Increasing cadence with a metronome and running barefoot changes the sagittal kinematics of the lower limbs and trunk.

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ABSTRACT

The purpose was to compare two non-laboratory based running retraining programs on lower limb and trunk kinematics in recreational runners. Seventy recreational runners (30 ± 7.3 years old, 40% female) were randomised to a barefoot running group (BAR), a group wearing a digital metronome with their basal cadence increased by 10% (CAD), and a control group (CON). BAR and CAD groups included intervals from 15 to 40 minutes over 10 weeks and 3 days/week. 3D sagittal kinematics of the ankle, knee, hip, pelvis, and trunk were measured before and after the retraining program, at comfortable and high speeds. A 3 × 2 mixed ANOVA revealed that BAR and CAD groups increased knee and hip flexion at footstrike, increased peak hip flexion during stance and flight phase, decreased peak hip extension during flight phase, and increased anterior pelvic tilt at both speeds after retraining. In addition, BAR increased ankle plantar flexion at footstrike and increased anterior trunk tilt. Both retraining programs demonstrated significant moderate to large effect size changes in parameters that could reduce the mechanical risks of injury associated with excessive knee stress, which is of interest to coaches, runners and those prescribing rehabilitation and injury prevention programs.

KEYWORDS: mobile app; long-term usage; step rate; unshod; running form.

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INTRODUCTION

Endurance running is an activity that has become widespread among the recreational population with the aim of improving health and personal performance (1,2). However, the annual incidence of running-related injuries can rise to 74% among long-distance runners (3–5). Excessive knee loading, and high vertical and horizontal impact forces have been associated with running-related injuries such as knee injuries (6,7), which are common among recreational long-distance runners (8). Running retraining is a process of learning a new running motor pattern, which has been associated with improved performance and injury prevention and is often included in rehabilitation programmes (9). A fundamental purpose of running retraining is to modify a motor pattern associated with a potential risk of running-related injury due to overuse, which is often considered to be a faulty motor pattern.

Increasing cadence has been proposed as a method for running retraining that could be integrated into a non-laboratory setting through the use of a mobile metronome application (10,11), and has been suggested to reduce impact forces and knee loading (12–14). Furthermore, this reduction in impact forces and knee loading has been associated with changes in lower limb kinematics, such as an increase in knee flexion at footstrike or a decrease in knee flexion during stance phase and ankle dorsiflexion at footstrike (10–12,14). For example, a two-week retraining program that increased cadence by 10% was shown to reduce foot and ankle angles at footstrike, impact forces and anterior trunk tilt, but no changes were found in knee and hip flexion (14). However, reduced hip flexion at footstrike was found to be an immediate effect of a 10% increase in cadence under laboratory conditions (15). After 12 weeks of field-based retraining using 10% increased cadence feedback, participants reduced impact forces, foot angle at footstrike, and peak knee flexion during stance phase (11). A reduction in peak knee flexion has been shown to be a useful predictor of a reduction in knee loading (12).

Barefoot running has also been considered as an non-laboratory retraining alternative that promotes impact attenuation, which influences changes in lower limb kinematics (16–21) and has been hypothesised to reduce the risk of injury (16,22,23). Some of the kinematic indicators associated with a reduced risk of injury were reduced ankle dorsiflexion at footstrike, increased knee flexion at footstrike and reduced peak knee flexion at stance (16–21). An 8-week barefoot running program found a subgroup of responders who reduced impact forces and ankle dorsiflexion (18). However, two other fully immersive 8-week barefoot running programs showed no significant changes in ankle dorsiflexion, cadence or stride length (24,25), nor in foot or knee kinematics (24). In contrast, a recent more conservative 10-week programme of barefoot running intervals and habitual footwear training showed a reduction in foot angle at initial contact and some changes in spatiotemporal parameters when evaluating runners running in their natural footwear condition, but lower limb kinematics were not assessed (26).

While several studies of barefoot running and studies of increasing basal cadence by 10% separately provide strong evidence of reduced impact (12–14,17,18) and changes in foot kinematics and spatiotemporal parameters, such as a reduction of ankle dorsiflexion and foot at footstrike or increase in cadence (10,11,23,25,26,12,14,16–21), the effects of long-term and out-of-laboratory retraining programs on lower limb kinematics remain inconsistent. Although the effects of barefoot running and a 10% increase in cadence on running kinematics are similar, these effects have not been compared in a homogeneous sample. Except for a recent study that evaluated the effect of increasing cadence versus barefoot running on spatiotemporal parameters, footstrike angle and prevalence of rearfoot strike in a homogeneous population over 10 weeks (26). Furthermore, as mentioned above, there is a lack of evidence on the effects of these programs on the kinematics of proximal body regions (i.e., pelvis and trunk). A more flexed trunk during running demands more hip extensor work and less extensor work during running reducing patellofemoral pain (27,28).

Therefore, the aim of this study was to compare the effects of two non-laboratory based 10-week running retraining programs on lower limb and trunk running kinematics in recreational runners at comfortable and high speeds. The groups considered were; a barefoot group (BAR) and a cadence group (CAD) who were compared to a control group (CON). The hypothesis of the present study was that running barefoot and increasing cadence by 10% might induce certain similar changes in ankle, knee, and hip kinematics.

METHODS AND MATERIALS

Experimental design

The effect of the two running retraining programs were explored through changes from baseline in the angles and joint excursions of ankle, knee, hip, pelvis and trunk, and angular velocities of ankle, knee and hip. These variables were measured at two different running speeds: i) comfortable speed (CS) which was self-selected by the runners in the warm-up, and ii) high speed (HS), which was self-selected by considering the best 5 km time in the current season of the participant, adapted from Latorre et al. (23). The participants visited the laboratory twice, at baseline (pretest) and at the end of the running retraining program (post-test). Participants were asked to not perform any heavy physical exertion for 72 hours prior to data collection.

Participants

A total of 103 runners, with no previous experience of running retraining programs, were initially recruited from local running clubs, and randomly assigned to one of three groups; BAR, CAD and CON, see Figure 1. Inclusion criteria were: all the participants were healthy, had regularly participated in running training with a minimum frequency of three sessions per week over the last two years, and had no history of injury in the previous six months that had limited their training. Exclusion criteria were, participants with cardiorespiratory diseases such as asthma, allergies, diabetes, or other cardiac pathologies were not included. A simple blind randomisation method was used to establish the experimental groups. This study conformed to the Declaration of Helsinki (2013) and was approved by the Ethics Committee at the University of XXXX (No. XXXXX). Participants were informed about the study and signed a consent form. Those participants who discontinued the study were due to injuries unrelated to the retraining programs or personal reasons.

*** FIGURE 1 ABOUT HERE ***

Instruments and procedures

Body height and weight were measured to the nearest 0.1 kg and 0.1 cm respectively (SECA Instruments, Germany), and body mass index (kg/m²) was calculated. An 8-camera motion capture system (model mvBluecougar-XD104C, Matrix Vision GmbH, Germany) operating at 100 Hz with a resolution of 2048 x 1088 pixels and the Simi Motion software v.9.2.2. (Simi Reality Motion Systems GmbH, Germany) were used to collect kinematic data. A total of 28 markers were placed on the participants according to the International Society of Biomechanics (ISB) standard (29,30). Retroreflective markers were placed bilaterally on the acromioclavicular joint, posterior superior iliac spine, anterior superior iliac spine, greater trochanter, thigh, lateral epicondyle of the femur, medial epicondyle of the femur, shank, lateral malleolus, medial malleolus, second and third metatarsal heads and the posterior surface of the calcaneus. Two additional markers were placed on the spinous process of the 7th cervical and 8th thoracic vertebra. Following the placement of all anatomical markers, the subject was asked to stand on the treadmill for a static trial which was performed to define the anatomical coordinate systems for the foot, shank, thigh, pelvis and trunk segments (29,30).

Before the running test, the participants were asked to run consistently on a professional treadmill (Woodway Pro XL, Waukesha, WI, USA) for an 8 minute warm-up at their self-selected comfortable speed (CS) and wearing their own running shoes (26). The indications for the CS condition were: “Run comfortably and non-stop at a speed that allows you to speak and breathe easily”. Once the CS was selected and the warm-up completed, participants were instructed to run consistently for 120 s and the data collection was carried out during the last 15 s. HS was defined by participants’ best 5 km pace in the current season (26). To control for the potential effect of fatigue during the running test, intensity was measured using the Borg’s 0–10 scale (31), and were reported as: very light (<2), light (2-3.9), moderate (4-6.9), vigorous (7-8.9), very hard (9-9.9) and maximum effort (10). For each participant, there was no more than one week between data collection and the intervention period (start and end).

