Journal of Science and Medicine in Sport 24 (2021) 30–35

Contents lists available at ScienceDirect

Journal of Science and Medicine in Sport

journal homepage: www.elsevier.com/locate/jsams

Original research

Biomechanical effects following footstrike pattern modification using wearable sensors

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A R T I C L E I N F O

Article history:
Received 13 December 2019
Received in revised form 8 May 2020
Accepted 18 May 2020
Available online 30 May 2020

Keywords:
Biofeedback
In-field
Kinetics
Training
Running
Slope

A B S T R A C T

Objectives: This study sought to examine the biomechanical effects of an in-field sensor-based gait retraining program targeting footstrike pattern modification during level running, uphill running and downhill running.
Design: Quasi-experimental design.
Methods: Sixteen habitual rearfoot strikers were recruited. All participants underwent a baseline evaluation on an instrumented treadmill at their preferred running speeds on three slope settings. Participants were then instructed to modify their footstrike pattern from rearfoot to non-rearfoot strike with real-time audio biofeedback in an 8-session in-field gait retraining program. A reassessment was conducted to evaluate the post-training biomechanical effects. Footstrike pattern, footstrike angle, vertical instantaneous loading rate (VILR), stride length, cadence, and knee flexion angle at initial contact were measured and compared.
Results: No significant interaction was found between training and slope conditions for all tested variables. Significant main effects were observed for gait retraining (p-values ≤ 0.02) and slopes (p-values ≤ 0.01). After gait retraining, 75% of the participants modified their footstrike pattern during level running, but effects of footstrike pattern modification were inconsistent between slopes. During level running, participants exhibited a smaller footstrike angle ($p \leq 0.01$), reduced VILR ($p \leq 0.01$) and a larger knee flexion angle ($p = 0.01$). Similar effects were found during uphill running, together with a shorter stride length ($p = 0.01$) and an increased cadence ($p \leq 0.01$). However, during downhill running, no significant change in VILR was found ($p = 0.16$), despite differences found in other biomechanical measurements (p-values = 0.02–0.05).
Conclusion: An 8-session in-field gait retraining program was effective in modifying footstrike pattern among runners, but discrepancies in VILR, stride length and cadence were found between slope conditions.

Practical Implications

- An 8-session in-field sensor-based gait retraining program was capable of modifying footstrike pattern from rearfoot strike to non-rearfoot strike during level running.
- During level running, effect of in-field gait retraining on reducing loading rate was comparable to laboratory-based training, providing another flexible approach for runners to reduce injury risk.
- Effect of gait retraining on uphill running was similar to level running, while a difference in loading rate reduction was found between downhill running and level running.

1. Introduction

Distance running is a popular sport across the globe. There are approximately 92 million active runners in Europe and the U.S.A.[1,2] However, running-related injuries are also very common. According to a review on 17 epidemiological studies, up to 79% of regular

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https://doi.org/10.1016/j.jsams.2020.05.019
1440-2440/

runners incur a single injury in a given year.[3] Although the etiology of running-related injury is multifactorial, a considerable amount of evidence has suggested that running biomechanics is related to the development of running injury.[4]

A recent meta-analysis has suggested that runners with previous running-related injuries exhibit higher vertical impact loading than their healthy counterparts.[5] Therefore, reducing the impact loading, which is usually expressed as vertical instantaneous loading rate (VILR), may potentially decrease injury risk in runners.[6] Previous studies have reported that footstrike pattern and running cadence affect vertical impact loading.[7,8] Specifically, runners with rearfoot strike (RFS), which are the majority of the running population,[9] have shown to experience greater VILR than those with midfoot strike (MFS) or forefoot strike (FFS).[10] Such higher vertical impact loading can be explained by a greater effective mass at initial contact with RFS.[11] A number of studies have reported that running with non-RFS accompanies with a higher running cadence[12,13] and greater knee flexion at initial contact,[14] which may lead to lower vertical impact loading. In addition, RFS runners were found to have approximately twice the rate of repetitive stress injury than FFS runners.[15]

