wb} trajectory gravitational potential and translational kinetic energy (TKE) over time were computed. Gravitational potential energy was determined by multiplying the vertical displacement of the COM_{wb} within the global coordinate system by body mass and gravity (9.81 m·s^{-1}). The TKE of the COM_{wb} was determined by squaring the COM_{wb} velocity and multiplying this by half body mass. This was performed for the COM_{wb} velocity in the vertical and anterior-posterior directions. Total external energy was the sum of gravitational potential energy and translational kinetic energy. The sum of positive increments of the total external energy–time curve is the W_{ext}. Therefore, W_{ext} refers to the work required to accelerate the COM_{wb} relative to the environment. Internal energy was the sum of rotational and translational kinetic energy. Rotational kinetic energy (RKE) was determined using the following equation:

$$\boldsymbol{RKE_i} = \frac{1}{2}\sum_{\boldsymbol{i}=1}^{\boldsymbol{n}} \boldsymbol{m_i} \cdot \boldsymbol{K_i^2} \cdot \boldsymbol{\omega_i^2}$$

where n is the total number of segments, i is the segment number and ω is the segmental angular velocity, which is the first-time derivative of the segment angles. The RKE for each segment was computed and then summed to produce the total RKE. Translational kinetic energy of the segments was calculated by:

$$TKE_{s,i} = \frac{1}{2}\sum_{i=1}^{n} m_{i s,i}^{2}$$

where $V_{s,i}$is the linear velocity of the centre of mass of the i th segment relative to the COM_{wb}. Total TKE was the sum of all segmental TKE. The total internal energy was the sum of the total RKE and TKE. The sum of positive increments of the total internal energy–time curve is the W_{int} and reflects the work required to accelerate the limbs relative to the COM_{wb}. As the sum of increments represents positive work done, the time between two successive maxima needed to exceed 20 ms (Willems et al., 1995) for W_{ext} and W_{int}.

All energy and work calculations were performed for complete strides only. A stride being one left-foot contact to the next consecutive left-foot contact. Left-foot contacts and toe-offs were visually determined from a sagittal plane video recording (100 Hz) that was synchronised to the motion analysis data. Stride time was the time between each consecutive left-foot contact and stride frequency (Hz) was the reciprocal of stride time. Ground contact time was the time between left-foot contact and left-foot toe-off.

Efficiency and movement smoothness calculations

All strides during the final 2 minutes of each 6 minute run were used to compute the work done and movement smoothness. This aligned the mean work done with the mean $\dot{V}O_2$ during the same period. The W_{tot} was computed per unit body mass per unit distance ($J \cdot kg^{-1} \cdot m^{-1}$) and mechanical efficiency (%) was the ratio of W_{tot} to energy cost.

Movement smoothness was quantified using spectral arc (SPARC) length, which is independent of temporal movement scaling and is more robust to measurement noise than the log of dimensionless jerk (Balasubramanian et al., 2015). The left foot's centre of mass and COM_{wb} vertical displacement and velocity data obtained using motion analysis were inputted into the SPARC formula (Balasubramanian et al., 2015) to determine movement smoothness for the end point (foot) and whole body. An event-based segmentation procedure was implemented using the left-foot contact frames as the starting event and the subsequent left-foot contact frame as the end event. The stride smoothness components were then entered into a weighted average function to estimate the movement smoothness during the last 2 minutes of each block and a weighting of one was used. Increasing negative SPARC values correspond to reduced smoothness. A customised MatLab script was used for all computations performed on the metabolic and coordinate data.