Kinematics data processing

Visual 3D software (v6; C-Motion, Rockville, MD) was used to compute the 3D running kinematic variables. The raw data were filtered with a cut-off frequency of 8 Hz using a fourth-order low-pass Butterworth filter (32). Footstrike was defined using the technique described by Handsaker et al. (33), which was cross checked against the video recordings. This algorithm involves using the peak vertical acceleration of the marker placed on the posterior surface of the calcaneus for rearfoot strike runners, and the marker placed on the second and third metatarsal heads for forefoot strike runners. Prior to the application of the algorithm, the runners were classified according to their footstrike pattern (23). An 8-segment model of the lower limb and trunk was then constructed (29,30). Angles, velocities and excursions of the joints and segments (ankle, knee, hip, pelvis and trunk) were calculated for the sagittal plane, see Figure 2. Peak and footstrike values were obtained for joint and segment angles and velocities. Using the peak values and the footstrike values, the excursions were calculated (e.g., from footstrike to peak knee extension, or from peak knee flexion to peak knee extension, …).

*** FIGURE 2 ABOUT HERE ***

Retraining program

The retraining programs were implemented by coaches and supervised by the principal researcher with regular random visits to the track each week to check compliance. The retraining programs consisted of three retraining sessions per week with the same amount of time and similar workload, adapted from Latorre et al. (23), Table 1. The BAR group performed a progression of barefoot runs on a soft, flat, non-slip grass surface (i.e., a football pitch). The CAD group was asked to land to the beat of a metronome which increased by 10% of their baseline cadence (at pre-test) at a CS. This speed was controlled on a treadmill, or using a GPS, or by lap time running on a 400-metre track, depending on the runners' preference or ability to maintain their CS. Both groups received a weekly training diary, setting a minimum of 85% compliance, and monitoring the intensity of the sessions using the Borg scale from 0 to 10 (31). The CON group was allowed to run at a comfortable speed and perform running drills (i.e. skipping, high knees, etc.) while the BAR and CAD groups performed their retraining sessions for the same amount of time. All three groups were asked to keep their weekly volume unchanged. All participants were advised to decrease the intensity or even abandon the retraining program if pain or injury occurred. Training loads and habits were maintained by all groups.

*** TABLE 1 ABOUT HERE ***

Statistical Analysis

The distribution and homogeneity of all data were tested before analysis using the Kolmogorov-Smirnov and Levene's tests respectively, and all data were found to be suitable for parametric testing. Descriptive data were reported using the mean and standard deviations (SD). A 3 x 2 mixed model ANOVA was conducted to examine the effects of time (pre-test and post-test) and groups (BAR, CAD and CON) for each variable. Paired t-tests were used as post-hoc Bonferroni tests when a significant interaction between groups and time was detected. The significance level was set at $p < 0.05$. Additionally, effect sizes for group differences were expressed using Cohen's *d* (34) and were reported as: trivial (<0.2), small (0.2-0.49), medium (0.5-0.79), and large (≥0.8) (34). All data were analysed using SPSS, v.25.0 for Windows (SPSS Inc, Chicago, USA). To verify that there were no differences between groups at baseline, a one-way ANOVA was used for continuous variables and a chi-square test ($\chi 2$) was used for the sex variable (dichotomous).

RESULTS

Seventy out of the 103 participants who were randomly assigned underwent analysis. The retraining program was successfully completed by 79 individuals with a minimal attendance rate of 85% (BAR group = 86% and CAD group = 86%). Technical issues resulted in 9 participants being excluded from the 3D tracking analysis. During each acquisition period, none of the participants indicated a score higher than 6 out of 10 on the Borg scale while performing the running protocol. Average scores on the Borg scale over the ten weeks were 3.6 for the BAR group, 3.5 for the CAD group and 3.5 for the CON group. There were no differences for any of the demographic and training characteristics between the three groups (Table 2). Supplementary Tables 1 and 2 show pre- and post-test means and standard deviations, and mean difference 95% confidence intervals for joint and segment angles, velocities and excursions at both speeds.

*** TABLE 2 ABOUT HERE ***

A significant Time x Group interaction effect was seen for joint and segment angles at both speeds, see Table 3. Further post-hoc paired t-tests showed that the BAR and CAD groups increased knee flexion and hip flexion at footstrike, peak hip flexion during stance and flight phase, and pelvic anterior tilt (maximum and minimum) at both speeds; and decreased peak hip extension during flight phase (at both speeds) and peak knee extension during flight phase (at comfortable speed) after retraining, see Figure 3, Figure 4, and Table 4. Additionally, the BAR group increased anterior trunk tilt (maximum and minimum, at both speeds), decreased ankle dorsiflexion at footstrike (at both speeds) and peak ankle dorsiflexion during flight phase (at high speed) after retraining. In contrast, the CON group decreased hip flexion at footstrike (at high speed), peak hip extension during the flight phase (at both speeds), pelvic anterior tilt (maximum and minimum, at comfortable speed), maximum trunk anterior tilt (at comfortable speed), and minimum trunk anterior tilt (at both speeds) after the two time points.

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A significant Time x Group interaction effect was seen for joint angular velocities at both speeds see Table 3. Further post-hoc paired t-tests showed that the BAR and CAD groups increased peak ankle dorsiflexion velocity during stance phase (at comfortable speed and only for the BAR group at high speed); the CAD group decreased peak hip extension velocity during stance phase (at comfortable speed); and finally, the CON group decreased peak ankle dorsiflexion velocity during stance phase (at both speeds), and increased peak ankle plantarflexion velocity during stance phase (at high speed), after the two time points, see Table 4.

A significant Time x Group interaction effect was observed for joint excursions at both speeds, see Table 3. Further post-hoc paired t-tests, showed that the BAR and CAD groups decreased knee flexion excursion in stance phase (at both speed); the BAR group decreased hip extension excursion from stance to flight phase (at comfortable speed) and increased ankle dorsiflexion excursion during stance phase (at high speed); and finally, the CON group decreased ankle dorsiflexion excursion during stance phase (at high speed)., after the two time points, see Table 4.

DISCUSION

The main findings of this study were: i) the BAR and CAD groups increased knee and hip flexion at footstrike and stance phase, decreased knee and hip extension in flight phase, and increased anterior pelvic tilt with moderate to large effect sizes at both speeds; and ii) the BAR group significantly reduced ankle dorsiflexion and increased trunk anterior tilt with a small or moderate effect sizes at both speeds. Both retraining programs produced significant kinematic changes in lower limbs and trunk running kinematics with large effect sizes. No running-related injuries were reported during the running retraining programs. The average intensity over the 10 weeks of the retraining programs was light to moderate, between 3 and 4 on the Borg scale for both the BAR and CAD groups (31). The results of the study confirmed the hypothesis that barefoot running and a 10% increase in cadence produced similar changes in ankle, knee and hip kinematics at comfortable and high speeds, although only barefoot running retraining produced changes for the trunk. To our knowledge, this is the first study to investigate the effects of two retraining programs on lower limb and trunk running kinematics in a similar cohort of recreational endurance runners.

Previous findings from immersive programs for barefoot running or with habitual barefoot runners showed an increase in knee flexion at footstrike and at 10% of the stance, and a decrease in peak knee flexion at mid-stance, as well as a decrease in foot angle at footstrike (17,18,20,26), and a decrease in hip flexion at footstrike (35). The knee and ankle appear to be the two joints most sensitive to changes after barefoot running. Compared to previous transitions to barefoot running, our results are consistent as runners increased knee flexion at footstrike, and decreased ankle dorsiflexion. However, peak knee flexion did not decrease during the stance phase for the BAR group. The decrease in knee joint excursion from initial contact to peak flexion found at both speeds may indicate less eccentric knee movement during the first half of the contact phase due to the reduced range of motion. In addition, our results showed an increase in hip flexion, anterior pelvic tilt and anterior trunk tilt during the running cycle. This is a finding that has not been mentioned in several barefoot running programs, mainly because the kinematics of the pelvis and trunk have not been studied, focusing on the foot, ankle and knee (17,18,25). Nevertheless, and similar to our findings, a greater hip flexion, greater knee flexion and less dorsal ankle flexion at footstrike has been observed in habitual barefoot runners (16), or running with a forefoot strike (14). It should be noted that during our intervention the participants were not completely immersed in barefoot running, but combined periods of barefoot running (i.e., warm-up and cool-down) with their running training in shoes and were also assessed in shoes during data collection. Therefore, the BAR group, who completed a program of barefoot running periods with shod running, showed certain similar running performance to habitual barefoot runners when assessed with shod running.