Considering the association between footstrike pattern, cadence and impact loading, modification in running cadence and footstrike pattern have been proposed to reduce impact loading during running. Two studies reported successful vertical impact loading reduction with an increase of running cadence.[7,8] Findings of these two studies suggested a 10–18% increase in running cadence could reduce VILR by 9–16%.[7,8] Footstrike pattern modification from RFS to non-RFS appeared to effectively lower VILR by 27–47%.[16–18] A previous study examined the immediate effect of real-time visual feedback of the ankle joint position in the sagittal plane at initial contact, i.e., footstrike angle (FSA),[19] to help runners avoid RFS. Runners following training exhibited a 47% reduction of vertical loading rate.[17] Another case study using an 8-session training protocol with real-time audio feedback reported up to 27% reduction of VILR.[16] However, the effect of gait retraining aiming to modify footstrike pattern and reduce impact loading is equivocal. A more recent gait retraining study which utilized real-time footstrike information to promote MFS among RFS runners reported no significant difference in VILR following an 8-session gait retraining program.[18] Thus, the effect of gait retraining program on footstrike pattern modification and VILR requires further research to confirm.

Moreover, most previous gait retraining programs were confined to a laboratory environment as they require expensive and non-portable equipment. A recent study has shown that the training effect following a laboratory-based gait retraining may not be fully translatable to in-field running.[20] It is necessary to further explore the effects of in-field real-time biofeedback gait retraining programs. To date, only two biofeedback gait retraining studies were conducted in-field. Both studies targeted on adjusting the running cadence using a mobile biofeedback device.[21,22] Although they both reported significant increase in cadence and one reported a reduction in vertical loading rate after the gait retraining, both studies only examined the training effects on a flat surface.[21,22] It is unclear whether the training effects can be translated to slope conditions, of which downhill running was associated with greater vertical impact loading.[23,24] In addition, these in-field gait retraining studies only focused on the adjustment of running cadence. Footstrike pattern modification has not been implemented with real-time biofeedback gait retraining outside a laboratory environment.

Hence, the present study tested the effects of an in-field sensor-based gait retraining program using a novel footstrike pattern feedback system[25] to modify footstrike pattern in distance runners. Specifically, we sought to evaluate the biomechanical effects on various slope conditions, including level, uphill and downhill running. The primary variables of interest were FSA and VILR. The secondary outcomes included stride length, cadence and knee flexion angle at initial contact (Knee-Flex$_{IC}$). We hypothesized that after the sensor-based gait retraining, runners would demonstrate a footstrike pattern transition from RFS to non-RFS in all running conditions. In addition, we expected a reduction in the VILR, accompanied with a decrease in stride length and an increase in running cadence and Knee-Flex$_{IC}$.

2. Methods

A total of 40 experienced distance runners (>2-year experience and >15 km/week training) between 18 and 55 years old were recruited from local running clubs as potential participants. After providing written consents, runners underwent an initial screening. Specifically, runners were asked to run on an instrumented treadmill (AMTI, Watertown, MA, USA) at their preferred speed with two reflective markers affixed onto the heel and the second metatarsal head of the right foot[19] for 10 min. The marker trajectories were recorded at 200 Hz using an 8-camera motion capture system (MX, VICON, Oxford, UK) and the ground reaction force data were sampled at 1000 Hz for the last minute of the run. FSA, which was defined as the sagittal intercept angle between the foot and the ground at initial contact,[19] was calculated from the marker trajectories to identify footstrike patterns. In particular, FFS was defined as FSA less than -1.6°; MFS was defined as FSA between -1.6° and 8° and RFS was defined as FSA greater than 8°.[19] Based on the pre-set inclusion criteria, only runners with RFS for over 70% of the footfalls were eligible. In order to avoid floor effect, runners who ran with VILR below 70 body weight per second (BW/s) were excluded in the study.[6] We estimated the required sample size prior to the experiment using G*POWER 3.1 (Universitat Kiel, Germany). A sample of 16 would be sufficient to power the present study, with alpha at 0.05, power at 0.8, and an effect size of 0.76 based on a previous in-field gait retraining study using audio feedback.[22] The first 16 eligible distance runners (13 males, 3 females; age = 36.3 ± 8.4 years; height = 1.70 ± 0.08 m; body mass = 63.9 ± 9.2 kg; running experience = 5.5 ± 3.9 years) were included in this study. All participants were free from any active musculoskeletal conditions that affected their usual training for the recent six months. The experimental procedures were reviewed and approved by the institutional ethical committee.