Statistical and thematic analysis

Means (±SD) for each condition within each group were computed for biomechanical and physiological variables. These data were used in further analysis, except for number of strides which is presented for descriptive purposes only. Medians and interquartile ranges (IQRs) were computed for cPRE and pRPE. Linear mixed-effect models were used to assess performance (2×4; Group x Condition [control and cued 1st, 2nd and 3rd]) and retention (2×2; Group x Condition [control-retention]) effects. The retention effects addressed our first hypothesis, whilst the performance effects addressed our second and third hypothesis. All linear mixed-effect models incorporated a random intercept at the participant level. Estimates for the linear mixed-effects model were optimised based on maximum likelihood criterion. The F test was performed using Satterthwaite approximations of degrees of freedom to limit Type I error inflation, but maintain power (Luke, 2017). Post-hoc analysis of interactions and condition main effects were undertaken with pairwise comparisons. Log transformations of ground contact time and W_{int} were used to deal with violations of heteroscedasticity when comparing control to cued conditions. Thematic analysis (Braun & Clarke, 2006) was conducted to examine responses to the open-ended questions relating to what individuals focused on during the runs and what technique changes they believed they had made (if any). Wilcoxon rank sum tests were used to assess the closed questions that examined: 1) whether focus had been appropriately directed to the cue, 2) the perceived extent of technique change, and 3) the participants' focus during the retention run. All statistical analyses were performed using the *lmerTest, emmeans* and *effectsize* packages in R and alpha was set as 0.05.

Results

A total of 14,373 strides were analysed, with the mean number of strides per condition ranging from 153 to 166 (Table 1). Running velocity was similar between the internal and external group (9.3 ± 0.9 vs. 9.6 ± 1.3 km·h^{-1}, respectively). In terms of the analysis of the control and cued conditions, an interaction effect was observed for foot angle at initial contact ($F(3,54) = 9.861$, $p < 0.001$, $\eta^2 = 0.35$), with the IF group having a reduced foot angle in the 1st ($t = 4.418$, $p = 0.001$), 2nd ($t = 4.665$, $p < 0.001$) and 3rd ($t = 4.506$, $p < 0.001$) cued conditions compared to the control condition. The EF group's 3rd cued condition had a larger foot angle than all the IF cued conditions, but all EF conditions were similar to each other. The control and retention comparisons for foot angle did not reach significance. There was a main effect of group for stride frequency for the control and cued comparisons ($F(1,18) = 9.041$, $p = 0.008$, $\eta^2 = 0.33$) and control and retention comparison ($F(1,18) = 7.296$, $p = 0.015$, $\eta^2 = 0.29$), with the IF group having a 5.3% higher stride frequency than the EF group (Table 1). Additionally, for control and cued comparisons, there was an interaction effect for ground contact time ($F(3,54) = 3.339$, $p = 0.026$, $\eta^2 = 0.16$), with the EF group having longer contact times in the 1st ($p = 0.007$), 2nd ($p = 0.022$) and 3rd ($p = 0.016$) cued conditions compared to the control condition. All of the EF cued conditions also had longer contact times than the IF cued conditions. For the control and retention comparisons an interaction was also present ($F(1,18) = 8.849$, $p = 0.008$, $\eta^2 = 0.33$), but post-hoc tests did not reach significance.

An interaction effect for mechanical efficiency was present ($F(3,56) = 11.839$, $p < 0.001$, $\eta^2 = 0.40$; Figure 1(a)). Post-hoc tests showed the control condition in the IF group had higher mechanical efficiency than the 1st (5.6%; $t = 5.171$, $p < 0.001$), 2nd (4.1%; $t = 3.789$, $p = 0.008$) and 3rd cued conditions (4.8%; $t = 4.463$, $p < 0.001$). There were no main effects or interactions for the control and retention conditions.

Internal work had a condition effect for the control and cued comparison ($F(3,54) = 3.249$, $p = 0.029$, $\eta^2 = 0.15$), as well as control and retention comparison ($F(1,18) = 9.096$, $p = 0.007$, $\eta^2 = 0.34$). Post-hoc analysis showed the 3rd cued condition and retention condition had a higher W_{int} than the control condition (Figure 1(b)). However, interactions were identified for external work ($F(3,54) = 11.839$, $p < 0.001$, $\eta^2 = 0.27$; Figure 1(c)). The IF group produced less external work in the 1st cued condition compared to the control condition ($t = 3.871$, $p = 0.006$). No differences were observed in the EF group. There were no main effects or interactions for the control and retention conditions.

