Title

Can Directed Compliant Running Reduce the Magnitude of Variables associated with the Development of Running Injuries?

Abstract

Running is one of the most popular modes of activity worldwide and provides numerous health benefits. However, impact forces associated with the foot contacting the ground have been implicated in the development of running related injuries. As such, previous studies have used various methods to alter running to reduce the magnitude of these impact forces. However it is unclear what kinematic changes facilitate this reduced loading or how loading further up the body changes. In this study, verbal direction was used to teach participants to run with a more compliant running technique. Kinetic and kinematics characteristics of each participants "normal" running technique and new "compliant technique" were measured in a fatigued and unfatigued state. Energy expenditure of each running style was also measured. Verbally directed compliant running significantly decreased (17%) vertical ground reaction force impact peaks, sacral (41%) and head (28%) impact accelerations, and increased energy expenditure (21%), in comparison to normal running. Findings suggest that verbally directed compliant running may reduce the magnitude of variables associated with the development of running injuries.

Key words

Gait-retraining; Impact accelerations; Kinematics; Kinetics

INTRODUCTION

Running is one of the most prevalent and accessible modes of physical activity. Data from the USA suggests that those regularly participating in running as a physical activity has increased by 10% between 2010 and 2012, reaching in excess of 35 million (27). It is well established that physical activity has important cardiovascular and musculoskeletal health benefits (35). However, between 19-80% of runners sustain a running related injury within a one-year period (33).

Collision with the ground during running generates high impact forces that travel through the foot and up the musculoskeletal system. These forces, measured via external force transducers or tibial mounted accelerometers, have been implicated in the development of running injuries (10, 23). Given the high incidence of running related injuries, the positive health benefits associated with running, and the detrimental health effects of inactivity, developing a method of reducing running injuries is a priority.

To date, a number of studies have examined the effect of altering running technique to reduce impact loading, and have displayed positive results (reductions in peak tibial impact accelerations of 17-60%) (3, 5, 7, 9, 20). These changes in running style have been induced via various mechanisms such as technology driven real-time feedback (using an accelerometer) in visual (3, 5, 7), and audio formats (40), and via verbal feedback (8, 22). These studies demonstrate acute changes only, however recent evidence suggests that gait alterations introduced via acceleration-based feedback, are retained at a one-year follow up (1). Creaby et al (7) demonstrated that verbal feedback was equally effective at reducing peak tibial impact accelerations as visual accelerometer-based feedback following acute bouts of both, suggesting that verbal feedback may be a promising low-cost solution to reducing impact loading at the tibia, thereby potentially reducing injury development. Despite the successful reduction of peak tibial impact accelerations in the aforementioned studies, it remains unclear as to what kinematic strategies are being employed to facilitate these reductions. Only one of the above-mentioned studies offers a comprehensive report of kinematic changes observed as peak tibial impact accelerations decreased (5). Clansey et al (5) reported a change from a rear-foot to a more forefoot strike pattern as a result of the acceleration-based visual feedback, with no change to hip or knee kinematics. This is perhaps surprising given that increased compliance can also be achieved with greater knee and hip flexion (17, 20); two joints that may have a greater potential to attenuate loading due to their larger muscle mass. In addition, an emphasis on lowering the centre of mass and keeping the feet closer to the ground has been shown to reduce the vertical velocity of the body at initial contact (21) and may therefore further act to reduce impact loads. This may point to a potential benefit of directing runners verbally, as the runner can be guided to specific desirable running style adaptations, that may not be identified when adopting a more self-discovery approach to adapting running technique, such as accelerometer-based real-time feedback. Furthermore, none of the aforementioned studies have examined the effect of a more compliant running style on loading further up the body (such as at the sacrum), which may be important, as transmission of impact from the tibia up the body has been implicated in tibial and femoral stress fractures (22).

Since a change in running style may influence energy expenditure and running economy, it is important to determine how a change to the proposed more compliant running style may influence these measures. This has a practical implication in that the likelihood of a person adopting the suggested compliant running style may be affected by these responses. Clansey et al (5) reported no effect on energy expenditure, while McMahon et al (20) reported increases of up to 50%. The difference is likely to be related to the different running adaptations employed. Clansey et al (5) induced predominantly foot orientation changes, while McMahon et al (20) induced more hip and knee adaptations.

