The Effects of Midfoot Strike Gait Retraining on Impact Loading and Joint Stiffness

Journal: Physical Therapy in Sport

Author
Zoe Y.S. Chan1; Janet H. Zhang1; Reed Ferber2,3; Gary Shum4 Roy T.H. Cheung1
Institution and affiliations
1 Gait & Motion Analysis Laboratory, Department of Rehabilitation Sciences, The Hong Kong Polytechnic University, Hong Kong
2 Running Injury Clinic, University of Calgary, Calgary, Canada
3 Faculties of Kinesiology, Nursing, and Cumming School of Medicine, University of Calgary, Calgary, Canada
4 Faculty of Sport & Health Sciences, Plymouth Marjon University, Plymouth, United Kingdom
Corresponding author:
Zoe Y.S. Chan
Telephone: 852-2766-4830
Fax: 852-2330-8656
Email: zoe-ys.chan@connect.polyu.hk

Acknowledgement:
This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors. The authors would like to thank Mr. Winko An and Mr. Ivan Au for their valuable technical support and assistance in data collection.

ABSTRACT

Objective: To assess the biomechanical changes following a systematic gait retraining to modify footstrike patterns from rearfoot strike (RFS) to midfoot strike (MFS). **Design:** Pre-post interventional study. All participants underwent a gait retraining program designed to modify footstrike pattern to MFS. **Setting:** Research laboratory. **Participants:** Twenty habitual RFS male runners participated. **Main Outcome Measures:** Gait evaluations were conducted before and after the training. Footstrike pattern, loading rate (LR), ankle and knee joint stiffness were compared. **Results:** Participants' footstrike angle was reduced ($p<0.001$, Cohen's $d=1.65$) and knee joint stiffness was increased ($p=0.003$, Cohen's $d=0.69$). No significant difference was found in the vertical loading rates ($p>0.155$). Further sub-group analyses were conducted on the respondents (n=8, 40% of participants) who exhibited MFS for over 80% of their footfalls during the post-training evaluation. Apart from the increased knee joint stiffness ($p=0.005$, Cohen's $d=1.14$), respondents exhibited a significant reduction in the ankle joint stiffness ($p=0.019$, Cohen's $d=1.17$) when running with MFS. **Conclusions:** Gait retraining to promote MFS was effective in reducing runners' footstrike angle, but only 40% of participants responded to this training program. The inconsistent training effect on impact loading suggests a need to develop new training protocols in an effort to prevent running injuries.

HIGHLIGHTS

• A transition from RFS to MFS does not guarantee a reduction in impact loading.

• MFS transition is coupled with an increase in knee joint stiffness.

• Adopting MFS is not a "one-size-fits-all" approach in reducing running injury risk.

Keywords: landing pattern; footstrike pattern; running; loading rate

INTRODUCTION

Recreational running is one of the most popular sporting activities across the world. However, it is also accompanied by a high prevalence of running-related injuries (RRIs). Specifically, research has reported an annual incidence of RRIs as high as 79% (van Gent et al., 2007), with an injury risk of up to 7.7 RRIs per 1,000 hours of running (Videbæk et al., 2015). The development of RRIs is multifactorial and apart from risk factors such as injury history, training errors, and anthropometry (Hreljac, 2005; Messier et al., 2018), a considerable amount of research has been focused on atypical running biomechanics. For example, high impact loading has been associated with a number of common RRIs in both retrospective and prospective studies (Chan et al., 2018; Davis et al., 2016). Specifically, a two-year prospective study reported that higher loading rates were associated with higher injury risk in female runners, as compared to their healthy non-injured counterparts (Davis et al., 2016). In a more recent randomized controlled trial, Chan *et al*. reported that a group of novice runners who reduced their impact loading through a gait retraining program exhibited a 62% lower injury risk compared to controls (Chan et al., 2018). Therefore, lowering impact loading by modifying running gait patterns may be a viable approach to reduce RRIs.