The 10-week program based on increasing the basal cadence using a mobile metronome (CAD group) showed an increase in knee flexion at footstrike, and an increase in hip flexion and anterior pelvic tilt throughout the running cycle. These results are in agreement with those of Heiderscheit et al. (13) who found an increase in knee flexion at footstrike. And also with Lenhart et al. (12)

who also found an increase in knee flexion at footstrike, in addition to a decrease a decrease in knee flexion and ankle flexion (decrease in dorsiflexion) at mid-phase. However, we found a reduction in knee flexion excursion during stance at both speeds for the CAD group, which may help to reduce the eccentric load on the knee as this range of motion was reduced. None of these studies found kinematic changes at the hip, and they did not measure pelvic kinematics. However, Lenhart et al. (12) observed a reduction in the muscle activity of the hip extensors (e.g. gluteus maximus), and our results showed a reduction in the peak velocity of hip extension, which could be related to a lower energy generation during the propulsion phase (13). Our results also showed an increase in hip flexion during running and an anterior trunk limb, both kinematic changes were previously associated by Huang et. al. (15). after a short-term approach. They also reported less awkwardness and effort when running on non-heel strike than on heel strike, which may be related to less ankle dorsiflexion at foot strike. Comparing our results with a non-laboratory setting using a mobile metronome over 12 weeks (11), knee flexion at mid-stance was reduced, but no changes in knee flexion at footstrike or hip kinematics were found. Our findings suggest that although there are some common kinematic changes between studies. There is no predominant pattern when comparing our findings with those of other studies and further research is needed.

As mentioned above, the two 10-week retraining programs, i.e., the 10% cadence increase and barefoot running, share several kinematic changes at the knee, hip and pelvis. These common kinematic changes have been associated with a 14% reduction in peak knee force and reduced peak muscle extensor forces at the hip, knee and ankle joints (12), as well as reduced mechanical energy absorption at the knee and hip (13). Greater anterior trunk tilt, observed only after the barefoot running retraining program, has been associated with less patellofemoral joint pain (27,28) and may reduce lumbopelvic loading (36). The authors of the present study believe that pelvic anteversion can be a movement associated with anterior trunk tilt. Teng H. and Power C. observed a reduced dependence on knee extensor moments during stance by increasing hip extensor moments using a more anterior trunk tilt (28). Therefore, these changes have been suggested to be strong predictors of a reduction in patellofemoral joint loading (12,13,17,18), and the prevention of high impact injuries, such as, patellofemoral pain syndrome (37), iliotibial band syndrome (38) and tibial stress fractures (39). However, caution should be exercised in this regard as the current study did not measure kinetic parameters.

In the CON group, changes were found in the opposite direction to the two running retraining programmes. A more extended hip, posterior pelvic tilt and posterior trunk tilt with a small to moderate effect size. These kinematic changes have been observed in habitual shod runners (16). As the runners in the CON group had a short running experience (3.0 ± 1.2 years), they did not maintain their running pattern, but slightly changed some parameters towards the pattern observed in habitual shod runners, with a small effect size.

It is noteworthy that considering that both running retraining programs were performed at a comfortable speed, our results showed very similar changes in lower limb kinematics in the high speed condition. This confirms that not only was the new motor pattern acquired at the same speed as the retraining sessions, but also that the learning was transferred to higher running speeds for both retraining programs. Two studies have examined the effects of similar retraining programs performed at a comfortable and high speeds on the foot kinematics and spatiotemporal parameters (23,26). To our knowledge, this is the first study to examine changes in ankle, knee, hip, pelvis and trunk kinematics using a three-dimensional motion capture system for these two retraining programs. These retraining programs may induce adaptations in musculoskeletal structures that could affect running effectiveness in real race conditions, in the same way that short periods of barefoot running at a comfortable speed have induced changes in the shod running at a comfortable and high-speed running in these recreational runners, but further research is needed.

Finally, there are some limitations to consider. First, the effects of two 10-week retraining programs were studied in healthy recreational runners a low training load. We should be cautious about their effects on injured runners or on experienced long-distance runners with a high training load. Second, although the main focus was on sagittal plane kinematics, information on other planes of motion, ground reaction forces, joint moments or muscle activation remains unknown.

Third, the effects of two 10-week retraining programs were evaluated, but their long-term effects (e.g. a 12-month follow-up) were not assessed.

From a practical approach, both retraining programs could be useful in non-laboratory settings, using clinically feasible and simple methods to induce changes in lower limb and trunk kinematics in recreational runners towards a running pattern that could reduce the mechanical risk of injury associated with excessive knee loading. These two programs differ in certain characteristics that may lead us to choose one option over the other. Barefoot running does not require the use of a mobile phone and a digital metronome. Nevertheless, it may not be recommended for runners who need plantar insoles, and barefoot running may not be recommended for runners with certain pathologies. As for the cadence increase program, it can be used with the runner's footwear and possibly with their insoles, although this use was not evaluated in this study. Another slight difference is that the barefoot running programme included higher intensities for short periods in addition to comfortable speeds. However, the cadence based intervention does not allow for these speed changes as cadence is dependent on running speed.

CONCLUSIONS

A progression of periods of barefoot running and periods of 10% increase in cadence, both performed at a comfortable running speed, showed an increase in knee flexion at footstrike and hip angle flexion and pelvic anterior tilt during the running cycle with a moderate to large effect sizes at both comfortable and high running speeds after 10 weeks. In addition, the progression of barefoot running periods showed a significant reduction in ankle dorsiflexion at footstrike and an increase in anterior trunk tilt with a small to moderate effect size at both speeds after the 10-week retraining program. Barefoot running was slightly more effective as a running retraining program than increasing cadence with a digital metronome. This may be useful for reducing knee risk factors and increasing running efficiency, but further research is needed to explore the long-term effects.

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REFERENCES

1. Carmack MA, Martens R. Measuring Commitment to Running: A Survey of Runners' Attitudes and Mental States. J Sport Psychol. 2016;

2. Urbaneja JS, Farias EI. Trail running in Spain. Origin, evolution and current situation; natural areas. Retos. 2018;2041(33):123–8.

3. Buist I, Bredeweg SW, Lemmink K a PM, van Mechelen W, Diercks RL. Predictors of Running-Related Injuries in Novice Runners Enrolled in a Systematic Training Program. Am J Sports Med. 2010 Feb 4;38(2):273–80.

4. Daoud AI, Geissler GJ, Wang F, Saretsky J, Daoud Y a., Lieberman DE. Foot strike and injury rates in endurance runners: A retrospective study. Med Sci Sports Exerc. 2012;44(7):1325–34.

5. Hollander K, Baumann A, Zech A, Verhagen E. Prospective monitoring of health problems among recreational runners preparing for a half marathon. BMJ Open Sport Exerc Med. 2018 Jan;4(1):e000308.

6. Gaitonde DY, Ericksen A, Robbins RC. Patellofemoral Pain Syndrome. Am Fam Physician. 2019;99(2):88–94.

7. Lankhorst NE, Bierma-Zeinstra SMA, van Middelkoop M. Risk Factors for Patellofemoral Pain Syndrome: A Systematic Review. J Orthop Sport Phys Ther. 2012 Feb;42(2):81-A12.

8. Van Gent RN, Siem D, Van Middelkoop M, Van Os AG, Bierma-Zeinstra SMA, Koes BW. Incidence and determinants of lower extremity running injuries in long distance runners: A systematic review. Br J Sports Med. 2007;41(8):469–80.

9. Winstein CJ. Movement science series knowledge of results and motor implications for physical therapy learning. Mov Sci Ser. 1991;71(2):140–9.

10. Bramah C, Preece SJ, Gill N, Herrington L. A 10% Increase in Step Rate Improves Running Kinematics and Clinical Outcomes in Runners With Patellofemoral Pain at 4 Weeks and 3 Months. Am J Sports Med. 2019;47(14):3406–13.