Finally, given that fatigue is common in running, the effect of fatigue should also be considered when examining the effect of altering running style. This is important for two reasons. Firstly, if an increase in energy expenditure is evident it has implications for time to fatigue and calorific expenditure. Secondly, fatigue has been shown to increase the magnitude of impact accelerations in normal running (4) and in drop jump performance (24), but it is unclear what effect fatigue has on a compliant style of running.

This study therefore aimed to examine the effect of a verbally directed compliant running style on impact accelerations, ground reaction forces, joint moments, and kinematics in both fatigued and unfatigued conditions. Secondly, this study aimed to examine the influence of this verbally directed compliant running style on energy expenditure. It was hypothesised that directed compliant running would reduce impact accelerations at the tibia, sacrum, and head, reduce vertical ground reaction forces and joint moments, increase knee and hip flexion, and increase energy expenditure, in comparison to normal running. Furthermore, it was hypothesised that all kinetic variables would increase as a result of fatigue.

METHODS

Participants

Twelve healthy, male participants between the ages of 18-31 were recruited from a university population (height, 177 ±6.5cm; mass, 78 ±6.5kg). All participants had been involved in running activities for greater than 6 months, took part in running activities at least three times a week, and completed a running distance of greater than 10 km per week. Only participants with a heal strike running action, and who had no previous experience of compliant running strategies were included. Participants were excluded from the study if they had a lower limb injury in the previous six months, or if they ran barefoot or in minimalist footwear, as this was considered a compliant strategy. Therefore only traditionally shod runners were examined. Informed consent was obtained from all participants in accordance with university guidelines, and Dublin City University's ethical committee granted ethical approval.

Experimental Approach to the Problem

Involvement in the study required participants to visit the biomechanics laboratory a total of five times which involved three 30-minute familiarization sessions and two 1 hour visits to complete the experimental protocol (figure 1). Three weeks before the experimental trials began, participants were provided with verbal direction on how to run using a compliant running style on three occasions. For the purpose of this research compliant running is defined as running with increased knee and hip flexion, reduced vertical oscillation, and with no change to foot strike (maintaining a heel strike). To achieve this, participants were instructed to "drop their hips slightly, to keep their feet close to ground (reducing aerial phase of gait), and to run with more flexed knees as naturally as possible". Instruction sessions increased in duration from 8 minutes of running in week 1, 10 minutes in week 2, and 12 minutes in week 3, and participants were required to practice compliant running a minimum of two times between each session for the same duration as their last supervised instruction. An attempt to monitor these unsupervised practice sessions was made by asking each participant to fill out a diary detailing the duration of each practice session and how they felt (represented by a Rating of Perceived Exertion [RPE] value). If participants could not adequately perform the required compliant technique within three practice sessions, further practice was performed until competency was reached. Competency was subjectively judged by the researcher (COC), and was accepted if appropriate technique was maintained for 8 minutes treadmill running at 8km/hr. Of the 12 participants, 2 required one additional practice session. At the end of each familiarization session a self-selected pace, deemed as each participant's normal running pace, was determined. This was defined as a pace that participants could comfortably run at for 30 minutes. To do this, each participant was asked to start running on the treadmill and speed was increased every minute until a pace was reached that participants considered their normal running pace. This was completed for both compliant and normal running styles. Each participant's self-selected pace was determined during the familiarization phase by taking an average of the paces they selected at each supervised familiarization session. This speed was then used for running trials where kinetic and kinematic data were collected.

All experimental trials were completed after the familiarization phase. Compliant running and normal running techniques were examined on separate days, with one week between trials, and in random order. Participants were asked to refrain from vigorous exercise for 24hrs prior to each testing day, to wear the same running shoes for each test, and to follow the same pre-test nutrition routine. Both tests were carried out at the same time on different days. For both the compliant and normal running trials participants completed a 15-minute self-selected warm-up followed by the following measurements: over-ground motion analysis, running economy, fatigue trial, and fatigued over-ground motion analysis.