Various previous studies have examined the effectiveness of lab-based gait retraining programs on the vertical average (VALR) and instantaneous loading rate (VILR) (Chan et al., 2018; Cheung & Davis, 2011; Crowell & Davis, 2011; Tate & Milner, 2017). These programs employed different strategies to achieve 'softer' footfalls. Tate and Milner (Tate & Milner, 2017) reported a 34-36% reduction in the vertical loading rates in a group of runners after a 15-minute gait retraining bout aiming to make the footfall sound quieter while running on a treadmill. In another study, Crowell and Davis provided real-time feedback of tibial shock to a group of runners and found a significant reduction in the VALR and VILR after an 8-session gait retraining program (Crowell & Davis, 2011). Despite the promising effects of these gait retraining programs, all of them require sophisticated instruments, e.g. force plate to provide timely biofeedback. A more manageable approach would be to target a particular running style based on explicit running kinematics such as footstrike pattern. Unfortunately, very few studies have examined the effect of gait retraining in reducing impact loading through modification to the footstrike pattern (Cheung & Davis, 2011; Diebal et al., 2012; Giandolini, Horvais, et al., 2013). Moreover, altering a runner's footstrike pattern has not been comprehensively investigated to understand the efficacy or potential unintended consequences at other lower extremity joints.

A runner's footstrike pattern can be classified as a rearfoot strike (RFS), midfoot strike (MFS) or forefoot strike (FFS) based on the location of the center of pressure during initial contact with the ground (Cavanagh & Lafortune, 1980). Previous gait retraining studies have reported favorable results for the management of pain in injured runners and reducing loading rates when RFS runners adopted a non-RFS pattern (Cheung & Davis, 2011; Diebal et al., 2012; Roper et al., 2016). Conversely, a transition of RFS to FFS was found to have unintended consequences. For instance, ankle joint stiffness was found to be reduced when habitual RFS runners ran with a FFS, while the knee joint stiffness displayed an opposite trend (Hamill et al., 2014). Increased knee joint stiffness was found to increase the odds of sustaining RRIs in a recent large-scale study on RRIs (Messier et al., 2018). Moreover, several studies have suggested that FFS runners are exposed to higher injury risk in the ankle and foot owing to higher loading in the metatarsus, plantarflexor musculature and Achilles tendon (Rice & Patel, 2017; Rooney & Derrick, 2013; Williams et al., 2000). Therefore, a footstrike pattern between the two extremes of RFS and FFS may balance the benefits and risk.

The immediate effects of switching footstrike patterns for habitual RFS runners in order to adopt a MFS landing has been previously evaluated by a few studies and significant reductions in the loading rates were observed, ranging between 25 and 39.0% (Chen et al., 2016; Giandolini, Arnal, et al., 2013). However, there is also a lack of evidence to understand the biomechanical effects of a systematic gait retraining to promote a MFS pattern in distance runners, and no study has determined whether switching to a MFS would alter ankle and knee joint stiffness in a manner similar to a FFS pattern.

Therefore, this study aimed to evaluate the efficacy of gait retraining, for the purpose of modifying footstrike pattern from RFS to MFS, on vertical loading rates and joint stiffness. This study also aimed to investigate the subsequent biomechanical changes from initial RFS to MFS among respondents of the training. It was hypothesized that upon completion of the gait retraining, runners would be able to achieve MFS, as indicated by a reduction of footstrike angle (FSA) to below 8°. We also hypothesized reduction in VALR and VILR, and changes in joint stiffness when running with a MFS amongst trained runners, as compared to their RFS pattern.