11. Wang J, Luo Z, Dai B, Fu W. Effects of 12-week cadence retraining on impact peak, load rates and lower extremity biomechanics in running. PeerJ. 2020 Aug 24;8:e9813.

12. Lenhart RL, Thelen DG, Wille CM, Chumanov ES, Heiderscheit BC. Increasing Running Step Rate Reduces Patellofemoral Joint Forces. Med Sci Sport Exerc. 2014 Mar;46(3):557–64.

13. Heiderscheit BC, Chumanov ES, Michalski MP, Wille CM, Ryan MB. Effects of step rate manipulation on joint mechanics during running. Med Sci Sports Exerc. 2011;43(2):296–302.

14. dos Santos AF, Nakagawa TH, Lessi GC, Luz BC, Matsuo HTM, Nakashima GY, et al. Effects of three gait retraining techniques in runners with patellofemoral pain. Phys Ther Sport. 2019;36:92–100.

15. Huang Y, Xia H, Chen G, Cheng S, Cheung RTH, Shull PB. Foot strike pattern, step rate, and trunk posture combined gait modifications to reduce impact loading during running. J Biomech. 2019;86:102–9.

16. Lieberman DE, Venkadesan M, Werbel WA, Daoud AI, D'Andrea S, Davis IS, et al. Foot strike patterns and collision forces in habitually barefoot versus shod runners. Nature. 2010 Jan 27;463(7280):531–5.

17. Azevedo AP da S, Mezêncio B, Amadio AC, Serrão JC. 16 Weeks of Progressive Barefoot Running Training Changes Impact Force and Muscle Activation in Habitual Shod Runners. Fisher G, editor. PLoS One. 2016 Dec 1;11(12):e0167234.

18. Tam N, Tucker R, Astephen Wilson JL. Individual Responses to a Barefoot Running Program. Am J Sports Med. 2016 Mar 7;44(3):777–84.

19. Hollander K, Liebl D, Meining S, Mattes K, Willwacher S, Zech A. Adaptation of Running Biomechanics to Repeated Barefoot Running: A Randomized Controlled Study. Am J Sports Med. 2019 Jul 5;47(8):1975–83.

20. Bonacci J, Saunders PU, Hicks A, Rantalainen T, Vicenzino BT, Spratford W. Running in a minimalist and lightweight shoe is not the same as running barefoot: A biomechanical study. Br J Sports Med. 2013;47(6):387–92.

21. Hall JPL, Barton C, Jones PR, Morrissey D. The biomechanical differences between barefoot and shod distance running: A systematic review and preliminary meta-analysis. Sport Med. 2013;43(12):1335–53.

22. Murphy K, Curry EJ, Matzkin EG. Barefoot running: Does it prevent injuries? Sport Med. 2013;43(11):1131–8.

23. Latorre-Román PA, García-Pinillos F, Soto-Hermoso VM, Muñoz-Jiménez M. Effects of 12 weeks of barefoot running on foot strike patterns, inversion–eversion and foot rotation in long-distance runners. J Sport Heal Sci. 2019 Nov;8(6):579–84.

24. Hollander K, Liebl D, Meining S, Mattes K, Willwacher S, Zech A. Adaptation of Running Biomechanics to Repeated Barefoot Running: A Randomized Controlled Study. Am J Sports Med. 2019;47(8):1975–83.

25. Tam N, Tucker R, Astephen Wilson J, Santos-Concejero J. Effect on Oxygen Cost of Transport from 8-Weeks of Progressive Training with Barefoot Running. Int J Sports Med. 2015 Sep 2;36(13):1100–5.

26. Molina-Molina A, Latorre-Román PÁ, Mercado-Palomino E, Delgado-García G, Richards J, Soto-Hermoso VM. The effect of two retraining programs, barefoot running vs increasing cadence, on kinematic parameters: A randomized controlled trial. Scand J Med Sci Sports. 2022 Mar 9;32(3):533–42.

27. Teng HL, Powers CM. Sagittal plane trunk posture influences patellofemoral joint stress

during running. J Orthop Sports Phys Ther. 2014;44(10):785–92.

28. Teng HL, Powers CM. Hip-extensor strength, trunk posture, and use of the knee-extensor muscles during running. J Athl Train. 2016;51(7):519–24.

29. Wu G, Siegler S, Allard P, Kirtley C, Leardini A, Rosenbaum D, et al. ISB recommendation on definitions of joint coordinate system of various joints for the reporting of human joint motion--part I: ankle, hip, and spine. International Society of Biomechanics. J Biomech. 2002 Apr;35(4):543–8.

30. Wu G, Van Der Helm FCT, Veeger HEJ, Makhsous M, Van Roy P, Anglin C, et al. ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion - Part II: Shoulder, elbow, wrist and hand. J Biomech. 2005;38(5):981–92.

31. Borg GA. Psychophysical bases of perceived exertion. Med Sci Sport Exerc. 1982;

32. Chan ZYS, Zhang JH, Ferber R, Shum G, Cheung RTH. The effects of midfoot strike gait retraining on impact loading and joint stiffness. Phys Ther Sport. 2020;42:139–45.

33. Handsaker JC, Forrester SE, Folland JP, Black MI, Allen SJ. A kinematic algorithm to identify gait events during running at different speeds and with different footstrike types. J Biomech. 2016;49(16):4128–33.

34. Cohen J. Statistical power analysis for the behavioral sciences. Vol. 2nd, Statistical Power Analysis for the Behavioral Sciences. 1988. 567 p.

35. McCarthy C, Fleming N, Donne B, Blanksby B. Barefoot running and hip kinematics: Good news for the knee? Med Sci Sports Exerc. 2015;47(5):1009–16.

36. Seay J, Selbie WS, Hamill J. In vivo lumbo-sacral forces and moments during constant speed running at different stride lengths. J Sports Sci. 2008 Dec 15;26(14):1519–29.

37. Willson JD, Davis IS. Lower extremity mechanics of females with and without patellofemoral pain across activities with progressively greater task demands. Clin

Biomech. 2008 Feb;23(2):203–11.

38. Hamill J, Miller R, Noehren B, Davis I. A prospective study of iliotibial band strain in runners. Clin Biomech. 2008 Oct;23(8):1018–25.

39. Pohl MB, Mullineaux DR, Milner CE, Hamill J, Davis IS. Biomechanical predictors of retrospective tibial stress fractures in runners. J Biomech. 2008;41(6):1160–5.

TABLES

Table 1: Running volumes and speeds of the 10-week running retraining programs.

	Weeks						
	1 - 2	3 - 4	5 - 6	7	8	9	10
Barefoot retraining group	15’ CS	20’ CS	25’ CS	30’ CS	10’ CS 10’ MS 10’ CS	35’ CS	10’ CS 10’ MS 10’ CS 5’ MS 5’ CS
Cadence retraining group	15’ CS	20’ CS	25’ CS	30’ CS	30’ CS	35’ CS	40’ CS
Weekly volume by group	45’	60’	75’	90’	90’	105’	120’

Comfortable speed (CS); Medium speed (MS). In weeks 4, 6, and 9, the BAR group completed five sets of 80-meter progressive sprints.

Table 2: Demographic, anthropometric and training characteristics of runners expressed as mean (SD)

Variable	BAR (n = 23)	CAD (n = 23)	CON (n = 24)	P value
Gender (percentage)	43.5% females, 56.5% males	47.8% females, 52.2% males	29.1% females, 70.9% males	0.432
Age (year old)	31.4 (7.4)	29.4 (7.4)	29.2 (7.1)	0.543
Height (cm)	175.3 (10.4)	173.1 (7.2)	173.1 (6.7)	0.593
Body mass (kg)	73.0 (12.2)	69.8 (11.3)	70.2 (11.5)	0.598
Body mass index (kg/m^2)	23.7 (3.0)	23.2 (2.5)	23.3 (2.8)	0.795
Comfortable speed (km/h)	9.9 (1.1)	10.2 (1.0)	10.5 (0.9)	0.150
High speed (km/h)	14.0 (2.0)	14.2 (1.9)	15.1 (1.4)	0.095
Running experience (years)	3.4 (1.3)	3.4 (1.7)	3.0 (1.2)	0.457
Running’s sessions (n/wk.)	3.8 (1.0)	3.9 (1.1)	3.0 (1.0)	0.625
Workload per week (kms)	27.0 (14.2)	21.9 (11.7)	26.4 (9.3)	0.287
Competitions per year (n)	10.6 (7.9)	8.0 (6.6)	7.3 (4.3)	0.202

Barefoot retraining group (BAR), cadence retraining group (CAD) and control group (CON). $P < 0.05$

Table 3. Interaction effects Time (pre-test and post-test) *vs.* Groups (BAR, CAD and CON) of the mixed model 2 x 3 ANOVA for each variable at both speeds.

