Full length article

Can runners maintain a newly learned gait pattern outside a laboratory environment following gait retraining?

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ABSTRACT

Background: Previous peak tibial shock gait retraining programs, which were usually conducted on a treadmill, were reported to be effective on impact loading reduction in runners. However, whether the trained runners can translate the training effect at different running modes (treadmill/overground), or running slopes (uphill/downhill), remains unknown.
Research question: Is the training effect from a treadmill-based gait retraining translatable to unconstrained running conditions, including overground and uphill/downhill running?
Methods: The peak tibial shock was measured during treadmill/overground running, as well as level/uphill/downhill running before and after a course of treadmill-based gait retraining. The 8-session training aimed to soften footfalls using real-time biofeedback of tibial shock data. Repeated measures ANOVA was used to examine the effect of training, running mode, and running slope, on a group level. Reliable change index of each participant was used to assess the individual response to the training protocol used in this study.
Results: Eighty percent of the participants were responsive to the gait retraining and managed to reduce their peak tibial shock following training. They managed to translate the training effect to treadmill slope running (Level: $p < 0.05$, Cohen's $d = 1.65$; Uphill: $p = 0.001$, Cohen's $d = 0.91$; Downhill: $p < 0.05$; Cohen's $d = 1.29$) and overground level running ($p = 0.014$, Cohen's $d = 0.85$). However, their peak tibial shock were not reduced during overground slope running (Uphill: $p = 0.054$; Cohen's $d = 0.62$; Downhill $p = 0.12$; Cohen's $d = 0.48$).
Significance: Our findings indicated that a newly learned gait pattern may not fully translate to running outside of the laboratory environment.

1. Introduction

High vertical loading rate has been widely considered a bio-mechanical risk factor for the development of running injuries [1]. Traditionally, the measurement of the vertical loading rate requires a force plate, which is relatively heavy and costly. Additionally, experimental setup with a force plate can only capture a single footfall at one time. Peak tibial shock, which can be measured by a light-weight and wireless accelerometer affixed on the distal tibia, enables the data collection of continuous strides in an outdoor running environment. Thus, it has become necessary to provide information related to impact loading [2,3], as previous studies have indicated a strong association between peak tibial shock and vertical loading rate [4].

Peak tibial shock has been used as biofeedback in gait retraining programs to soften the footfalls in runners. Past gait retraining programs reported a successful reduction in peak tibial shock as well as vertical loading rate during treadmill [5–7] and overground level running [2,3]. In spite of the positive findings of gait retraining in level running conditions, whether or not the runners can translate the training effect to slope running conditions remains unclear. It has been reported that running on slopes changes impact loading by affecting landing pattern [8], vertical stiffness [9,10], and temporal-spatial parameters [11]. Previous studies have reported a significantly higher loading rate during downhill running compared to level or uphill running [12]. Thus, it could be challenging for the runners to maintain softer footfalls while running on slopes after a course of gait retraining conducted on the level surface.

Additionally, running mode (i.e., treadmill vs. overground) could potentially affect the translation of the training effect. Although previous studies reported similar joint kinematics [13], ground reaction forces

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[14,15], and peak tibial shock [16] between the two running modes, treadmill running condition was still considered to have more constraints compared to the overground running condition [17]. Runners demonstrated shorter stride length and higher cadence when running on a treadmill [18]. While there are potential differences between these two running modes, it is unknown how much the runners can translate the newly learned running pattern from a treadmill to overground running following an indoor gait retraining program.

Despite the positive training effect in a familiar training condition, which is treadmill level running, how a runner will translate the training effect to untrained conditions, such as treadmill slope running or overground running, is yet unknown. On top of investigation of the training effect translation, it is important to consider the individual response to the gait retraining protocol used in this study. Through investigating the training effect on an individual level, we can gather a better understanding of the gait retraining protocol used in this study, and in turn, refine the training program for more effective motor learning. Crowell et al. assessed the training effect on an individual level and reported that the overall reduction in peak tibial shock after training varied from 17% to 60% in respondents, with only a single subject not showing peak tibial shock reduction after training [7]. Reliable change index (RCI) is a metric that could provide a robust measurement to assess the effect of gait retraining on an individual level [19].