METHODS

Participants

Sample size estimation was performed using G*POWER 3.1 (Universität Kiel, Germany). An effect size of 0.67 was used which based on previous studies on footstrike pattern transition (Chen et al., 2016; Giandolini, Arnal, et al., 2013; Hamill et al., 2009). With alpha set at 0.05, 20 participants were required to obtain a power of 0.8. Twenty male recreational distance runners (age=37.5±7.5 years; body mass=69.7±8.6 kg; body height=1.75±0.06 m; running experience=5.2±3.3 years; weekly mileage 28.9±13.9 km) were recruited from local running clubs. We included runners who had more than two years of running experience, weekly mileage of more than 15 km, and were free from any RRI or musculoskeletal conditions that would affect their running for at least six months. Furthermore, an initial screening was set to exclude participants with a non-RFS pattern. The experimental procedures were reviewed and approved by the institutional ethical committee, and the participants provided written informed consent.

Procedures

A self-reported training speed used for a typical 30-minute training session was recorded for each participant. This speed was used for all assessments and throughout the gait training. Two reflective markers were affixed onto the heel and the second metatarsal head of the right foot, according to the model established in a previous study (Altman & Davis, 2012). The angle between the running surface and an imaginary line joining the two reflective markers with the participant standing on the treadmill was recorded as the FSA offset. The participants were instructed to run on an instrumented treadmill (Force-sensing tandem treadmill, AMTI, Watertown, MA, USA) in the recorded speed while marker trajectories were recorded at 200 Hz for five minutes using an 8-camera motion capture system (MX, VICON, Oxford, UK). The FSA was calculated as the angle of the foot with respect to the ground in the sagittal plane of the lab during initial foot-ground contact. The FSA offset was subtracted from the FSA obtained during running. A positive FSA indicated an inclined foot with the metatarsus higher than the heel (Altman & Davis, 2012). Only runners with an FSA $> 8^{\circ}$ for more than 90% of all footfalls were included in this study.

Following the initial screening, all eligible participants were evaluated in a baseline assessment session, while they wore their usual running shoes. The same pair of shoes was used for each participant throughout the entire experiment. Sixteen reflective markers were placed over specific anatomical landmarks based on the validated lower-body Plug-In Gait model (Vicon, Oxford, UK) to obtain lower limb kinematics (Kadaba et al., 1990). Participants were given five minutes to warm up on the treadmill and verbal confirmation of a natural running style by the participant marked the beginning of the one-minute data collection. Ground reaction force data were sampled at 1,000 Hz using the instrumented treadmill.

Each participant underwent the same gait retraining protocol to modify their footstrike pattern from RFS to MFS, and the training schedule was based on previous investigations (Cheung & Davis, 2011; Crowell & Davis, 2011). The gait retraining was conducted on the instrumented treadmill and the training time was gradually increased from 15 minutes to 30 minutes across eight different sessions over two weeks. The same marker model used for the initial screening was applied to obtain the FSA during the training sessions. Each footstrike was categorized based on the following FSA ranges: FFS: $< -1.6^{\circ}$; MFS: between -1.6° and 8°; RFS: $> 8^{\circ}$ (Altman & Davis, 2012). Real-time footstrike information of the training foot (i.e. the right foot) was computed using customized MATLAB code (The MathWorks, Inc, Natick, MA, USA) and displayed graphically together with a three-letter label (FFS, MFS or RFS) on the monitor placed in front of the treadmill (Figure 1). Participants were instructed to change their footstrike and maintain a MFS pattern whilst running for the prescribed period of time. Visual feedback was removed gradually for 2 to 28 minutes during the last four training sessions (Cheung & Davis, 2011; Crowell & Davis, 2011) by switching off the monitor.

Figure 1. Footstrike information provided to participants during training for rearfoot strike (RFS), midfoot strike (MFS) and forefoot strike (FFS) (from left to right).

Following the completion of the 8-session gait retraining protocol, an instrumented gait evaluation identical to the baseline assessment was conducted on the following day.