Metabolic cost demonstrated a main effect for condition ($F(3,54) = 4.392$, $p = 0.008$, $\eta^2 = 0.20$), with post-hoc tests showed that the 3rd cued condition produced a higher metabolic cost than the control run ($t = -3.368$, $p = 0.007$; Figure 1(d); Table 1). There were no main effects or interactions for the control and retention conditions.

CoM and foot SPARC presented no interactions or main effects when comparing control to cued conditions or control to retention conditions. Both central and peripheral RPE had a main effect for condition ($F(4,54) = 8.450$, $p < 0.001$, $\eta^2 = 0.32$ and $F(4,54) = 4.603$, $p = 0.006$, $\eta^2 = 0.20$, respectively). Central RPE was higher in the 2nd and 3rd cued condition compared to the control condition (means(SD); 10(2), 10(2) and 9(1), respectively; $t = -3.147$, $p = 0.013$ and $t = -4.637$, $p = 0.0001$, respectively). There were no main effects or interactions for the control and retention conditions. Peripheral RPE was higher in the 3rd cued condition compared to the control condition (means(SD); 10(2) vs. 9(2) respectively; $t = -3.435$, $p = 0.006$). There was a main effect for condition when comparing control and retention conditions, with the retention condition (mean-(SD); 10(2)) having a higher peripheral RPE than the control condition ($F(1,18) = 6.472$, $p = 0.020$, $\eta^2 = 0.26$).

Focus of attention and cue interpretation

Thematic analysis of the open-ended questions revealed a clear shift in thoughts from the control condition in which participants in both groups referred to monitoring holistic elements of running (e.g., position on the treadmill and cadence), to the cued conditions, where the focus

Table 1. Means (SD) of the number of strides, biomechanical and physiological variables across groups and conditions.

			Cued experimental conditions				
Variable	Cue group	Control	1st	2nd	3rd	Retention	All conditions
Number of strides	Internal	166 (7)	169 (10	165 (16)	169 (10)	156 (34)	165 (18)
	External	154 (13)	158 (6)	156 (10)	153 (11)	153 (12)	155 (11)
Foot angle (°)	Internal	17.4 (5.2)	13.5 (5.1)^{a,b}	13.3 (4.9)^{a,b}	13.4 (5.5)^{a,b}	15.4 (5.7)	14.6 (5.3)
	External	19.4 (3.7)	20.0 (3.8)	20.4 (4.2)	21.3 (4.3)	20.7 (5.9)	20.3 (4.3)
Stride frequency (Hz)	Internal	1.39 (0.06)	1.41 (0.08)	1.42 (0.08)	1.41 (0.08)	1.39 (0.06)	1.40 (0.07)
	External	1.33 (0.06)	1.33 (0.05)	1.31 (0.08)	1.31 (0.08)	1.31 (0.08)	1.32 (0.07)^{d}
Ground contact time (s)	Internal	0.311 (0.014)	0.299 (0.019)	0.304 (0.030)	0.302 (0.029)	0.296 (0.017)	0.302 (0.022)
	External	0.318 (0.029)	0.346 (0.035)^{a,c}	0.342 (0.044)^{a,c}	0.343 (0.048)^{a,c}	0.328 (0.044)	0.335 (0.040)
CoM SPARC	Internal	−3.90 (0.16)	−4.14 (0.30)	−4.16 (0.26)	−4.09 (0.22)	−4.00 (0.23)	−4.06 (0.25)
	External	−4.04 (0.27)	−4.05 (0.35)	−4.04 (0.37)	−4.01 (0.34)	−4.05 (0.48)	−4.04 (0.35)
Foot SPARC	Internal	−5.66 (0.91)	−6.03 (0.80)	−6.06 (0.96)	−6.03 (1.06)	−6.18 (1.15)	−5.99 (0.95)
	External	−5.83 (1.34)	−6.45 (1.22)	−6.20 (0.94)	−6.29 (0.94)	−5.29 (1.51)	−6.01 (1.23)

CoM = centre of mass. SPARC = spectral arc. [a]significantly different to the control condition ($p < 0.05$). [b]significantly different to the external focus of attention 3rd cued condition. [c]significantly different to the internal focus of attention cued conditions. [d]significantly different to the internal focus of attention group.