Hence, this study sought to examine the peak tibial shock during treadmill and overground running on different slopes before and after a course of treadmill running retraining. We hypothesized that there would be training non-respondents, who failed to reduce the peak tibial shock during treadmill level running after gait retraining. Runners who were responsive to the gait retraining would maintain the training effect during overground and slope running.

2. Methods

2.1. Participants

Sample size estimation was performed using G*Power [20], and the primary variable of interest was peak tibial shock. The effect size of running retraining on peak tibial shock was based on a previously published study [6]. With alpha set at 0.05 and power at 0.8, 15 participants were adequate to power this study.

Volunteers from local running clubs were invited for a screening test. They were all recreational runners with at least 2-year running experience and a weekly mileage of 10 km or above. All participants were free from any active lower-limb injuries and known musculoskeletal conditions upon enrolment. Verbal and written consent was obtained from each participant before the experiment, which was reviewed and approved by concerning institutional review board.

2.2. Screening

One wireless accelerometer (± 24 g, Noraxon, Scottsdale, AZ, USA) was firmly attached on the anterior-medial side of the right distal tibia. The participants were given five minutes to warm up on a treadmill at a self-selected speed, and their preferred running speeds were recorded at the end of the warm-up period [21]. Vertical acceleration was recorded at 500 Hz for one minute after the warm-up period [6], and data were then filtered at 50 Hz using a fourth order Butterworth filter [4]. The peak tibial shock in the last ten footfalls was then identified. To avoid the floor effect, only participants with average peak tibial shock greater than 8 g were invited to the pre-training assessment [2]. Based on a previously published study, a peak tibial shock higher than 8 g was considered higher than the mean value plus one standard deviation in a group of uninjured young adults [22]. This study screened 18 runners in total to find 15 eligible runners who meet the inclusion criteria (4 females, 11 males; age = 40.9 ± 7.4 years; height = 1.67 ± 0.07 m;

weight = 60.5 ± 8.6 kg). They were invited for the following assessments and running retraining.

2.3. Pre-training assessment

The pre-training assessment included both indoor treadmill and outdoor overground running evaluations. The testing sequence was randomized, and the participants were running in their usual running shoes in all training and assessment sessions.

During the indoor treadmill running evaluation, all of the participants were asked to run on a treadmill at preferred running speed in three slopes, i.e., level running (LR), 10% uphill running (UR), and 10% downhill running (DR). Peak tibial shock was collected for one minute at each slope using the method identical to the procedures in the screening test [6]. In an outdoor overground running evaluation, the UR and DR were conducted on a 20-m concrete surface with 10% elevation, and outdoor LR were conducted on a 20-m flat concrete runway. The outdoor running speed was monitored using two pairs of photogates set in the middle of the runway. Based on a synchronization signal sent out from the photogates, we identified the acceleration data in the middle of the runway. The participants were instructed to maintain their preferred running speed, and a 5% variance in speed was allowed for each attempt [15]. We collected a total of 9 successful strides from each participant for each condition during outdoor running evaluation, and a successful footfall was defined as a trial within target speed range [23]. To match with the number of footfalls in outdoor running, the last 9 footfalls per condition during indoor treadmill running were extracted for further analysis.

2.4. Gait retraining

All the included participants then underwent a 2-week 8-session gait retraining program on a treadmill according to a previously established protocol [2]. In brief, continuous tibial shock data measured at the right distal tibia was provided on a screen at eye level. We provided a line indicating 80% of the average peak tibial shock measured in the pre-training assessment [6], instead of 50% as in the previously protocol [2]. Participants ran at their preferred speed and were instructed to maintain their peak tibial shock below the threshold. The training time increased from 15 min to 30 min across the eight sessions, while the feedback was gradually removed in the last four sessions. The participants were allowed to run outside the laboratory training protocol to maintain their weekly mileage. In the meantime, they were also encouraged to maintain the newly learned running gait during their daily running.

2.5. Post-training assessment

A post-training assessment was conducted within one week after the completion of the gait retraining [6] and the testing procedure was identical to the pre-training assessment.

2.6. Statistical analysis

The Shapiro-Wilk test was used to assess the normality of the data. For normal data, repeated measures ANOVA was used to compare the peak tibial shock under training effect (pre- and post-training test), two running modes (treadmill and overground), and three running slopes (LR, UR, and DR). If indicated, paired t-tests with Bonferroni corrections were performed for pairwise comparisons. Global alpha was set at 0.05.