All included participants were evaluated in a baseline assessment with their usual running shoes. The same pair of shoes was used for each participant during post-training reassessment. In order to obtain lower limb kinematics, 16 reflective markers were placed over specific anatomical landmarks based on the lower-body Plug-In Gait model.[26] Each participant was instructed to run on the same instrumented treadmill used for initial screening in three different conditions in a randomized order: level (0%), uphill (+10%) and downhill (−10%). For each trial, markers trajectories and ground reaction data were collected for 1 min with procedures similar to the initial screening, except a 4-min adaptation period was given instead of a 9-min period for each trial. A 5-min rest period between trials was introduced to prevent fatigue.[6] Foot size of each participant was measured by a Brannock device (Brannock, Liverpool, NY, USA) for customization of a pair of 3-D printed sensing insoles (Fig. A1). The sensing insoles provided real-time feedback of footstrike pattern with up to 84% reported accuracy.[25] The insoles measured the onset time difference between two force sensing resistors affixed at the heel and the second toe of the insoles. Footstrike patterns were categorized based on the onset time difference normalized by foot length as follows: FFS: onset time difference > 28.2 ms or no heel sensor onset is detected; MFS:

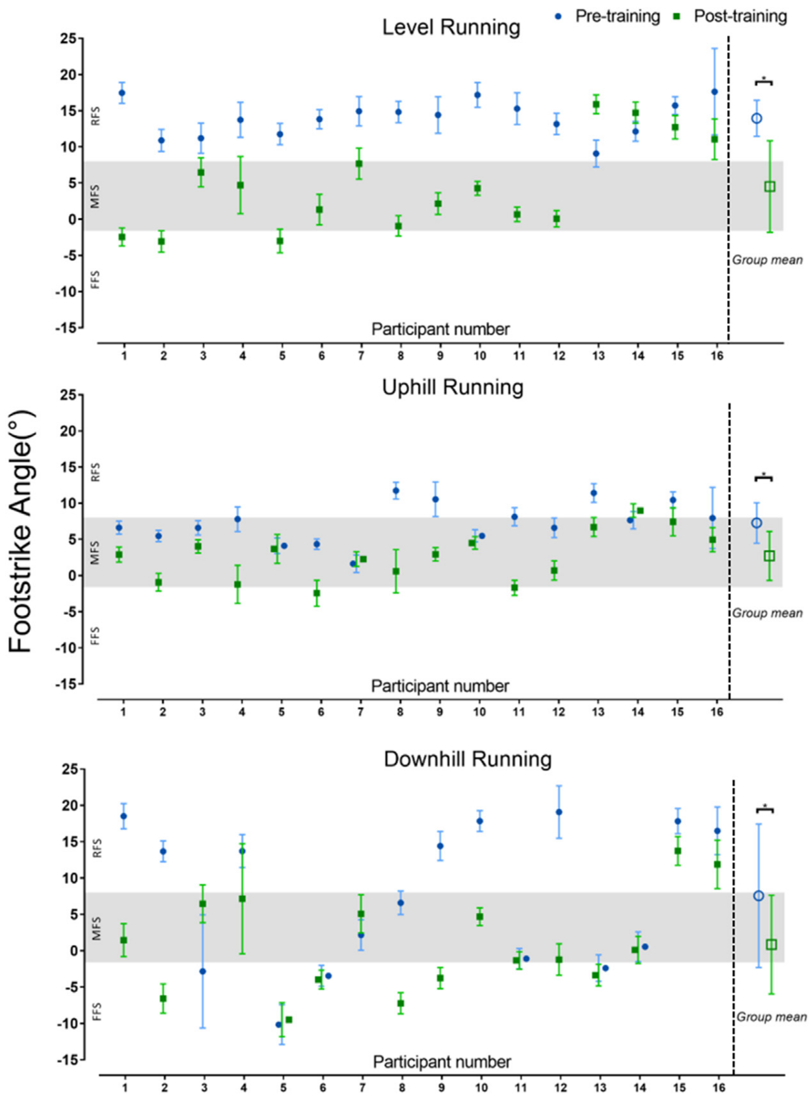

Fig. 1. Comparisons of footstrike angle during level, uphill and downhill running before and after gait retraining. Individual and group averages are indicated by filled and open symbols respectively. The gray bands indicate MFS. RFS, rearfoot strike; MFS, midfoot strike; FFS, forefoot strike. * indicates significant difference between pre- and post-training (p-value < 0.05).

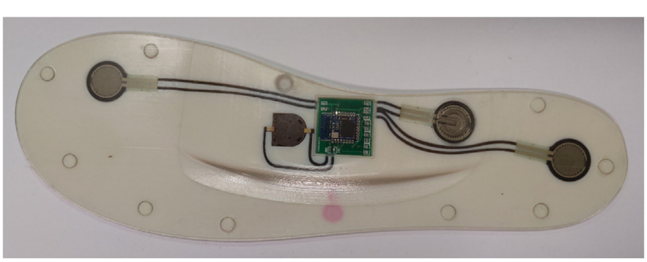

Fig. A1. 3D-printed sensing insole for in-field gait retraining.

onset time difference between 28.2 ms and −46.9 ms; RFS: onset time difference < −46.9 ms; where a positive onset time difference indicated an earlier triggering of the toe sensor than the heel sensor.[25]