Speed	Phase	Variable	*P* value Group x time	F-test (df_1, df_2)	η^2
Comfortable speed	Stance Phase	Ankle dorsiflexion at footstrike (°)	0.049	3.163 (2, 65)	0.089 M
		Knee flexion at footstrike (°)	<0.001	8.899 (2, 65)	0.215 L
		Hip flexion at footstrike (°)	<0.001	12.507 (2, 63)	0.284 L
		Peak hip flexion (°)	<0.001	11.341 (2, 62)	0.268 L
		Knee flexion excursion (°)	0.004	5.955 (2, 64)	0.157 L
		Peak ankle dorsiflexion velocity (°/s)	0.001	8.230 (2, 62)	0.210 L
		Peak hip extension velocity (°/s)	0.043	3.304 (2, 64)	0.094 M
	Flight Phase	Peak knee extension (°)	0.003	3.609 (2, 64)	0.101 M
		Peak hip extension (°)	<0.001	16.665 (2, 63)	0.346 L
		Peak hip flexion (°)	<0.001	10.327 (2, 63)	0.247 L
	Full cycle	Maximum pelvic anterior tilt (°)	<0.001	14.347 (2, 64)	0.310 L
		Minimum pelvic anterior tilt (°)	<0.001	16.960 (2, 64)	0.346 L
		Maximum trunk anterior tilt (°)	<0.001	11.457 (2, 63)	0.267 L
		Minimum trunk anterior tilt (°)	<0.001	9.149 (2, 63)	0.225 L
		Hip extension excursion (°)	0.010	5.006 (2, 63)	0.139 M
High speed	Stance Phase	Ankle dorsiflexion at footstrike (°)	0.004	5.912 (2, 63)	0.158 L
		Knee flexion at footstrike (°)	0.001	7.963 (2, 62)	0.204 L
		Hip flexion at footstrike (°)	<0.001	9.280 (2, 62)	0.230 L
		Peak hip flexion (°)	0.001	8.212 (2, 62)	0.209 L
		Ankle dorsiflexion excursion (º)	<0.001	9.236 (2, 63)	0.227 L
		Knee flexion excursion (º)	0.012	4.740 (2, 62)	0.133 M
		Peak ankle dorsiflexion velocity (°/s)	<0.001	9.416 (2, 62)	0.233 L
		Peak ankle plantarflexion velocity (°/s)	0.021	4.140 (2, 62)	0.120 M
	Flight Phase	Peak ankle dorsiflexion (°)	0.005	5.772 (2, 63)	0.155 L
		Peak hip extension (°)	<0.001	13.999 (2, 62)	0.311 L
		Peak hip flexion (°)	0.001	8.249 (2, 62)	0.210 L
	Full cycle	Maximum pelvic anterior tilt (°)	<0.001	9.317 (2, 61)	0.234 L
		Minimum pelvic anterior tilt (°)	0.001	8.193 (2, 62)	0.209 L
		Maximum trunk anterior tilt (°)	0.001	7.542 (2, 59)	0.204 L
		Minimum trunk anterior tilt (°)	<0.001	9.218 (2, 59)	0.228 L

Barefoot group (BAR); Cadence group (CAD); Control group (CON); Degrees of freedom (df); Partial eta squared (η^2); Small effect size = 0.01 (S); Medium effect size between = 0.06 (M); Large effect size = 0.14 (L)

Table 4. Post-hoc paired t-tests for joint and segment angles, velocities and excursions before (pre-test) and after (post-test) the 10-week programs at comfortable and high speed.

Speed	Phase	Variable	Barefoot retraining group		Cadence retraining group		Control group	
			Mean difference	P value (Cohen´s d)	Mean difference	P value (Cohen´s d)	Mean difference	P value (Cohen´s d)
Comfortable speed	Stance Phase	Ankle dorsiflexion at footstrike (°)	-2.09 ± 0.91	**0.024 (0.40)**	-1.16 ± 0.87	0.186 (0.26)	0.93 ± 0.85	0.159 (0.28)
		Knee flexion at footstrike (°)	5.10 ± 1.09	**<0.001 (1.01)**	4.70 ± 1.04	**<0.001 (0.91)**	-0.44 ±1.02	0.524 (0.13)
		Hip flexion at footstrike (°)	6.53 ± 1.65	**<0.001 (0.96)**	6.76 ± 1.54	**<0.001 (1.06)**	-2.90±1.54	0.064 (0.46)
		Peak hip flexion (°)	6.28 ± 1.70	**<0.001 (0.88)**	6.21 ± 1.62	**<0.001 (1.00)**	-3.16 ±1.59	0.051 (0.50)
		Knee flexion excursion (°)	-2.98 ± 1.08	**0.009 (0.67)**	-3.50 ± 1.06	**0.002 (0.64)**	1.10 ± 1.01	0.282 (0.20)
		Peak ankle dorsiflexion velocity (°/s)	30.68 ± 9.87	**0.003 (0.50)**	20.64 ± 9.87	**0.041 (0.39)**	-21.19 ± 9.43	**0.028 (0.57)**
		Peak hip extension velocity (°/s)	8.90 ± 7.13	0.117 (0.86)	-14.53 ± 6.65	**0.033 (0.30)**	3.79 ± 6.51	0.563 (0.49)
	Flight Phase	Peak knee extension (°)	3.19 ± 0.84	**<0.001 (0.86)**	2.07 ± 0.82	**0.014 (0.60)**	0.16 ± 0.78	0.844 (0.03)
		Peak hip extension (°)	8.01 ± 1.66	**<0.001 (1.27)**	6.63 ± 1.59	**<0.001 (1.08)**	-3.65 ±1.52	**0.019 (0.48)**
		Peak hip flexion (°)	8.25 ± 1.92	**<0.001 (1.11)**	6.92 ± 1.83	**<0.001 (0.92)**	-2.39 ±1.75	0.178 (0.33)
	Full cycle	Maximum pelvic anterior tilt (°)	5.58 ± 1.40	**<0.001 (1.01)**	5.56 ± 1.36	**<0.001 (1.10)**	-3.16 ± 0.12	**0.018 (0.53)**
		Minimum pelvic anterior tilt (°)	5.82 ± 1.40	**<0.001 (1.04)**	6.00 ± 1.36	**<0.001 (1.15)**	-3.58 ± 0.08	**0.008 (0.55)**
		Maximum trunk anterior tilt (°)	2.05 ± 0.56	**0.001 (0.59)**	0.91 ± 0.54	0.094 (0.27)	-1.48 ± -0.42	**0.005 (0.41)**
		Minimum trunk anterior tilt (°)	1.57 ± 0.54	**0.005 (0.39)**	0.38 ± 0.51	0.458 (0.11)	-1.50 ± -0.26	**0.003 (0.50)**
		Hip extension excursion (°)	-1.47 ± 0.61	**0.018 (0.33)**	-0.17 ± 0.58	0.748 (0.02)	1.15 ± 0.57	0.470 (0.02)
High speed	Stance Phase	Ankle dorsiflexion at footstrike (°)	-3.19 ± 0.95	**0.001 (0.58)**	-1.41 ± 0.93	0.134 (0.29)	1.30 ± 0.91	0.140 (0.28)
		Knee flexion at footstrike (°)	4.81 ± 1.08	**<0.001 (0.85)**	3.77 ± 1.03	**0.0001 (0.71)**	-0.64 ± 1.00	0.524 (0.13)
		Hip flexion at footstrike (°)	6.55 ± 1.83	**0.001 (0.85)**	4.73 ± 1.75	**0.009 (0.66)**	-3.43 ± 0.77	**0.049 (0.42)**
		Peak hip flexion (°)	5.71 ± 1.80	**0.002 (0.70)**	4.66 ± 1.71	**0.008 (0.65)**	-3.24 ± 1.66	0.058 (0.40)
		Ankle dorsiflexion excursion (º)	1.64 ± 0.62	**0.009 (0.43)**	0.83 ± 0.61	0.164 (0.30)	-1.83 ± 0.59	**0.003 (0.53)**
		Knee flexion excursion (º)	-2.12 ± 1.01	**0.040 (0.38)**	-2.15 ± 0.96	**0.029 (0.35)**	1.47 ± 0.92	0.123 (0.24)
		Peak ankle dorsiflexion velocity (°/s)	52.44 ± 14.24	**< 0.001 (0.78)**	28.28 ± 14.24	**0.051 (0.29)**	-30.22 ± 13.60	**0.030 (0.45)**
		Peak ankle plantarflexion velocity (°/s)	-27.03 ± 15.60	0.088 (0.64)	-18.11 ± 15.24	0.240 (0.36)	31.75 ± 15.60	**0.046 (0.59)**
	Flight Phase	Peak ankle dorsiflexion (°)	-4.14 ± 1.06	**<0.001 (0.63)**	-1.13 ± 1.04	**0.278 (0.24)**	0.82 ± 1.01	0.421 (0.17)
		Peak hip extension (°)	7.66 ± 1.75	**<0.001 (1.07)**	6.13 ± 1.67	**<0.001 (1.00)**	-3.81 ± 1.63	**0.023 (0.49)**
		Peak hip flexion (°)	8.28 ± 1.87	**<0.001 (0.86)**	6.76 ± 1.78	**<0.001 (0.85)**	-1.23 ± 1.74	0.484 (0.14)
	Full cycle	Maximum pelvic anterior tilt (°)	6.69 ± 1.67	**<0.001 (1.01)**	4.16 ± 1.59	**0.011 (0.76)**	-2.82 ± 1.59	0.081 (0.46)
		Minimum pelvic anterior tilt (°)	6.98 ± 1.79	**<0.001 (0.93)**	4.48 ± 1.71	**0.011 (0.75)**	-2.46 ± 1.67	0.142 (0.32)
		Maximum trunk anterior tilt (°)	2.13 ± 0.66	**0.002 (0.51)**	1.178 ± 0.62	0.064 (0.32)	-1.21 ± 0.61	0.052 (0.30)
		Minimum trunk anterior tilt (°)	1.81 ± 0.58	**0.003 (0.36)**	0.61 ± 0.56	0.277 (0.15)	-1.54 ± 0.19	**0.006 (0.47)**