Data collected by the instrumented treadmill and motion capture system were calculated for the trained side only. Both marker trajectories and ground reaction force data were filtered by fourth-order Butterworth recursive low-pass filter, with a cut-off frequency of 8 Hz and 50 Hz respectively (Zhang et al., 2016). A cut-off threshold of 10 N was used to identify initial foot-ground contact and toe-off (Crowell & Davis, 2011). Vertical loading rates, including VALR and VILR, were obtained using a method previously described (Crowell & Davis, 2011) wherein the vertical impact peak was defined as the local maximum of the vertical ground reaction force within the first 50 ms of initial contact. For any footfall with an unidentifiable impact peak, the force value at 13% stance phase was used as the impact peak value (Blackmore et al., 2016). The average slope of the line through the 20% and 80% point of the impact peak was defined as the VALR, while VILR was the maximum slope between consecutive points within the region. Both VALR and VILR were normalized by body weight. Ankle and knee joint angles and moments were computed based on the Plug-In Gait model with lower limb anthropometry data, body mass and height for subject-specific calculations (Kadaba et al., 1990; *Plug-in Gait Dynamic pipeline - Nexus 2.5 Documentation - Vicon Documentation*, n.d.). The linear fit of the slope in the sagittal moment-angle profile between initial foot-ground contact and maximum ankle dorsiflexion and knee flexion were presented as ankle and knee joint stiffness respectively (Hamill et al., 2009). All biomechanical variables were averaged across all footfalls of the training side within the one-minute data collection period for the baseline assessment and post-training assessment.

To better understand the biomechanical changes from RFS to MFS following the gait retraining, VALR, VILR and joint stiffness for the knee and ankle joints for those respondents who were operationally defined as successfully demonstrating a MFS landing for > 80% of footfalls during the post-training assessment were also compared. Ankle and knee joint stiffness, together with VALR and VILR, were averaged across the last 10 footfalls during baseline assessment (Pre-RFS) and the last 10 MFS footfalls during post-training assessment (Post-MFS). All variables of interest including FSA, VALR, VILR, ankle joint stiffness and knee joint stiffness were processed using customized MATLAB codes.

Statistical analyses

Paired *t*-tests compared the dependent variables before (Pre-All) and after (Post-All) gait retraining for all participants as well as within the subgroup of participants that ran with MFS after training (Pre-RFS vs. Post-MFS). Cohen's *d* was calculated to evaluate effect size. The global level of significance for all statistical calculations was set at 0.05. Statistical tests were computed using SPSS for Windows, Version 22 (SPSS, Inc., Chicago, IL, USA).

RESULTS

The average (± 1 SD) assessment and training speed was 2.9±0.3 m/s. Individual changes in the FSA before and after training are presented in Figure 2. The post-training FSA (9.4±6.3°) was significantly lower when compared to pre-training FSA (18.5±3.7°; $p<0.001$, Cohen's d=1.65). No differences were observed in the vertical loading rates for either VALR (Pre-All: 79.3±23.2 BW/s vs. Post-All: 73.3±28.6 BW/s; p=0.250; Cohen's d=0.23) or VILR (Pre-All: 89.5±24.5 BW/s vs. Post-All: 81.7±28.9 BW/s; p=0.155; Cohen's d=0.29) following the MFS gait retraining. As for joint stiffness, no significant changes were found for ankle (Pre-All: 21.2±6.5 Nm/° vs. Post-All: 19.1±9.3 Nm/°; p=0.285; Cohen's d=0.27), but significantly higher knee joint stiffness (Pre-All: 7.4±3.5 Nm/° vs. Post-All: 10.2±4.4 Nm/°; p=0.003; Cohen's d=0.69) was found after the MFS training.