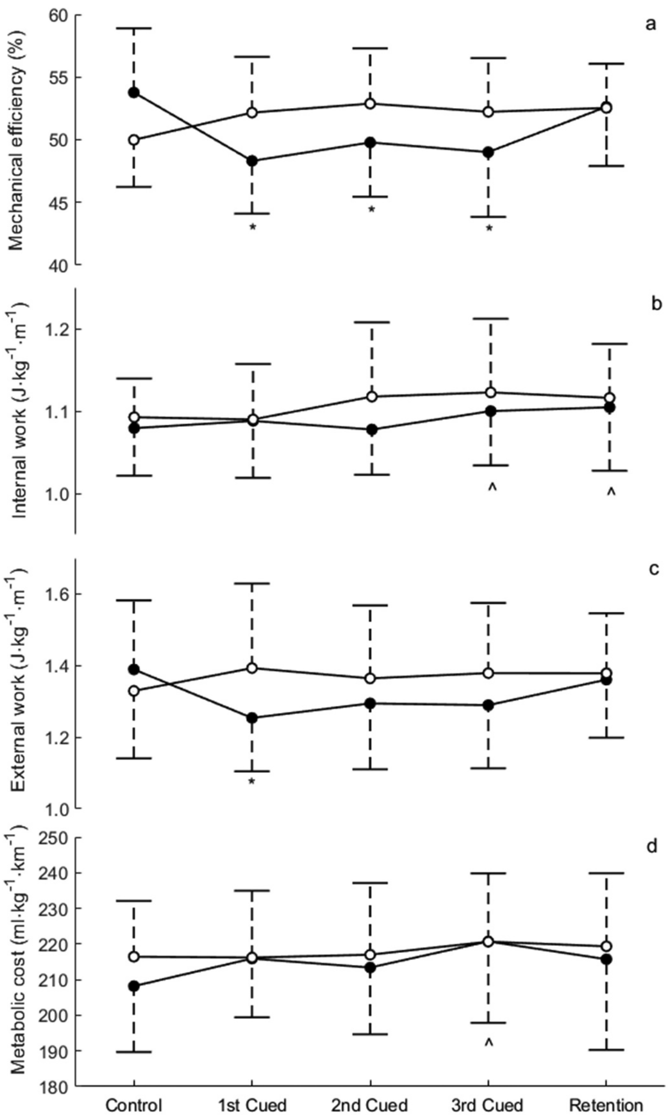

Figure 1. Means (± SD) for internal focus (IF; black circles) and external focus (EF; white circles) of attention groups during each condition for: a) mechanical efficiency; b) internal work; c) external work and; d) metabolic cost. * interaction effect. Significantly lower than the if control condition ($p < 0.05$). ^ main effect for condition. Condition significantly higher than the control condition.

shifted towards more technical aspects of running. The shifts in attention were movement control related for both groups, but more aligned with the desired change (i.e., flatter foot strike) in the IF group (e.g., "running with my foot flat to the floor"; "make the ball of my foot and my heel touch the ground at the same time") than the EF group (e.g., "Lowering my hips", " … shorten stride length and reduce flight time", "run like a ninja … "). Further, in the EF group, only three participants believed they had employed a flatter foot strike and two participants perceived that the cue had no impact on their technique at all. With regard to the retention, while some participants ($n = 4$) in the IF group maintained their thoughts about movement control generally, cued thoughts dissipated and most participants (in both groups; $n = 15$) reverted to attending to thoughts akin to those in the control condition.

Assessment of the closed questions revealed that the focus afforded to the verbal cues by the internal and external groups was not significantly different during cued running (W = 57.5, $p = 0.119$; medians: 5 and 4, respectively) and the retention run (W = 32, $p = 0.463$; medians: 2 and 2, respectively). In addition, no difference was observed regarding perceptions of technique change between the IF and EF groups (W = 52.5, $p = 0.275$; medians: 4 and 4, respectively). Finally, when combining the groups, a greater focus on the verbal cue was present during the cued conditions compared to the retention contention (W = 262, $p = 0.001$; medians: 4 and 2, respectively).