We also computed RCI to compare the peak tibial shock difference on an individual level using the following function [19],

$$RCI = \frac{TS_1 - TS_2}{\sqrt{2 \times (SD_1 \times \sqrt{1 - r_{xx'}})^2}},$$

where TS_1 and TS_2 represent the average peak tibial shock measured in pre- and post-training assessment sessions; SD_1 represents the standard deviation in the pre-training assessment. The reliability coefficient of peak tibial shock ($r_{xx'}$) was set at 0.877, based on previously published data [24]. An RCI value greater than 1.96 indicates 95% confidence that there is a significant difference in peak tibial shock following gait retraining [19].

3. Results

All 15 participants completed the gait retraining and assessment sessions without adverse effect reported. The Shapiro-Wilk test showed that the dataset was normally distributed. Repeated measures ANOVA indicated that there was no interaction effect between running mode (i.e., treadmill vs. overground) and slopes. While peak tibial shock was significantly affected by running slopes (F = 4.40, p = 0.041), it remained comparable between running modes (F = 3.242, p = 0.093).

The comparison between pre- and post-training assessments showed that the 15 participants significantly reduced their peak tibial shock by 28.5% following gait retraining (p < 0.05, Cohen's d = 1.65). However, on an individual level, three participants exhibited less than 4.29% reduction in peak tibial shock during treadmill running (Fig. 1a, RCIs < 1.44). Thus, those three participants were regarded as non-respondents and they were excluded from further analysis assessing both overground and slope running performance.

The averaged peak tibial shock from the remaining 12 respondents in each running condition are presented in Fig. 2. Statistically, the effect of gait retraining, running mode (treadmill vs. overground), and running slope significantly interacted with each other (F = 4.31; p = 0.026). Training effect significantly interacted with running mode (F = 11.45, p = 0.006) as well as running slope (F = 4.42; p = 0.024).
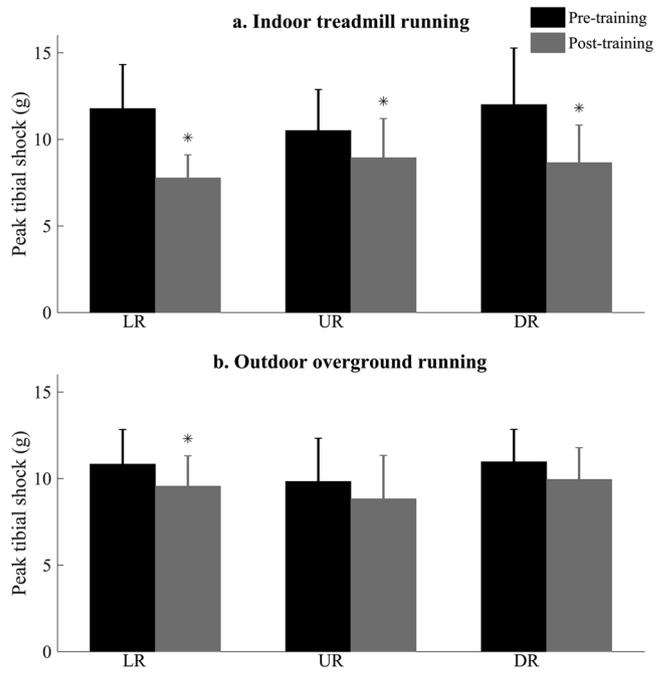

Fig. 2. Comparison of peak tibial shock before and after gait retraining during treadmill and overground running in the three slopes.
* Significant reduction compared to pre-training assessment.