Figure 1: Schematic of Experimental Design

Experimental Procedures

Motion Analysis

Motion analysis was used to determine differences in joint moments, ground reaction forces, and joint kinematics between running conditions (compliant versus normal; fatigued versus non-fatigued). In contrast to the analysis of peak impact accelerations and running economy (detailed below), the motion analysis assessment was completed over ground (non-treadmill) in order to collect ground-mounted force plate data. This process was completed both before and after the fatigue trial described in the next section.

This involved five 25-meter runs at a self-selected pace, which was determined in the familiarization phase of testing. Running speed was measured using speed gates (Bower Timing Systems, CM L5 MEM, Salt Lake City, Utah, USA) set over 20 meters. Trials were only accepted if running speed was within ± 5 % of the self-selected speed and if the participant made a right foot contact with the force plate. Successful contact was monitored via on screen viewing of 3D markers and starting position was altered to ensure full contact with the covered force plate, with no mention of its presence to avoid participants manipulating gait to target its location. Ground reaction force data were collected with a covered AMTI force-plate (1200 X 600 mm, 1000 Hz, Advanced Mechanical Technology Inc., Watertown, MA) that was longitudinally orientated and inserted level with the ground. Kinetic and kinematic information was captured using 12 infrared cameras (200Hz; ME, Vicon Oxford Metrics, UK) by tracking the position of retrofelective markers attached to 21 specific anatomical sites on each participant’s body. The 21 markers were placed on each participant in accordance with the Vicon lower body and torso Plug-in-Gait model (Vicon Oxford Metrics, UK). Marker data and force plate data were filtered using a second order, recursive, low pass, Butterworth filter (39), with a cut-off frequency of 15 Hz for both (16). An inverse dynamics approach was adopted to calculate internal joint moments(39). Variables were calculated using a custom code written in Matlab software package (R2012a, MathWorks Inc., USA). Anthropometric measurements included body mass (78 ± 6.5 kg), height (177 ± 6.5 cm), leg length (95.3 ± 4.7 cm), knee width (109 ± 4.4 mm), and ankle width (72.9 ± 3.6 mm). A threshold of 20 N was used to detect initial contact (>20 N) and toe-off (< 20 N) with the force plate. The vertical ground reaction force impact peak was detected using the ground reaction force data and visually identifying the first peak. All kinetic data is reported normalized to body mass. Hip and knee flexion angles are reported relative to full extension. These are reported at initial contact and at toe-off. Moments at the hip, knee, and ankle are reported as peak net moments. For each participant, data from the 5-trials was used to calculate an average value for each variable.

Fatigue Trial

An incremental running protocol was used in order to determine the effect of neuromuscular fatigue on impact loading in running. Participants began running at a self-selected pace (compliant= 10km/hr ± 1.4, normal= 12km/hr ± 1.4) and the speed was increased by 1km/hr every 4 minutes. An RPE of 17, determined as “very hard” according to the Borg scale, was chosen to determine the end of the test (24). RPE has been used widely as a tool for prescribing physiological intensities (24) during exercise and has been reported to be a valid measure for this purpose (31). Furthermore, following a similar running protocol, an RPE of 17 has been shown to be associated with increased tibial accelerations in drop jumps (24).

During the test, impact accelerations were measured under fatigued and unfatigued conditions. Two fifteen-second windows (1 minute into the test, and prior to termination at an RPE of 17 when fatigue is reached) were selected to measure impact accelerations. When measuring impact accelerations in a fatigued state, the pace was reduced to the original self-selected pace at which the test began. This was done to eliminate the effect of running speed on impact acceleration magnitude.

Impact acceleration measurement

Peak impact accelerations were measured at a sampling rate of 1000 Hz using a lightweight, a lightweight (17 g) uniaxial accelerometer (ADXL78, Analog Devices, Limerick, UK; sensitivity 38 mV/g, range ± 50 g). Accelerometers were attached to the skin at the tibia (overlying the proximal, anterior-medial aspect and aligned along the longitudinal axis of the tibia) (24), the sacrum (mid-way between the posterior superior iliac spines, aligned along the longitudinal direction of the spine)(34), and on the forehead (anterior aspect of the skull) (21). Accelerometers were fixed in position using double sided tape and prewrap (Durapore, 3M, Bracknell, UK), and secured with an elastic strap wrapped around the tibia, waist, and head, pressing the accelerometers onto the skin as tightly as comfortably allowed (34). Skin mounted accelerometers have been shown to underestimate the magnitude of impact accelerations (18), however the effect is considered to be consistent across conditions (fatigued versus unfatigued) and running style (compliant versus normal), and does not require an invasive procedure. Peak impact acceleration was defined as the maximum positive acceleration that occurred during stance, and mean values were calculated for each 15- second window described above.