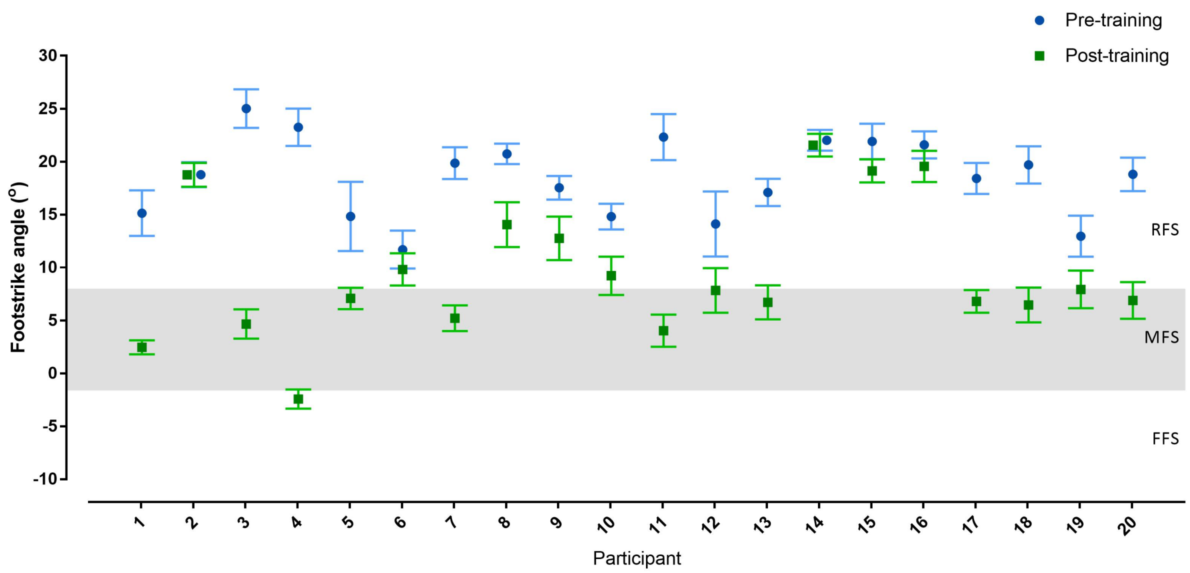

Figure 2. Individual's mean footstrike angle before and after training. Error bars denotes SDs. Shaded region indicates MFS with footstrike angle between -1.6° and 8°.

RFS, rearfoot strike; MFS, midfoot strike; FFS, forefoot strike

The percentage of footstrike pattern demonstrated during pre- and post-training are presented in Figure 3. Using the a priori criteria, only 8 out of 20 participants (40%) were identified as successfully exhibiting a MFS landing pattern in response to gait retraining. Among these respondents, the vertical loading rates, ankle and knee joint stiffness between Pre-RFS and Post-MFS are shown in Figure 4. Significantly lower ankle joint stiffness (Pre-RFS: 19.9±7.5 Nm/° vs. Post-MFS: 12.0±2.1 Nm/°; p=0.019) and higher knee joint stiffness (Pre-RFS: 6.3±2.8 Nm/° vs. Post-MFS: 9.5±2.8 Nm/°; p=0.005) were found after MFS training, compared to Pre-RFS baseline values. However, no differences were observed in the vertical loading rate (p=0.330-0.519).

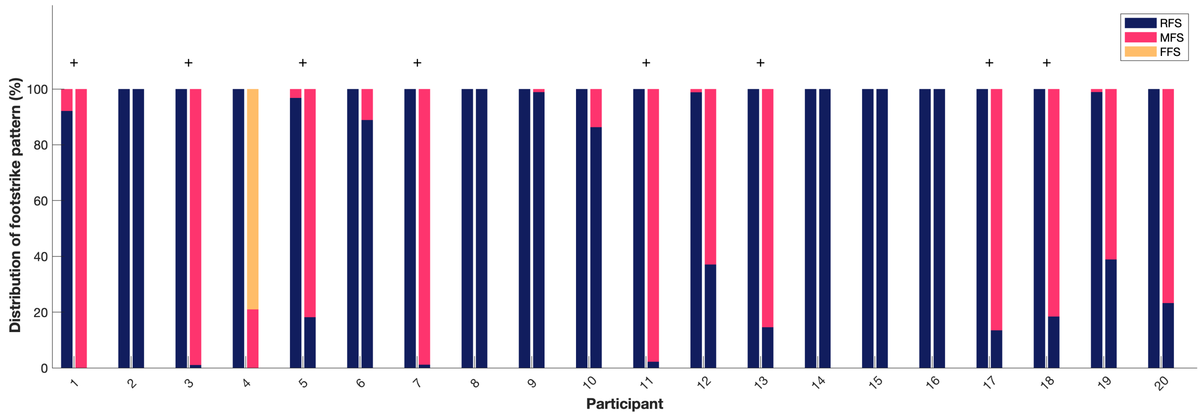

Figure 3. Pairs of bars showing the percentage of footstrike pattern achieved during pre- (left) and post-training (right) condition for each participant.