However, there was no significant interaction between running mode and slope (F = 0.78; p = 0.47). Peak tibial shock was significantly affected by gait retraining (F = 28.48; p < 0.05), but it was comparable between treadmill and overground running (F = 0.028; p = 0.87), and across the three slopes (F = 2.51; p = 0.11). Pairwise comparison indicated that during treadmill running, the 12 respondents were able to
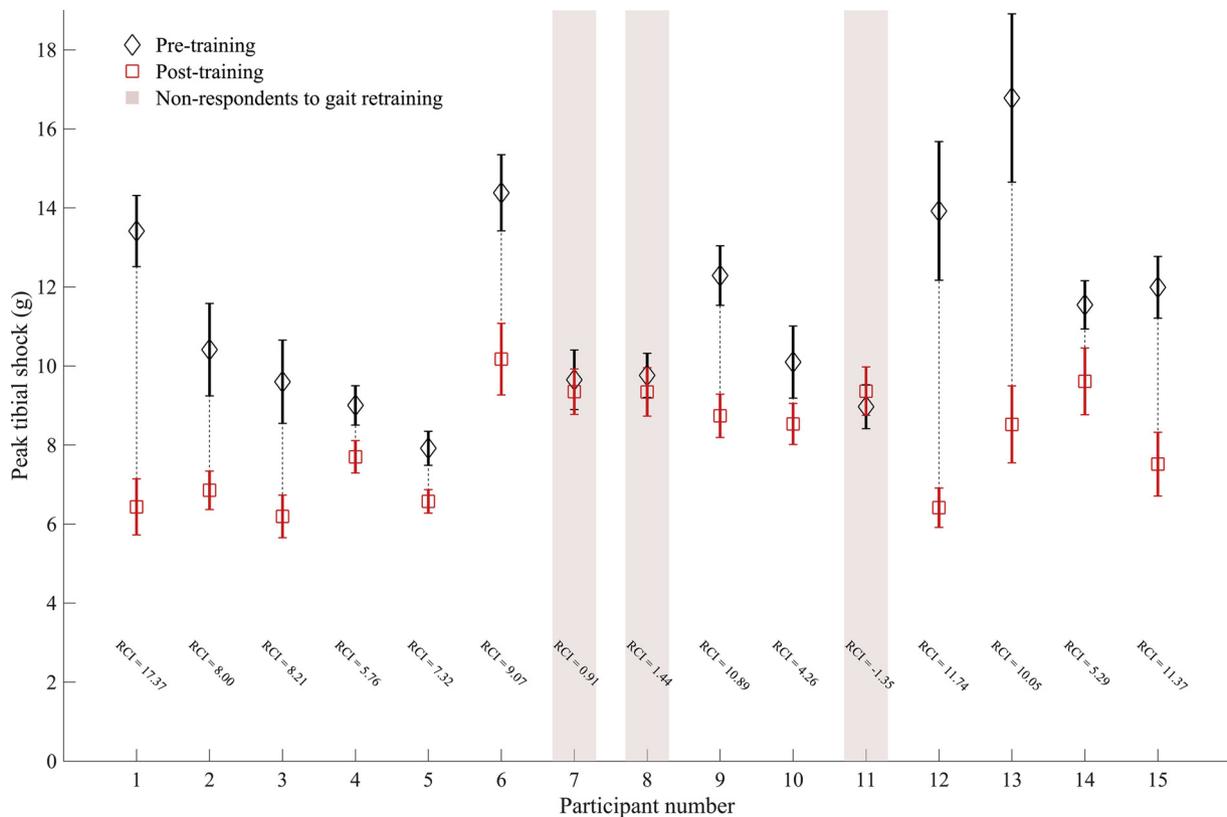

Fig. 1. Pre- and post-training comparison of peak tibial shock during treadmill level running condition.

reduce their peak tibial shock in UR (p = 0.001, Cohen's d = 0.91) and DR (p < 0.05; Cohen's d = 1.29) conditions. Moreover, they managed to reduce the peak tibial shock during outdoor level running (p = 0.014, Cohen's d = 0.85). However, they failed to translate the learning effect during outdoor UR (p = 0.054; Cohen's d = 0.62) and DR (p = 0.12; Cohen's d = 0.48).

4. Discussion

This study aimed to assess the translation of the training effect from a treadmill-based gait retraining program to overground, and to different running slopes. Runners experienced impact loading reduction in level treadmill running, and they were able to translate the effect to treadmill and slope running and outdoor level running. However, such skill was not fully translated when they were running on outdoor slopes.

In general, the gait retraining protocol used in this study reduced the peak tibial shock by 28.5% in the current participant sample, regardless of respondents and non-respondents. Such reduction fell within the range reported by previous gait retraining studies, which showed a 10.0% to 44.7% reduction in peak tibial shock following training [5–7]. The variation in the training effect could be due to different training targets (ranging from 10% to 50% lower than the baseline value) [2,3,5,6], and training intensity (from a single session 10-minute feedback training to a structured 8-session program) [2,5,21].