Running Economy measurement

To determine the energy cost of compliant running in comparison to normal running a six-minute treadmill running economy protocol was used (5). This involved each participant running sub-maximally, in metabolic steady state conditions. For the duration of this test participants ran at a pace of 8km/hr. This speed was selected as it has previously been demonstrated to produce steady state conditions for both compliant and normal running (30). Even at this slow speed participants were judged to be running based on the observation of a flight phase (subjectively determined). The oxygen cost of running and running speed have a linear relationship with a strong correlation (r=0.92) once steady state is maintained, thus differences in oxygen consumption and energy expenditure found at 8km/hr should be representative of differences at faster and slower paces (12). For the duration of the six minute run the treadmill was set to a 1% gradient level (to account for wind resistance), which is suggested to most accurately reflect oxygen cost of outdoor running (15). Steady state data was averaged over the last two minutes and the standard Weir equation (36) was used to calculate energy expenditure.

Statistical Analysis

Multiple 2 (Compliant Vs. Normal running) * 2 (fatigued Vs. unfatigued) repeated measure ANOVA's were employed to examine the effect of running style and fatigue on impact accelerations measured at the tibia, sacrum, and head, as well as other kinetic and kinematic variables. Furthermore, in order to determine the effect of the compliant running style on O_2 consumption and energy expenditure, multiple-paired sample t-tests were completed. An alpha value of $p< 0.05$ was used to indicate statistical significance. All results are presented as means with standard deviations. Normality of data was examined using the Shapiro-Wilk test for normality. Mauchleys test was used to examine sphericity. In cases where the assumption of sphericity was violated a Greenhouse-Geisser correction was employed.

RESULTS

Peak Impact Accelerations

Statistical analysis revealed that all data were normally distributed. There was no significant interaction effect between running style and fatigue for peak tibial impact accelerations (p = 0.21, partial eta squared = 0.17), and examination of main effects indicated no significant difference for either running style (p = 0.39, partial eta squared = 0.08), or fatigue (p = 0.42, partial eta squared = 0.074) (Figure 2). Similarly, there was no interaction effect between running style and fatigue for peak sacral impact accelerations (p = 0.22, partial eta squared = 0.16), however main effects indicated significant differences for both running style (p = 0.02 partial eta squared = 0.49 normal > compliant by 41%) and fatigue (p = 0.005, partial eta squared = 0.61, fatigued > unfatigued by 28%)(Figure 3). A similar pattern was observed for peak head impact accelerations with no interaction between running style and fatigue observed (p = 0.17, partial eta squared = 0.22), however main effects identified significant differences for both running style (p = 0.03, partial eta squared = 0.48 normal > compliant by 28%) and fatigue (p = 0.03, partial eta squared = 0.46 unfatigued > fatigued by 12%)(Figure 4).

Figure 2: The effect of running style and fatigue condition on peak tibial accelerations (Mean + Standard deviation).

Figure 3: The effect of running style and fatigue condition on peak sacral accelerations (Mean + SD) (* indicates a significant main effect for running style and for fatigue, p <0.05).

Figure 4: The effect of running style and fatigue condition on peak head accelerations (Mean + SD)(* indicates a significantly greater values for normal running and unfatigued running, p<0.05).