RFS, rearfoot strike; MFS, midfoot strike; FFS, forefoot strike

+ Respondent: participant who demonstrated MFS landings for > 80% of footfalls during the post-training

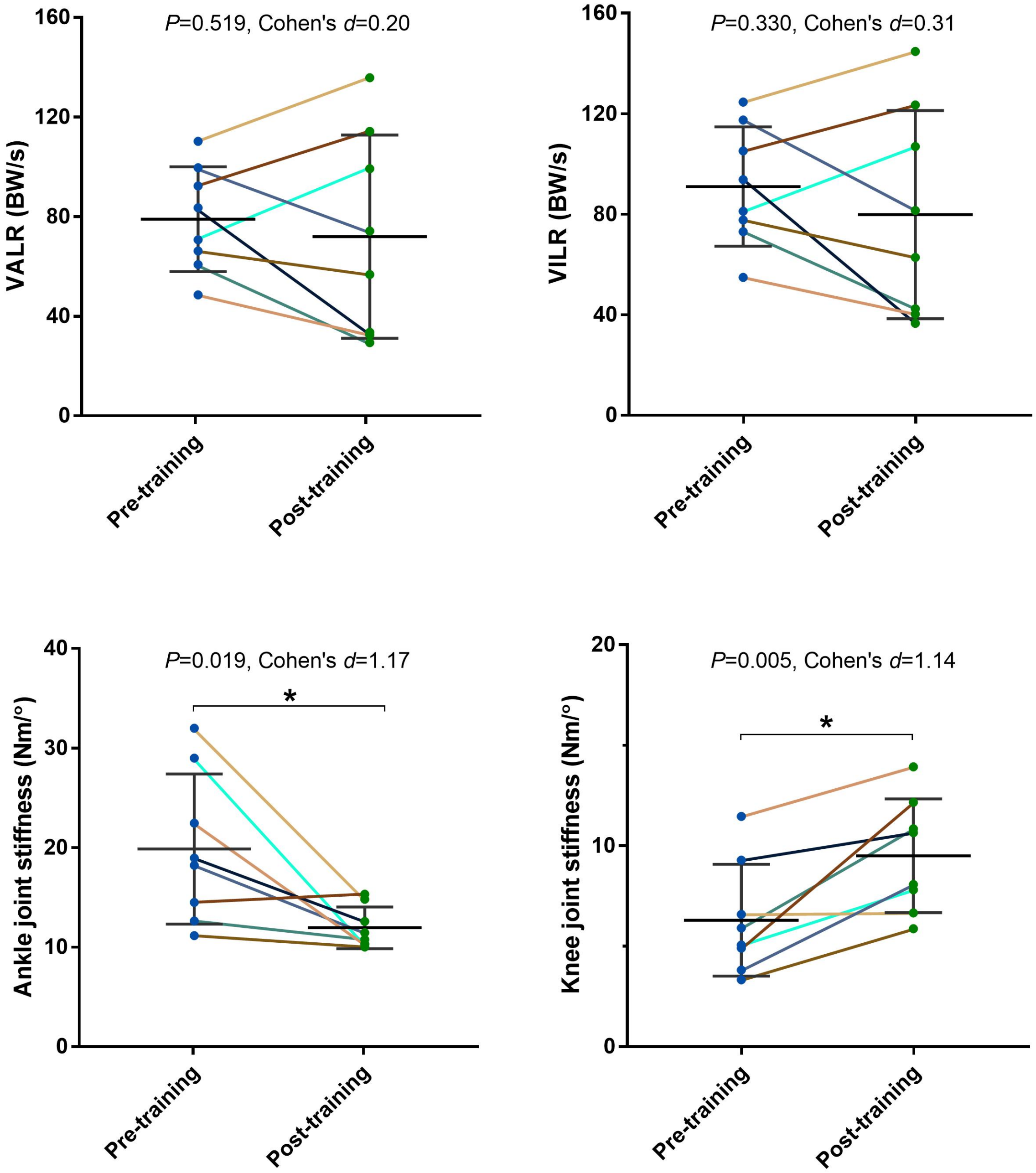

Figure 4. Vertical average loading rate (VALR), vertical instantaneous loading rate (VILR), ankle and knee joint stiffness of respondents before and after training.

BW, body weight

*P<0.05

DISCUSSION

The present study evaluated the biomechanical effect of gait retraining in order to promote a MFS landing in a group of habitual RFS runners. We observed a significant reduction in the FSA in participants following the training. However, this measured FSA reduction was not sufficient to result in a MFS group-effect, as a FSA of greater than 8° is still regarded as a RFS nor did our results support the hypothesis of reduced impact loading upon completion of training. The other objective of this study was to compare subsequent biomechanical changes between baseline RFS and post-training MFS among respondents. In support of our hypotheses, ankle and knee joint stiffness were significantly different, but surprisingly, no statistical difference in VALR and VILR was measured as compared to baseline RFS biomechanical gait patterns.

A main focus of the present study was on the change in footstrike pattern. Compared to baseline, a significantly lower FSA was found in the trained runners, supporting the notion that an 8-session gait retraining protocol was effective in reducing FSA in habitual RFS runners. Despite that, the average post-training FSA was still above 8° and thus should still be considered a RFS pattern. The lack of a group-wide response to the retraining protocol maybe attributed to the training target. In a previous study, a buzzing sensor was used to train runners to switch from RFS to either MFS or FFS (Cheung & Davis, 2011). In contrast, participants in the present study were specifically instructed to maintain a MFS without over-correcting to a FFS. Thus, it may be more challenging to avoid over-correction in an effort to achieve a MFS. Additionally, some participants may still rely on the visual-feedback after the gait retraining, as we observed that most of the participants were only able to maintain MFS in the presence of feedback, indicating a potential limitation of the current gait retraining protocol.