After the baseline assessment, all participants underwent an 8-session gait retraining program with fading feedback design according to a previously established training protocol.[27] In brief, participants were asked to run at their usual speed on a standard 400-m sportsground track and instructed to avoid RFS. During the training, participants were guided by audio feedback generated by a smartphone app. Specifically, audio feedback in different pitches were provided for each step, based on the onset time difference received from the sensing insole via Bluetooth communication. A 'beep' sound with high pitch, medium pitch and low pitch, corresponded to a RFS, MFS and FFS respectively. Participants were allowed to continue their usual running training between gait retraining sessions.

Post-training reassessment was conducted within one week upon the completion of the training. Testing procedures were identical to the baseline assessment. Individual test speed in each condition was kept constant between baseline and post-training assessments.

Marker trajectories and ground reaction force data were filtered by fourth-order Butterworth recursive low-pass filter, with cut-off frequency set at 8 Hz and 50 Hz, respectively.[28] Initial contact was identified by a cut-off threshold of 10 N based on the vertical ground reaction force.[27] VILR for each step was extracted from the vertical ground reaction force data by a method described in previous study.[27] Specifically, a local maximum within the first 50 ms after initial contact was identified as the vertical impact peak, whereas the force value at 13% stance phase would be used for any footfalls without discernible peaks within the first 50 ms.[29] VILR was then calculated as the maximum rate of change bounded within 20% and 80% of the impact peak, and further normalized by body weight. Stride length and cadence were calculated according to methods described in a previous study.[30] Knee-Flex$_{IC}$ was computed with a Dynamic Plug-in pipeline built from subject specific anthropometry inputs.[30] For each running trial, mean value of all variables of interest were calculated for each participant. Participants were categorized into RFS runners or non-RFS runners, based on their average FSA. Group mean of all variables of interest were further calculated for evaluating the effect of gait retraining.

To investigate the effect of the in-field gait retraining, two-way repeated measures ANOVAs were performed to examine the interaction effect between gait retraining (pre- and post-training) and slope conditions (level, uphill and downhill). Paired *t*-tests were conducted to evaluate the effect of gait retraining on each slope condition. Effect sizes were quantified as Cohen's *d*. All statistical tests were conducted by SPSS for Windows, Version 22 (SPSS, Inc., Chicago, IL, USA), with level of significance set as 0.05.