Discussion

The aim of this study was to examine the effect of attentional cues on foot angle for the purposes of retraining movement. This was the first study to quantify motor learning concepts, such as efficiency and smoothness, during gait retraining. An IF cue evoked desired changes in technique but at the cost of mechanical efficiency via reductions in external work, whilst the EF cue did not evoke desired changes in technique or affect mechanical efficiency and external work. Biomechanical changes were achieved within 6 minutes but only in the IF group; however, these changes were not preserved at retention. Perceived exertion increased with greater exposure to verbal cues.

In contrast to the predictions of the constrained action hypothesis, only the IF cue produced the desired technique response, flattening the foot angle at initial contact. This supports our previous work using IF cues (Moore, Phillips, et al., 2019) and the work of others that have successfully altered running gait using IF cues alongside biofeedback (e.g., mirrors (Willy et al., 2012), lower limb angles (Noehren et al., 2011) or metronomes with IF cues (Bramah et al., 2019; Futrell et al., 2020)). We argue that as running is a habituated movement, altering technique to alleviate pain or reduce the risk of injury will require constructive conscious control through an internal focus of attention, in a similar manner to experienced sports performers who use constructive conscious control to correct dysfunctional movement to improve their performance (Toner & Moran, 2015). Based on the collective evidence, practitioners may benefit from drawing upon the work of Shusterman rather than the constrained action hypothesis. Shusterman states that there is a need to direct attention towards our body's movements to "acquire new habits or refine or reconstruct our habitual modes of action" (p. 138) (Shusterman, 2009). However, the gait changes recorded during the cued phase were not retained in the retention condition. This contrasts with the work of Bramah and colleagues (Bramah et al., 2019); however, it should be noted that a true retention run was not implemented in their study as runners were reminded of their IF cue prior to the retention condition. In our study, short-term motor adaptation rather than motor learning was observed in the IF group. Despite the absence of long-term technique changes, runners afforded the opportunity to vary their technique when cued might be a useful rehabilitation strategy, as the runner has the ability to vary musculoskeletal load through temporary technique changes (motor adaptation) and manage lower limb load distribution. This is a similar biomechanical argument to that which has been used to explain the reduced injury risk associated with alternating footwear during running training (Malisoux et al., 2015), but with more conscious processing and specificity regarding the changes in gait. As such, we recommend that practitioners use internal focus of attention instructions to potentially evoke constructive conscious control during movement retraining and support runners to produce the desired technique changes. For example, the following cues could facilitate varying the degrees of foot angle at initial contact "Run with a flat foot", "Run on your toes", "Run on the balls of your feet" (Moore et al., 2021).

In partial support of our first hypothesis, the IF cue reduced mechanical efficiency, but by reducing external work. A reduction in external work would decrease the total work done, meaning less work is being performed for the same energetic cost and thus, mechanical efficiency is reduced. This contrasts with the theory which notes that focusing internally on the body's movement would increase internal work, but with a disproportionate increase in metabolic cost. Interestingly, the increase in internal work observed during the final cued condition mirrored the increase in metabolic cost, but this was across both groups. This means verbal instructions during gait retraining increase the work required to move body segments; however, specifically focusing on one segment (e.g., the foot) did not produce differing responses in internal work to focusing on movement effects (EF cue). It is conceivable that the reorientation of the foot segment was not large enough to uniquely affect energy requirements or that the changes to foot angle at initial contact were counteracted by other segmental changes or changes to the foot during other phases of the gait cycle. In contrast, only the IF cue reduced the work required to move the CoM relative to the environment. This global effect upon the body at a CoM (external work) rather than segmental (internal work) level was unexpected. Importantly, the magnitudes of mechanical efficiency and, external and internal work were consistent with the literature (Willems et al., 1995), whilst the change in efficiency (mean: 4.8%) is similar to that observed when running shod compared to barefoot (Divert et al., 2008). Specifically, barefoot running improves mechanical efficiency by 3.5% through increasing the work done, yet it typically promotes a flatter foot angle at initial contact than shod running (Hall et al., 2013). Different methods were used to calculate internal and external work, which may explain the opposing findings to the current study even though it induced a similar kinematic change. Regardless, in support of the constrained action hypothesis, an IF verbal cue reduced mechanical efficiency via reductions in external work to a similar extent throughout each 6 minute block of cued running.