Another observation on the footstrike pattern was a large variance between participants (Figure 2). In the post-training assessment, only 8 out of 20 participants were able to achieve a

MFS for over 80% of the footfalls, while 5 participants were not able to achieve MFS at all. This result suggests an inconsistent and individualized effect across the participants. One possible explanation was that the participants were instructed to change their footstrike pattern to a MFS using visual-feedback that indicated which part of the sole was in contact with the ground at initial contact. These instructions and feedback arrangement could induce either an internal or external focus of attention and unlike previous studies that provided externally focused feedback without instructions on the detailed movements (Chan et al., 2018), participants in the current study could interpret the instructions and feedback differently. An internal focus was previously found less effective in terms of automaticity and efficiency when compared with learning through feedback that induced an external focus (Wulf et al., 2010). Retention of the modified gait could have been compromised in participants who focused on their movement pattern internally and the optimal feedback for successful gait retraining could be individualized.

Based on previous findings from gait retraining studies on impact loading (Chan et al., 2018; Crowell & Davis, 2011), and the acute effects of reduced loading rates when running with a MFS (Chen et al., 2016; Giandolini, Arnal, et al., 2013), we hypothesized that the gait retraining protocol would be effective in lowering the VALR and VILR as RFS runners who were trained to run with a MFS. However, we were not able to observe a reduction in VALR or VILR in the trained runners. Although footstrike information is a visible and explicit biomechanical marker, gait retraining using other parameters, such as peak tibial shock (Crowell & Davis, 2011), step rate (Willy et al., 2016), and the ground reaction force curve (Chan et al., 2018), appear to be more effective in lowering vertical loading rates.