3. Results

All 16 participants completed the gait retraining with no adverse effects reported. The test speeds were 2.8 ± 0.4 m/s during level running, 2.2 ± 0.4 m/s during uphill running and 2.5 ± 0.5 m/s during downhill running.

12 out of 16 participants (75%) demonstrated non-RFS landing pattern during level running following gait retraining, with 9 participants landed with MFS and 3 participants exhibited FFS. Participants after gait retraining also exhibited a footstrike pattern switch during sloped running. The number of participants who ran with RFS was reduced from 5 to 1 for uphill running, and from 8 to 2 for downhill running (Fig. 1).

Results of the two-way repeated measures ANOVAs (Table 1) indicated that there was no interaction between gait retraining and slopes for all variables of interest (p-values ≥ 0.06), but there were significant main effects of gait retraining (p-values ≤ 0.02) and slopes (p-values ≤ 0.01, Table 1).

Pairwise comparisons showed a significant reduction in the FSA during level, uphill and downhill running following gait retraining (p-values ≤ 0.02, Cohen's d = 0.79–1.96, Table 2). The extent of FSA reduction was similar between level and uphill running, while the effect size was smallest in downhill running. However, VILR, stride length, cadence and Knee-Flex$_{IC}$ responded differently to the footstrike pattern modification (Table 2). During level running, participants exhibited a lower VILR and a greater Knee-Flex$_{IC}$ (p-values ≤ 0.01), while the stride length and cadence appeared to be unchanged (p-values > 0.11). During uphill running, participants showed a reduction in VILR and stride length, together with an increase in cadence and Knee-Flex$_{IC}$ (p-values ≤ 0.01). Participants demonstrated similar VILR during downhill running after gait retraining (p = 0.16), in spite of a significant reduction of stride length and increase of cadence and Knee-Flex$_{IC}$ (p-values = 0.03–0.05).

4. Discussion

This study examined the biomechanical effects of an in-field sensor-based gait retraining protocol targeting footstrike pattern modification. In accordance to our original hypothesis, most participants successfully modified their footstrike pattern from RFS to non-RFS during the level running condition. This modification was reflected by the reduction in FSA. Furthermore, reduction in FSA was also observed while participants ran in the untrained conditions i.e. uphill and downhill running. We also hypothesized the transition of footstrike pattern would lead to changes in VILR, stride length, cadence and Knee-Flex$_{IC}$. However, our results suggested that these changes were condition-specific.

The present in-field gait retraining protocol achieved a higher success rate (75%) compared to a laboratory-based gait retraining which targeted on footstrike pattern modification (40%).[18] Our success rate was comparable to another in-field retraining targeting cadence (75%)[21] and a laboratory-based tibial shock retraining which focused on reducing landing impact (80%).[20] Although these gait retraining programs had different targets, they adopted a similar fading feedback arrangement so that the participants could internalize the newly learnt running gait. Our results indicated that real-time biofeedback provided in-field was effective in modifying running biomechanics. Moreover, transition of footstrike pattern had resulted in kinetic and kinematic differences during level running. Kinetically, modification of FSA lowered VILR by 26% during level running, which is postulated to reduce injury risk.[6] Such result contradicted with a study with similar feedback target (8.7%, p = 0.155),[18] but was similar to the findings reported by Cheung and Davis (24%)[16], Crowell and Davis (34%).[27] Kinematically, gait retraining increased Knee-Flex$_{IC}$ by 4.6° during level running, which was similar with a previous gait retraining study reporting an increase in the Knee-Flex$_{IC}$ (6.0°) after retraining a group of RFS runners to run with FFS.[14] Regarding spatial temporal parameters, stride length and cadence remained similar following gait retraining. Our findings supported the notion that cadence and stride length might not be a determining factor in impact mechanics, as suggested by previous studies.[12,31] These studies reported similar stride length and cadence among RFS and non-RFS runners, and demonstrated either no or weak relationship between cadence and vertical loading rate.