Post-hoc paired tests were used when a significant interaction effect between Time × Group was seen. Bold denotes $p < 0.05$. A positive value in the mean difference indicates an increase from the pre-test to the post-test and vice versa.

Supplementary table 1. Means (SDs) and mean difference 95% Confidence Intervals for joint and segment angles, velocities and excursions before (pre-test) and after (post-test) the 10-week programs at comfortable speed.

		Barefoot retraining group			Cadence retraining group			Control group		
Phase	Variable	Pre-test Mean (SD)	Post-test Mean (SD)	Dif. 95% CI [low, high]	Pre-test Mean (SD)	Post-test Mean (SD)	Dif. 95% C [low, high]	Pre-test Mean (SD)	Post-test Mean (SD)	Dif. 95% CI [low, high]
Stance Phase	Ankle dorsiflexion at footstrike (°)	3.7 (5.2)	1.61 (5.21)	**[0.28, 3.90]**	4.31 (4.41)	3.16 (4.56)	[-0.57, 2.89]	3.13 (4.15)	4.06 (4.24)	[-2.63, 0.76]
	Knee flexion at footstrike (°)	11.69 (4.8)	16.79 (5.25)	**[-7.27, -2.92]**	11.49 (4.79)	16.18 (5.48)	**[-6.77, -2.62]**	14.93 (4.55)	14.48 (4.94)	[-1.59, 2.48]
	Hip flexion at footstrike (°)	31.73 (7.47)	38.26 (6.06)	**[-9.84, -3.23]**	30.94 (6.40)	37.70 (6.40)	**[-9.84, -3.68]**	41.06 (5.38)	38.16 (7.08)	[-0.18, 5.99]
	Peak hip flexion (°)	32.19 (7.38)	38.47 (6.88)	**[-9.68, -2.88]**	31.01 (6.29)	37.21 (6.07)	**[-9.45, -2.96]**	41.58 (5.33)	38.42 (7.19)	[-0.01, 6.33]
	Knee flexion excursion (°)	23.66 (4.14)	20.68 (4.76)	**[-5.14, -0.81]**	23.47 (4.60)	19.98 (6.19)	**[-5.61, -0.84]**	22.89 (5.76)	23.99 (5.37)	[-0.93, 3.13]
	Peak ankle dorsiflexion velocity (°/s)	208.24 (46.01)	238.92 (73.14)	**[-50.42, -10.95]**	208.51 (56.5)	229.15 (48.38)	**[-40.38, -0.91]**	220.05 (42.27)	198.86 (30.60)	**[2.34, 40.05]**
	Peak hip extension velocity (°/s)	-277.40 (52.34)	-268.50 (39.00)	[-23.15, 5.35]	-259.37 (42.80)	-273.90 (54.19)	**[1.25, 27.82]**	-275.60 (42.54)	-271.81 (47.70)	[-16.8, 9.22]
Flight Phase	Peak knee extension (°)	8.73 (3.46)	11.92 (3.93)	**[-4.86, -1.51]**	9.88 (3.03)	11.94 (3.81)	**[-3.7, -0.43]**	13.00 (4.87)	13.16 (4.70)	[-1.72, 1.41]
	Peak hip extension (°)	-6.36 (5.92)	1.64 (7.06)	**[-11.33, -4.68]**	-6.73 (6.35)	-0.1 (5.95)	**[-9.8, -3.46]**	2.09 (8.11)	-1.56 (7.06)	**[0.62, 6.69]**
	Peak hip flexion (°)	43.67 (5.16)	51.92 (9.14)	**[-12.09, -4.4]**	42.4 (7.25)	49.32 (7.78)	**[-10.59, -3.25]**	49.86 (6.92)	47.47 (7.40)	[-1.12, 5.9]
Full cycle	Maximum pelvic anterior tilt (°)	20.79 (5.30)	26.37 (5.76)	**[2.79, 8.37]**	19.43 (5.44)	24.98 (4.66)	**[2.83, 8.28]**	26.88 (5.89)	23.72 (6.01)	**[-5.77, -0.55]**
	Minimum pelvic anterior tilt (°)	12.92 (6.07)	18.73 (5.12)	**[3.03, 8.61]**	12.73 (5.38)	18.73 (5.03)	**[3.27, 8.73]**	20.36 (6.51)	16.77 (6.59)	**[-6.19, -0.97]**
	Maximum trunk anterior tilt (°)	24.72 (3.94)	26.77 (2.99)	**[0.92, 3.17]**	23.88 (3.33)	24.79 (3.46)	[-0.16, 1.98]	26.23 (3.76)	24.76 (3.34)	**[-2.5, -0.45]**
	Minimum trunk anterior tilt (°)	19.81 (4.62)	21.38 (3.34)	**[0.49, 2.64]**	19.18 (3.55)	19.56 (3.47)	[-0.64, 1.41]	21.19 (3.11)	-19.68 (2.85)	**[-2.49, -0.52]**
	Hip extension excursion (°)	38.09 (4.60)	36.62 (4.22)	**[-2.69, -0.26]**	37.49 (4.47)	37.31 (3.92)	[-1.34, 0.97]	37.89 (4.59)	37.78 (4.47)	[0.02, 2.28]