In contrast to the predictions of the constrained action hypothesis and previous research, the EF cue did not affect mechanical efficiency (Moore, Phillips, et al., 2019) or work done. Several studies have used lower metabolic costs as an index of efficiency improvements whilst running with externally focused verbal cues, but often have failed to have a control condition (Hill et al., 2017; Schücker et al., 2014). In general, such studies have been used to indicate that an EF verbal cue improves movement efficiency. Yet, this study is the first to quantify energy and metabolic components, thus allowing efficiency to be quantified. Individuals were able to produce similar mechanical efficiencies even with 8% longer ground contact times when cued in the EF condition. The time spent in contact with the ground is an optimised and metabolically expensive phase of the gait cycle, with alterations in order of 8% expected to increase metabolic cost (Arellano & Kram, 2014; Moore, Ashford, et al., 2019). To accommodate the longer ground contact times, leg swing frequency would have had to increase to produce the observed stride frequency, which was unaltered with cueing, and explains the rise in internal work (Doke & Kuo, 2007). Of note, the EF group had higher stride frequencies that were maintained throughout all conditions compared to the IF group, likely due to non-significant but slightly faster running velocity. Therefore, whilst an EF cue did not enhance mechanical efficiency, it did appear to mitigate expected increases in metabolic cost that would accompany an increase in ground contact time.

In further opposition to the constrained action hypothesis-derived hypotheses, the provision of verbal cues did not affect running movement smoothness. Therefore, it appears that disruptions to mechanical efficiency can occur without jerkier movement execution. Given that movement smoothness is task-dependent (Balasubramanian et al., 2015), it is conceivable that the instructions used in the current study did not alter the constraints of the task to a large enough degree to induce movement intermittencies. Conversely, maintaining habitual movement smoothness may be a function of healthy gait, even with the occurrence of motor adaptation, as observed in the IF condition. This aligns with the theory that multiple constraints are driving gait selection, one being optimising movement smoothness (Hreljac, 2000). Other constraints include minimising metabolic cost (Moore et al., 2012) and potentially neural effort associated with controlling movement (Harris & Wolpert, 1998), and persevering stability (Birn-Jeffery et al., 2014). Thus, we hypothesise that the motor system is programmed to produce a certain level of smoothness during gait unless exposed to pathology (Beck et al., 2018) or long-term training (Hreljac, 2000).

Our final hypothesis was partially supported, as higher metabolic costs were produced with longer exposure to verbal cues, regardless of the type of cue provision and perceived exertion increased in line with metabolic costs. However, greater biomechanical changes were not observed with longer exposure. In fact, the flatter foot angle produced with the IF cue was achieved within the first 6 minutes. This may reflect participants setting their own target for altering foot angle and achieving this within the first block of cueing, as no numerical target was provided. These changes in metabolic cost, perceived exertion and technique are similar to previous work using one block of gait retraining lasting between five and 10 minutes (Bramah et al., 2019; Creaby & Franettovich Smith, 2016; Moore, Phillips, et al., 2019; Townshend et al., 2017). Furthermore, perceived peripheral exertion was still elevated during the retention run when biomechanical technique changes were not present. This elevated exertion may reflect the larger internal work observed during the retention compared to the control condition, meaning there is an increased mechanical demand to produce a habitual running gait following cued running that could lead to increasing perceived peripheral exertion. It could also reflect greater muscular work required when trying to alter gait during cued running, which persists after the removal of cues. Clinically, our findings suggest that once gait changes have been made, further improvements are unlikely to occur with greater exposure within a single visit when no numerical target is provided. Therefore, minimising the time exposed to gait retraining to 10 minutes may help limit the detrimental increases in metabolic cost and perceived exertion whilst still achieving the desired biomechanical changes.