However, when the training effect was examined on an individual level, our results indicated an 80% training-response rate to the protocol used in this study. Crowell et al. reported a similar training-responsive rate in their gait retraining [7]. From a motor learning perspective, real-time visual feedback indicating the effect of movement would attract an external focus of attention [25], decrease the cognitive load [26], and thus was considered beneficial to the learning process [27]. A faded feedback design was shown to be effective to avoid feedback dependency [2]. However, the optimal fading rate of the feedback was yet unknown. Regarding the varied learning capacity of individuals, the fading procedure adopted in this study was possibly not optimized for every participant. Recent studies using performance-based fading feedback showed better learning results compared to training courses using constant feedback fading rate for all learners [28]. Therefore, in future gait retraining studies, a more flexible feedback protocol should be considered for better individualized outcomes.

Following a course of gait retraining on a level treadmill, runners appeared to exhibit softer footfalls during treadmill slope running. However, the effect of training interacted significantly with running slope. Such interaction could also be shown from the Cohen's d value calculated based on the peak tibial shock collected in pre- and post-training assessments among different slopes. The effect size of training was relatively larger during DR than UR, which could be due to the relatively lower baseline peak tibial shock values during UR [4], leading to a possible floor effect [2]. The reason for a reduced impact loading in UR could be due to a change in the landing pattern [12], or reduced center of mass displacement [9,14]. As we did not collect motion data in this experiment, further studies would be needed to assess the kinematics changes following gait retraining.

The 12 training-responsive participants significantly reduced their peak tibial shock by 11.7% during overground level running. However, a significant interaction between the training effect and running mode (treadmill vs. overground) was demonstrated, which could be explained by the reduced effect size of training during overground level running (Cohen's d = 0.85). Compared to the present study, previous studies [2,3] reported larger effect (Cohen's d = 1.5) and greater reduction (31–48%) during overground running after treadmill-based gait retraining. Such discrepancy could be a result of a more strict training target (i.e., 50% off from the pre-training value) adopted in previous studies [2,3]. In contrast to our original hypothesis, the participants responding to the gait retraining were only able to demonstrate a lower

peak tibial shock during outdoor level running, but not on slopes. Post-hoc power analysis showed that the findings were sufficiently powered in the overground level running condition (Power = 0.86), but not in overground slope running conditions (Power = 0.47–0.65). A sample size estimation based on the current dataset showed a sample of 29 participants would be sufficient to power this investigation.

Running overground on slopes requires motor translation at two levels, from treadmill to overground, and from level ground to slopes. The increased task complexity could challenge the training effect translation. A previous gait retraining study reported that the peak tibial shock showed an increasing trend at the 3-month follow-up [2]. Combined with the results from the current study, changes to the current running retraining protocol may be needed to improve the learning effect. Previous motor learning studies put forward the importance of variation in training as well as training intensity [29,30]. It has been shown that training variation is important for skill retention and learning effect translation [29]. However, the current gait retraining protocol may only provide the participants with sufficient training intensity but not variation. Whether or not a running retraining protocol with variation, such as running speeds and slopes, could lead to a better learning effect are underexplored. Further studies will be needed to assess the effect of gait retraining with more diversified training conditions.

The limitations should be considered when interpreting the findings of the current study. Since this study mainly focused on the running kinetics, joint kinematics data were not assessed. Further studies assessing the running kinematics would be warranted. The participants' extra running mileage outside the training protocol was not controlled in this study, which could affect the training effect and the translation of the learning effect. In this study, the overground running tests were conducted on a concrete surface, which may limit the generalizability of the findings. The lack of significant difference in the peak tibial shock in outdoor slope running may be due to an insufficient number of subjects.

5. Conclusions

After completion of an indoor-treadmill based gait retraining program, 80% of the participants managed to reduce their peak tibial shock in treadmill level and slope running conditions. The training-responsive runners managed to reduce their peak tibial shock during outdoor level running, but not during outdoor slope running. In view of our findings, refinement of the training protocol used in this study may be needed to improve the effects of the gait retraining and increase the ratio of training-responsive runners.

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