A subgroup analysis was conducted to compare the running biomechanics among respondents for better understanding of the footstrike transition from a RFS to MFS. Interestingly, no significant differences were found in VALR or VILR between the Pre-RFS and Post-MFS, and a large variability among respondents was still observed. One of the respondents exhibited an increase in the VALR of up to 28.4 BW/s when running with MFS, while another participant showed a VALR reduction of 49.7 BW/s. Such findings are similar to that reported by Altman and Davis (Altman & Davis, 2009), when runners attempted a MFS after a short practice and an immediate increase in the VALR and VILR resulted for a subgroup of runners. Contrary to our hypothesis and other acute interventions promoting MFS transition, our results did not support the reduction in impact loading through footstrike pattern transition. While modification to the current gait retraining protocol may optimize the response rate, a transition to MFS may not be beneficial for all runners.

The present study showed that runners who attempted to change their footstrike pattern to a MFS pattern exhibited a more compliant ankle and a stiffer knee joint, similar to previously reported findings when habitual RFS runners attempted to run with a FFS (Hamill et al., 2014; Laughton et al., 2003). Joint stiffness refers to the relationship between joint moment and angle within the stance phase, and was suggested to be associated with the pattern of muscle activation and the degree of force development (Hamill et al., 2014). Hamill *et al.* suggested that stiffness measured at individual joints on the lower extremity may be an indicator of lower-limb injuries (Hamill et al., 2009). Therefore, understanding the changes in ankle and knee joint stiffness following the transition from RFS to MFS could allow researchers to understand the potential risks or benefits following the transition. Higher knee joint stiffness has been reported among runners suffering from low back pain when compared to healthy controls and the group with resolved pain, while the ankle stiffness was found to be comparable between the three groups (Hamill et al., 2009). In a recent large-scale study on running biomechanics and RRIs, greater knee joint stiffness was reported to significantly increase the odds of sustaining an RRI (Messier et al., 2018). Therefore, the contemporary increase in knee joint stiffness found among the participants of this study, irrespective of post-training footstrike pattern, suggested that the attempted transition into MFS is not suitable for runners with high knee joint stiffness at baseline. For example, runners with body weight over 80 kg (Messier et al., 2018).

Considering only the immediate effect of the training was one limitation of the current study. It is possible that follow-up sessions could provide a more comprehensive understanding of the training protocol. Second, only biomechanical factors were analyzed. While impact loading was found associated with certain common RRIs (Cheung & Davis, 2011; Pohl et al., 2008, 2009), other type of injuries could result from a change in footstrike pattern (Hamill & Gruber, 2017). The effect of similar interventions upon injury incidence should therefore be considered in future gait retraining studies to address the clinical effectiveness (Chan et al., 2018; Morris et al., 2019). Thirdly, the post-hoc power for the sub-group analyses ranged between 0.08 and 0.12 for the loading rates. This study may be insufficiently powered to conclude the lack of changes in impact loading within the respondents, yet, the small effect size and large variance among participants have suggested an inconclusive response to the training. Lastly, this study was conducted in a lab setting and the effect of a similar training in runners' more natural environment remains unknown (Napier et al., 2017; Willy et al., 2016). With the advancement in wearable sensor technology, future research is necessary to further study gait retraining outside the lab setting.

CONCLUSIONS

Visual-feedback gait retraining to promote changes in footstrike pattern from rearfoot to midfoot was found effective in reducing a runner's footstrike angle. However, only 40% of participants responded to the gait retraining protocol, adopting a MFS for over 80% of the footfalls. A transition from rearfoot to midfoot strike does not guarantee a reduction in vertical loading rates. Considering the potential increase in loading rates and knee joint stiffness, footstrike pattern transition should not be considered as a "one-size-fits-all" approach in reducing the risk of running injuries.

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