Kinetics and Kinematics

There was no significant interaction effect between running style and fatigue for any of the kinematic variables measured via motion analysis. However, there was a significant main effect of running style for hip flexion at heel-strike (P = 0.001, compliant > normal by 19%) and toe-off (P = 0.02, compliant > normal by 26%), with no significant main effect of fatigue for either. Similarly, knee flexion demonstrated a significant main effect for running style at both heel-strike (P < 0.001, compliant > normal by 52 %) and at toe-off (P < 0.001, compliant > normal by 19%), with no significant main effect of fatigue for either. There was no significant interaction effect between running style and fatigue for vertical ground reaction forces, peak plantar flexor moments, peal knee extensor moments, or peak hip flexor moments. However, there was a significant main effect of running style for vertical ground reaction forces (p = 0.001, normal > compliant by17%), peak plantar flexor moments (p < 0.001, normal > compliant by 43%), peak knee extensor moments (p = 0.03, normal > compliant by 49%), and for peak hip flexor moments (p = 0.04, compliant > normal by 52%). None of the joint moments displayed a significant main effect for fatigue. Table 1 displays results for the main effect of running style only.

Table 1: The effect of running style on kinetics and kinematics

Energy Expenditure

Statistical analysis revealed a significant effect of running style on calories expended per unit time (Kcal.kg^{-1}.min^{-1}) (T = 2.64, p = 0.02 compliant > normal by 21%) (Figure 5), and oxygen consumption per unit time ($\dot{V}O_2$ /ml/kg/min) (T = 2.55, p = 0.03, compliant > normal by 24%) (Figure 6).

Figure 5: The effect of running style on calories expended per unit time (Mean + Standard deviation) (* indicates a significant difference between running styles, p<005).

Figure 6: The effect of running style on Oxygen consumption (* indicates a significant difference between running styles, p<0.05) (Mean + Standard deviation).

DISCUSSION

The present study sought to investigate the effect of directed compliant running on impact accelerations, joint angles, and joint moments under both fatigued and unfatigued conditions and to determine the energy cost of this running style in comparison to normal running.

Our results indicate that verbally directed compliant running significantly decreased (17%) vertical ground reaction force impact peaks (vGRF), sacral (41%) and head (28%) impact accelerations, knee extensor moments (49%), and ankle plantar flexor moments (22%), in comparison to normal running. Vertical Ground reaction force impact peaks have been prospectively (10) and retrospectively (23) implicated in the development of running related injuries. Thus, a reduction of 17% associated with compliant running may decrease the overall risk of injury development. Furthermore, Edwards et al (2) suggests that small decreases in load may result in significant increases in the number of impacts required before bone tissue failure. Therefore, the observed decrease in ground reaction forces in compliant running may increase the number of loads required to cause stress fracture occurrence, and reduce the risk of injury. The reduced sacral and head accelerations may serve to further protect the body from injury as they have been implicated as factors associated with the development of lower back pain, osteoarthritis, headaches, and degenerative joint change (6, 37). Compliant running displayed smaller extensor moments at the knee (49%), and smaller plantar flexor moments at the ankle (22%). Increased joint moments result in increased loading across a joint (39), and thus may give a representation of the likelihood of injury development. It has been suggested that knee and ankle joint moments contribute largely to the magnitude of tibial contact forces and bone bending moments, both of which have been implicated in the development of tibial stress fractures (14, 28). Furthermore, Stefanyshyn (32) reported that increased knee moments resulted in increased stress within the patella-femoral joint leading to pain and the possible development of patella-femoral syndrome. Similarly, knee extensor moments have been implicated in contributing to the magnitude of Patella femoral joint stress (38). Hip flexor moments were shown to be significantly higher (52%) in compliant running than in normal running. This is likely due to an increased demand on the hip flexors to maintain the more compliant mechanics and may therefore increase injury risk at this location. Injury risk may be minimised by a slow and gradual transition from normal running to the more compliant style, allowing time to adapt to the increased demands, however this is currently unknown. This style may therefore not be a viable method for reducing loading in participants with previous injury to the hip. It should also be noted that only vertical ground reaction forces were examined in this study, thus it is possible that compliant running may have resulted in changes to the magnitude of reaction forces experienced in the other two planes. In addition, although 'compliant running' was completed at a slower running speed than 'normal running' (10 km.hr^{-1} Vs. 12 km.hr^{-1}), the changes reported for vertical ground reaction force are larger than previously reported for speed alone (25). Furthermore, large changes in velocity have previously been shown to have no effect on impact accelerations at the head (29). Therefore, compliant running may have reduced loading variables independent of speed, however future studies should include a matched speed to offer further clarity. Overall it appears that a verbally directed compliant running style may reduce a number of loading variables in comparison to normal running.