In this study, participants were trained on a flat running track. Interestingly, the effect of training was not only observable in level running, but untrained conditions (i.e., uphill and downhill running). A successful transition of footstrike pattern was observed in uphill and downhill running, which was in line with the recent findings reported by Zhang et al.[20] When assessing the effect of gait retraining during uphill running, both reduction in FSA (4.6°) and VILR (28%) were observed, with an increase in Knee-Flex$_{IC}$ (4.2°). Comparable biomechanical changes were observed during level running, as indicated by similar effect sizes. Moreover, during level and uphill running, the large effect sizes of VILR (Cohen's d = 1.00–1.04) were similar to a previous study reporting 62% lower injury risk following gait retraining (Cohen's d = 0.99–1.01).[6] Similarly, effect sizes of Knee-Flex$_{IC}$ (Cohen's d = 0.71–0.72) were comparable to a study showing reduced patellofemoral joint stress (Cohen's d = 0.78) during FFS running.[32] Regarding temporal spatial parameters, the changes in the stride length (−4%, Cohen's d = 0.19) and cadence (+3%, Cohen's d = 0.51) during uphill running were expected to have limited clinical significance, when compared to the effect sizes reported by another study showing clinical improvement in runners following FFS training (stride length Cohen's d = 0.66, cadence Cohen's d = 1.04).[33] Furthermore, according to Hobara et al.,[7] a 3% increase in cadence is expected to result in a reduction of VILR by 2.7%. Although the interaction between cadence and inclination on reduction of VILR remained unclear, the change in stride length and cadence was likely to play a less important role in the reduction of VILR during uphill, whereas the reduced FSA and increased Knee-Flex$_{IC}$ were the leading factors for achieving an effect size comparable to level running in VILR.

While the effect of gait retraining was similar between uphill and level running, insignificant reduction in VILR and smaller effect sizes found in downhill running had indicated a limited translation of gait retraining effect. In contrast to level and uphill running, effect size of FSA (Cohen's d = 0.79) during downhill running was similar to a cadence manipulation intervention (Cohen's d = 0.56).[34] The effect sizes of stride length, cadence and

Table 1
ANOVA results for the effect of gait retraining and slope on variables of interest.[a]

Factor		F	P-value	η_p^2
Gait retraining * Slope	FSA (°)	3.15	0.06	0.17
	VILR (BW/s)	2.07	0.14	0.12
	Stride length (m)	0.09	0.92	0.01
	Cadence (steps/min)	0.21	0.81	0.01
	Knee-Flex$_{IC}$ (°)	1.71	0.20	0.10
Gait retraining	FSA (°)	25.89	<0.01*	0.63
	VILR (BW/s)	9.41	<0.01*	0.39
	Stride length (m)	6.40	0.02*	0.30
	Cadence (steps/min)	7.99	0.01*	0.35
	Knee-Flex$_{IC}$ (°)	8.72	0.01*	0.37
Slope	FSA (°)	7.33	<0.01*	0.33
	VILR (BW/s)	35.53	<0.01*	0.68
	Stride length (m)	44.34	<0.01*	0.75
	Cadence (steps/min)	17.37	<0.01*	0.54
	Knee-Flex$_{IC}$ (°)	85.23	<0.01*	0.85

[a] FSA, footstrike angle; VILR, vertical instantaneous loading rate; BW, body weight; Knee-Flex$_{IC}$, knee flexion at initial contact.
* indicate a significant main effect (p-value <0.05) between factor and variable of interest.

Table 2
Comparisons of variables of interest before and after gait retraining.[a]