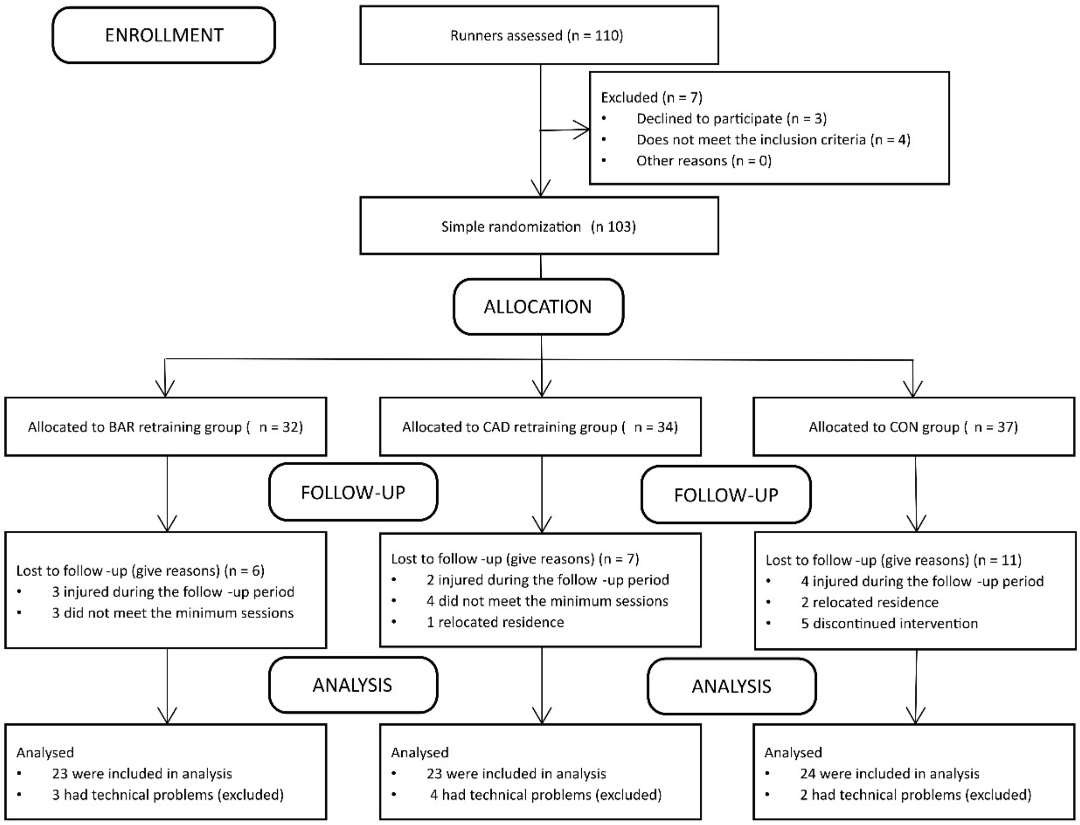
CI denotes Confidence Intervals; Bold in Dif. 95% CI denotes post-hoc paired tests by Time (pre-test *vs*. post-test) with $p < 0.05$.

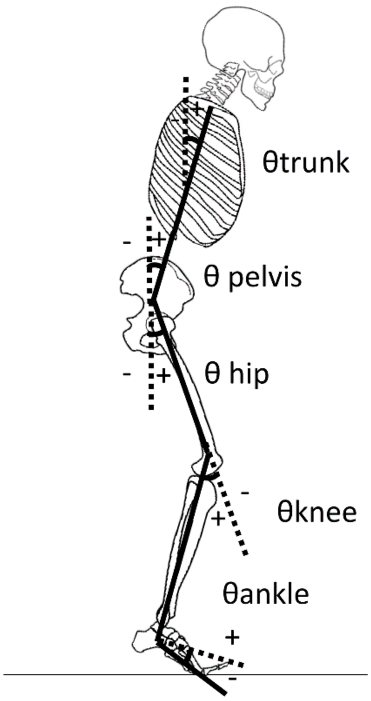
Supplementary table 2. Means (SDs) and mean difference 95% Confidence Intervals for joint and segment angles, velocities and excursions before (pre-test) and after (post-test) the 10-week programs at high speed.

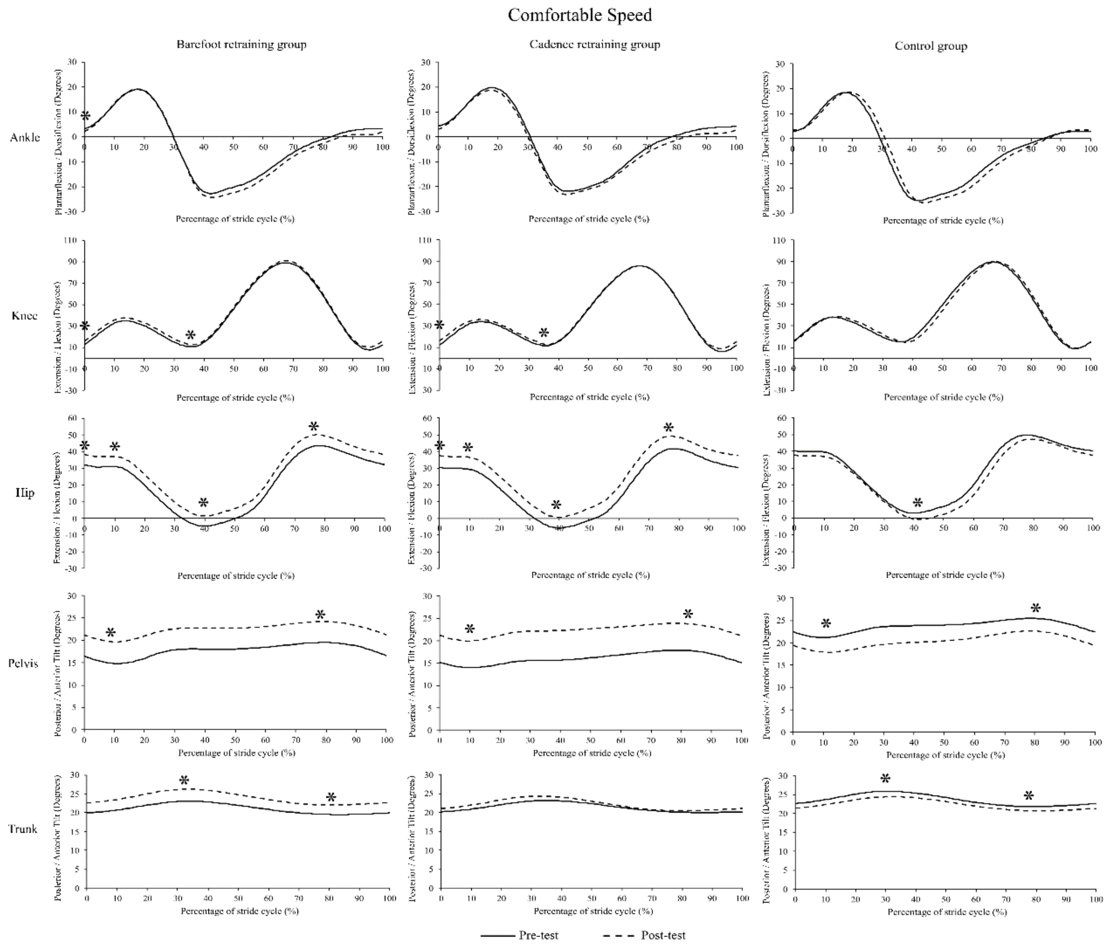
		Barefoot retraining group			Cadence retraining group			Control group		
Phase	Variable	Pre-test Mean (SD)	Post-test Mean (SD)	Dif. 95% CI [low, high]	Pre-test Mean (SD)	Post-test Mean (SD)	Dif. 95% C [low, high]	Pre-test Mean (SD)	Post-test Mean (SD)	Dif. 95% CI [low, high]
Stance Phase	Ankle dorsiflexion at footstrike (°)	4.06 (5.13)	0.87 (5.86)	**[1.28, 5.10]**	4.31 (4.58)	2.89 (5.19)	[-0.45, 3.28]	2.34 (4.74)	3.63 (4.43)	[-3.12, 0.52]
	Knee flexion at footstrike (°)	12.72 (5.23)	17.53 (6.11)	**[-6.97, -2.66]**	12.47 (4.75)	16.24 (5.78)	**[-5.82, -1.71]**	16.16 (4.40)	15.52 (5.23)	[-1.36, 2.65]
	Hip flexion at footstrike (°)	34.92 (8.75)	41.47 (6.44)	**[-10.22, -2.89]**	35.01 (6.94)	39.74 (7.51)	**[-8.23, -1.24]**	45.04 (7.78)	41.60 (8.55)	**[0.02, 6.85]**
	Peak hip flexion (°)	35.26 (8.90)	40.97 (7.27)	**[-9.31, -2.12]**	34.30 (6.77)	38.96 (7.48)	**[-8.08, -1.23]**	44.46 (7.71)	41.22 (8.68)	[-0.11, 6.59]
	Ankle dorsiflexion excursion (º)	16.03 (3.71)	17.70 (4.13)	**[0.43, 2.91]**	16.34 (2.91)	17.19 (2.67)	[-0.36, 2.07]	16.43 (2.65)	15.05 (2.60)	**[-3.01, -0.64]**
	Knee flexion excursion (º)	21.99 (5.51)	19.87 (5.52)	**[-4.13, -0.10]**	22.34 (5.72)	20.19 (6.57)	**[-4.08, -0.23]**	21.65 (6.47)	23.12 (5.90)	[-0.41, 3.35]
	Peak ankle dorsiflexion velocity (°/s)	224.94 (41.13)	277.38 (86.16)	**[-80.90, -23.98]**	233.78 (42.61)	262.06 (58.18)	**[-56.74, 0.18]**	271.91 (78.49)	241.69 (54.19)	**[3.03, 57.42]**
	Peak ankle plantarflexion velocity (°/s)	-547.10 (119.51)	-574.13 (66.16)	[-4.17, 58.23]	-571.18 (77.51)	-589.28 (60.59)	**[-12.38, 48.58]**	-620.68 (56.07)	-588.93 (51.22)	**[-62.94, -0.55]**
Flight Phase	Peak ankle dorsiflexion (°)	7.22 (6.31)	3.08 (6.76)	**[2.02, 6.27]**	6.87 (4.73)	5.74 (4.85)	**[-0.94, 3.21]**	5.22 (4.54)	6.04 (4.91)	[-2.85, 1.21]
	Peak hip extension (°)	-9.74 (7.64)	-2.09 (6.62)	**[-11.15, -4.16]**	-10.55 (6.39)	-4.43 (5.84)	**[-9.47, -2.79]**	-2.17 (7.96)	-5.98 (7.50)	**[0.55, 7.08]**
	Peak hip flexion (°)	53.14 (8.43)	61.41 (10.70)	**[-12.01, -4.54]**	52.29 (7.70)	59.05 (8.19)	**[-10.32, -3.2]**	59.28 (9.37)	58.05 (7.85)	[-2.26, 4.71]
Full cycle	Maximum pelvic anterior tilt (°)	20.89 (7.58)	27.57 (5.48)	**[3.36, 10.02]**	21.09 (5.57)	25.25 (5.34)	**[0.99, 7.34]**	28.44 (5.87)	25.62 (6.41)	[-5.99, 0.36]
	Minimum pelvic anterior tilt (°)	12.69 (9.19)	19.66 (5.25)	**[3.39, 10.56]**	14.17 (6.08)	18.65 (5.80)	**[1.06, 7.90]**	20.87 (8.44)	18.39 (7.10)	[-5.83, 0.86]
	Maximum trunk anterior tilt (°)	25.64 (4.91)	27.76 (3.30)	**[0.81, 3.44]**	24.79 (3.77)	25.97 (3.51)	[-0.07, 2.43]	26.84 (4.06)	25.63 (4.03)	[-2.43, 0.01]
	Minimum trunk anterior tilt (°)	19.22 (5.78)	21.03 (4.05)	**[0.64, 2.98]**	19.00 (4.12)	19.61 (3.80)	[-0.50, 1.72]	20.44 (3.19)	18.9 (3.38)	**[-2.63, -0.46]**