The principles of biomechanics indicate that reduction of any force or load results from manipulation of the impulse momentum relationship [$F = (m . \Delta v) / \Delta t$]. It is therefore likely that the observed reduction in the loading variables mentioned above is due to either a decrease in effective mass, a decrease in change of velocity, an increase in the time interval over which this interaction occurs, or a combination of each.

Increasing knee flexion at foot-strike (as was directed in this study) results in the body being split into different segments that are accelerated/decelerated as separate bodies. This causes a decrease in effective mass for each segment, with larger amounts of flexion resulting in smaller effective masses (11). Given that ground reaction forces are proportional to the mass they act on, this reduction in effective masses may act partly to explain the observed decrease in vertical ground reaction force impact peaks, and sacral and head impact accelerations. Furthermore, given that the vertical ground reaction force will, in part, determine the magnitude of joint moments, this may also partly explain the reduction in knee extensor and ankle plantar moments observed during compliant running. Increased knee flexion at foot strike has also been associated with a reduction in vertical landing velocity and an increase in contact time (20), which may further explain the observed decreases in the above loading variables. It is important to note that although maintenance of heel strike was required to determine compliant running competency, foot strike was not measured as an outcome variable. Therefore it is possible that participants may have shifted towards a midfoot strike, which may have also contributed to a reduction in loading.

There was no significant difference between compliant and normal running for peak tibial impact accelerations. Given the observed decrease in vGRF, peak sacral impact accelerations, and head impact accelerations, a significant decrease in tibial loading was also expected. It should be noted that in cases where large manipulations of knee angle occur, caution should be used when interpreting tibial acceleration data. As explained above, an increase in knee flexion at impact results in numerous alterations to the kinetic and kinematic characteristics of running that result in a decrease in loading, and therefore segmental accelerations. However, when a large amount of knee flexion occurs it becomes significantly easier to decelerate the tibia, due to a large reduction in effective mass (11). Therefore, despite the fact that a reduced effective mass will decrease loading (mass is proportional to force), this reduction in effective mass will also cause an increase in acceleration. This indicates that in cases where large changes to knee angle occur, peak tibial impact acceleration values may be artificially inflated, and may not be entirely representative of tibial loading. This is supported by McMahon et al (20), where altering knee angle to 60° increased tibial acceleration values relative to normal running by 20-100%.

In contrast to the peak tibial acceleration results of the current study, a number of studies have examined the effect of altering running technique to a more compliant style by employing real-time accelerometer based biofeedback, both in a visual format (3, 5, 8, 9) and in an audio format (40), and have demonstrated significant reductions in peak tibial impact accelerations (ranging from 17-60%). Given that the acceleration feedback in these studies was provided from a tibial mounted accelerometer, it is likely that participants avoided large manipulations to knee angle, as this would artificially inflate tibial acceleration values (as explained above). However joint kinematics were only reported in one of the above studies. Clansey et al (5) observed no change to hip or knee kinematics. This supports the notion that providing real-time feedback from a tibial mounted accelerometer may prevent large manipulations to knee angle, and thus may explain the above differences in peak tibial impact acceleration results.

Previous research has also indicated that verbal feedback can successfully reduce peak tibial impact accelerations (24%) (7) . Although joint kinematics were not measured, it is possible that the observed difference in tibial acceleration reduction (in comparison to this study) is due to the nature of the feedback. Creaby et al (7) directed participants to “run more softly” and make their foot strikes “more quiet” whereas the current study directly guided participants to a position of increased knee flexion. Therefore, it is possible that participants in the Creaby et al (7) study did not make large alterations to knee angle, and subsequently did not observe artificial inflations to tibial accelerations as proposed in the current study, and explained above.

At the sacrum impact accelerations in a fatigued state were found to be greater than unfatigued accelerations by 28%, which is in agreement with numerous studies that report an increase in the magnitude of impact loading under fatigued conditions in normal running (4, 34). This may be explained by a reduction in the functional capacity of muscle associated with neuromuscular fatigue, which results in a diminished ability to attenuate impact accelerations (24).