Condition		Pre	Post	P-value	Cohen's d
Level (0%)	FSA (°)	13.95 ± 2.49	4.52 ± 6.32	<0.01*	1.96
	VILR (BW/s)	117.42 ± 26.15	87.12 ± 31.96	<0.01*	1.04
	Stride length (m)	1.94 ± 0.28	1.88 ± 0.28	0.14	0.16
	Cadence (steps/min)	172.12 ± 11.09	176.39 ± 9.93	0.11	0.41
	Knee-Flex$_{IC}$ (°)	11.83 ± 5.66	16.42 ± 7.07	0.01*	0.72
Uphill (+10%)	FSA (°)	7.28 ± 2.80	2.71 ± 3.38	<0.01*	1.47
	VILR (BW/s)	68.98 ± 16.58	49.57 ± 21.95	<0.01*	1.00
	Stride length (m)	1.52 ± 0.19	1.46 ± 0.19	0.01*	0.19
	Cadence (steps/min)	172.08 ± 10.26	177.09 ± 9.26	<0.01*	0.51
	Knee-Flex$_{IC}$ (°)	18.89 ± 5.31	23.04 ± 6.31	0.01*	0.71
Downhill (−10%)	FSA (°)	7.56 ± 9.87	0.85 ± 6.79	0.02*	0.79
	VILR (BW/s)	110.87 ± 34.95	95.28 ± 34.40	0.16	0.45
	Stride length (m)	1.76 ± 0.36	1.73 ± 0.38	0.05*	0.11
	Cadence (steps/min)	165.83 ± 11.71	169.46 ± 10.05	0.03*	0.33
	Knee-Flex$_{IC}$ (°)	9.17 ± 4.11	11.89 ± 6.06	0.03*	0.53

[a] FSA, footstrike angle; VILR, vertical instantaneous loading rate; BW, body weight; Knee-Flex$_{IC}$, knee flexion at initial contact.
* indicate a significant difference (p-value<0.05) in variable of interest between pre-training and post-training.

Knee-Flex$_{IC}$ (Cohen's d = 0.11–0.53) were not comparable to the aforementioned studies.[6,32,33] These findings indicated the current intervention was not effective to induce clinically meaningful effect in downhill running, especially for VILR. One possible explanation for such findings might be the inhomogeneity of footstrike pattern during downhill running. In fact, a switch in the landing pattern between level and sloped running has previously been reported.[24] During the baseline assessment, half of the participants adopted a non-RFS pattern (25% MFS, 25% FFS) during downhill running. Participants who ran with a FFS during baseline experienced lower VILR, and might impose a floor effect and restriction on the degree of reduction in VILR, which could potentially dilute the training effect on reduction of VILR during downhill running on a group-level.

Although a positive result was found under the current gait retraining setup, such setup is subject to several limitations. Firstly, the training environment in this study was restricted to a 400-m flat running track, this highly controlled environment may not fully represent the runners' natural training conditions. The current cohort was recruited from running clubs which offered track training sessions, as this setup could control the effect of running training outside our gait retraining program. In addition, assessments were conducted on a laboratory-based treadmill with fixed inclination settings. Variations in running kinetics and kinematics has been previously reported between treadmill running and overground running.[35] Thus, future analyses should consider an in-field evaluation with less restriction on training and assessment environment. Secondly, the presence of an observer during the training and assessment sessions might induce Hawthorne effect, which may be overcome by the advancement of future wearable technology. Thirdly, the present study only evaluated the training effect immediately after the program. It is unclear whether the training effect could be sustained beyond the training (e.g., 1-month[27] or 3-month[16]). Fourthly, the absence of a control group in the present study also restrained a further exploration on the efficacy of our biofeedback system for modifying footstrike pattern. Finally, restricted by the present inclusion criteria, the effect of gait retraining on downhill running was not fully examined. Further analyses were necessary to fully examined the training effect on sloped running.

5. Conclusion

This study presented the biomechanical changes in runners following a course of in-field sensor-based gait retraining targeting footstrike pattern modification. Our findings indicated that the training resulted in a successful transition of footstrike pattern (from rearfoot strike to non-rearfoot strike) and the effects could be translated to both uphill and downhill running. However, the training led to inconsistent changes in the running kinetics, kinematics and temporal spatial parameters.

Declarations of interest

Dr. W.K. Lam is an employee from the Li Ning Sports Research Center, which is also a sponsor for this project. The sponsoring company only provided financial support in the form of research materials. The sensing insole technology had been patented at the State Intellectual Property Office of the People's Republic of China (Patent name: "Footstrike pattern measuring insole and algorithm"; Ref #1610200CN).

Acknowledgements

Funding: This work was supported by the Innovation & Technology Fund [Project reference number: ITP/085/15TI and ITT/026/17TI] under the Innovation & Technology Commission, The Government of HKSAR.

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