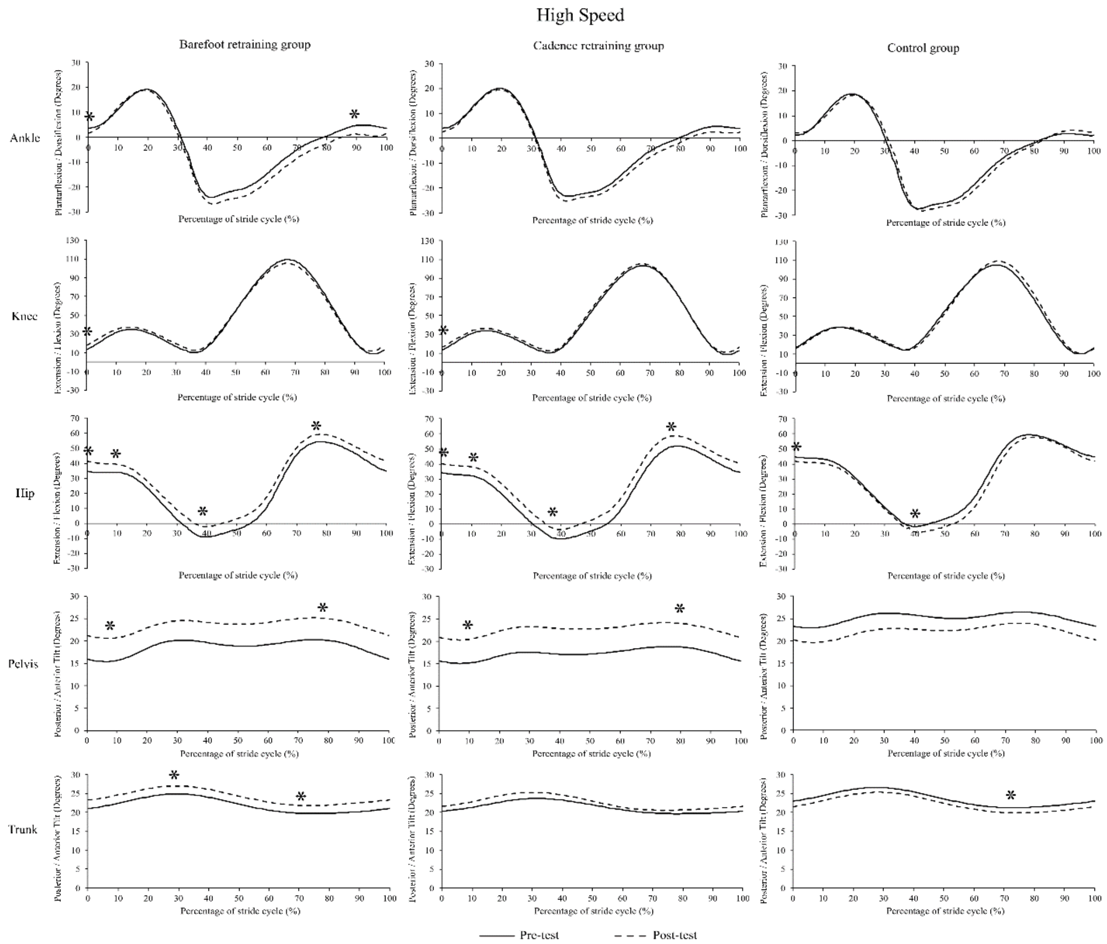
CI denotes Confidence Intervals; Bold in Dif. 95% CI denotes post-hoc paired tests by Time (pre-test *vs*. post-test) with $p < 0.05$.

FIGURES


ENROLLMENT
Runners assessed (n = 110)
Excluded (n = 7)
• Declined to participate (n = 3)
• Does not meet the inclusion criteria (n = 4)
• Other reasons (n = 0)
Simple randomization (n 103)
ALLOCATION
Allocated to BAR retraining group (n = 32)
Allocated to CAD retraining group (n = 34)
Allocated to CON group (n = 37)
FOLLOW-UP
FOLLOW-UP
Lost to follow -up (give reasons) (n = 6)
• 3 injured during the follow -up period
• 3 did not meet the minimum sessions
Lost to follow -up (give reasons) (n = 7)
• 2 injured during the follow -up period
• 4 did not meet the minimum sessions
• 1 relocated residence
Lost to follow -up (give reasons) (n = 11)
• 4 injured during the follow -up period
• 2 relocated residence
• 5 discontinued intervention
ANALYSIS
ANALYSIS
Analysed
• 23 were included in analysis
• 3 had technical problems (excluded)
Analysed
• 23 were included in analysis
• 4 had technical problems (excluded)
Analysed
• 24 were included in analysis
• 2 had technical problems (excluded)


θtrunk
θ pelvis
θ hip
θknee
θankle


Comfortable Speed
Barefoot retraining group
Cadence retraining group
Control group
Ankle
Knee
Hip
Pelvis
Trunk
Percentage of stride cycle (%)
Pre-test
Post-test



FIGURES CAPTIONS

Figure 1. Flow diagram of participant recruitment, follow-up and inclusion for analysis.

Figure 2. Calculated joint and segmental angles.

Figure 3. Changes during the stride cycle for the joint and segmental angles after the 10-week retraining programs at comfortable speed (*denotes significant difference between pre-test and post-test when an interaction effect between Time × Group was seen).

Figure 4. Changes during the stride cycle for the joint and segmental angles after the 10-week retraining programs at high speed (*denotes significant difference between pre-test and post-test when and interaction effect between Time × Group was seen).