However, accelerations measured at the head were significantly lower by 6% under fatigued conditions, which does not agree with the above-mentioned literature. A possible explanation is that somewhere between the sacrum and the head, there was an effect of increased localized muscle fatigue, which according to Flynn et al (13) causes an decrease in the force-generating capacity of the muscle (as a result of peripheral fatigue mechanisms) and subsequently a decrease in muscle tension and stiffness. This decrease in stiffness increases the muscles ability to attenuate impact accelerations, and may therefore be responsible for the greater impact accelerations found under unfatigued conditions in comparison to fatigued conditions at the head. However, localised fatigued was not measured and therefore cannot be confirmed.

It is important to note there was no interaction effect for fatigue and running style for tibial, sacral, or head peak impact accelerations, indicating that compliant running responded in a similar fashion to normal running under conditions of fatigue.

There was no significant effect of fatigue on ground reaction forces or joint moments, which is surprising given the effect of fatigue on impact accelerations (during treadmill running). Unfortunately, it is not possible to make conclusions based on these findings as an excessive amount of time occurred between fatiguing trials (on the treadmill) and motion analysis (over-ground). This increased time was due to difficulties with removing accelerometers and placing the 21 retrorefelective markers required for motion analysis. This did not influence impact acceleration values as accelerometers were attached for the duration of the fatigue trial on the treadmill.

In agreement with McMahon et al (20), compliant running was found to significantly increase energy expenditure (Kcal.kg^{-1}.min^{-1}) by 21% in comparison to normal running. Although McMahon recorded increases of up to 50%, this magnitude of increase was not present in all of their participants. In the present study, compliant running also displayed an increased oxygen cost of 24%, further supporting that adopting a more compliant running style may increase energy demands of running. These findings are in contrast to that of Clansey et al (5) who reported no significant change to running economy following a visual biofeedback protocol that reduced peak tibial impact accelerations. This may be explained by differences in kinematic strategies employed. The current study made large alterations to knee and hip angles, which reduced impact accelerations, but likely acts to decrease the ability to effectively utilise the stretch shortening cycle, thereby increasing energy expenditure. In comparison Clansey et al (5) displayed no change to hip or knee kinematics, but instead observed a shift to a more forefoot strike. Alterations in foot strike pattern have previously been shown not to influence running economy (26).

This increase in running expenditure may limit the use of compliant running as a possible running style during performance events. However, increased energy expenditure may yield greater health benefits than normal running, and may therefore be a useful tool for weight loss. This is due to the fact that for the same time period and running at the same pace, compliant running may expend more energy than normal running. For example, a run that burns 600 kcal employing a normal running style would burn 744 kcal using the compliant running style.

Increasing energy expenditure by 1000 kcal a week has been suggested to increase life expectancy by 20% (35), and an average of 2000 kcal expended during physical activity (a week) is associated with a decrease in morbidity and mortality of 20-30% (19). Employing compliant running mechanics may make it easier to reach these targets. However, it is possible that the increased effort associated with compliant running may result in a reduced running time and may therefore negate any potential health benefits.

PRACTICAL APPLICATIONS

Employing compliant running mechanics via verbal instruction results in a decrease in variables associated with the development of running injuries. However, it is currently unclear if compliant running influences the force experienced in the anterior-posterior, or medial-lateral planes. This should be investigated before the generalisability of compliant running, as an injury prevention tool, can be determined. Furthermore, compliant running appears to increase loading at the hip and could potentially increase injury risk at this location. A gradual and progressive transition to a more compliant style may minimise this risk, but without further study this is currently unknown. In addition, this change to compliant mechanics appears to be associated with an increased energy cost. Therefore, this style does not appear to be beneficial from a performance perspective, however, provided the increased energy cost does not reduce the amount of time spent running, compliant running may offer additional health benefits due to increased calorie expenditure. Finally, generalizations from the current study are limited both by sample size and by a single gender inclusion criterion. This may be particular important given that a lot of the current literature examining impact forces during running has focused on female athletes (23). Despite this, the data presented provides an interesting insight into how a verbally directed compliant running intervention may alter an individuals running style, and thus, warrants further examination.

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