Cue interpretation has been largely neglected in understanding task execution following verbal cues (Wulf & Lewthwaite, 2016). However, our findings show that movement control-related interpretations, and therefore, conscious control of movement, were present with both IF and EF cues. Additionally, both groups perceived a similar level of technique change and focus on verbal cues during the cued conditions. The varying degree and types of technical changes reported by the EF group, highlight how EF cues allow self-selected modifications to occur without imposing restrictions on which segmental changes should be made. This may explain why group-level foot angle at initial contact changes were not observed for the EF group. Different kinematic strategies to cueing may alter the load distribution through the lower limb, which may have unplanned consequences to injury risk. For example, our previous work identified a crouched running style to be exhibited when instructed to "run quietly" (EF cue), which may unintentionally increase tibial acceleration and the potential risk of tibial stress fractures (Milner et al., 2006; Moore, Phillips, et al., 2019). Ongoing gait assessments are therefore required during gait retraining to ensure self-selected kinematic adjustments are not exposing runners to unwanted outcomes. Clinically, it is also important to ascertain how an individual has interpreted the verbal cues provided to facilitate effective gait retraining. As a consequence, it may be necessary to provide additional cues or information to support an individual's understanding of the instructions provided.

One limitation of the study, from an ecological perspective, is that standardised verbal cues were provided throughout in a laboratory setting. However, this approach ensured a controlled test was conducted, clinically verbal cues are likely to be adjusted based on individual interpretation. This is supported by the thematic analysis reported here. To calculate mechanical efficiency, assumptions were made regarding energy transfer between segments. Methodological issues regarding mechanical efficiency calculations are explained in detail by Winter (Winter, 2009) and Willems et al (Willems et al., 1995), but it is acknowledged that the method used in this study assumes no transfer of energy between segments when calculating internal work. Nevertheless, by quantifying internal and external work, in addition to metabolic cost, this study has provided an important step towards understanding the application of the constrained action hypothesis and changing task execution. Finally, only short-term retention was examined in our study. Whilst longer-term gait retention (1–3 months) has been investigated within healthy and injured populations, these studies have not been anchored within the constrained action hypothesis (Bramah et al., 2019; Willy et al., 2012). Consequently, further work is required using such an approach to understand the long-term retention of altered gait and the most effective way to achieve such alterations. Additionally, we theorise that developing long-term retention of altered gait would be accompanied by metabolic cost and perceived exertion reverting to levels observed during habitual running. Further, habitual mechanical efficiency may be restored following its acute disruption under IF conditions.

An internal focus of attention produced the desired technique changes at the cost of reduced mechanical efficiency, created by reducing the amount of external work done without increasing metabolic cost. Contrastingly, an external focus of attention did not lead to desired technique changes or improvements in mechanical efficiency, but did have unintended biomechanical consequences by increasing ground contact time. From an applied injury perspective, current research and findings from this study support the promotion of constructive conscious control through the utilisation of verbal cues that foster an internal focus of attention, when specific changes to a habituated movement, such as running gait, are required (Moore, Phillips, et al., 2019; Noehren et al., 2011; Willy et al., 2012). However, the study demonstrated that changes to technique and efficiency were not retained with the removal of verbal cues. Clinically, this means that acute gait retraining with an internal focus of attention can produce motor adaptation, which may be a useful rehabilitation strategy to facilitate varying load distribution, but to facilitate long-term gait changes multiple retraining sessions may be required. Finally, movement smoothness was unaffected by cue provision, whilst perceived exertion increased regardless of the type of focus of attention. As a result, minimising the time that individuals are exposed to gait retraining may mitigate large increases in perceived exertion.

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Author contributions

IM, KA and RM conceived and designed the study. MMR, HJ and IM performed the data collection. MMR and HJ undertook the initial processing of the data. IM analysed the data and drafted the initial manuscript. All authors provided critical comments on the final draft of the manuscript.

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