Reducing the peak tibial acceleration of running with a music-based biofeedback system: A quasi-randomized controlled trial

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Abstract

Background: Running retraining with the use of biofeedback on an impact measure has been executed or evaluated in the biomechanics laboratory. Here, the execution and evaluation of feedback-driven retraining are taken out of the laboratory.

Purpose: To determine whether biofeedback can reduce the peak tibial acceleration with or without affecting the running cadence in a 3-week retraining protocol. **Study Design:** Quasi-randomized controlled trial.

Methods: Twenty runners with high peak tibial acceleration were allocated to either the retraining (n=10, 32.1±7.8 yrs., 10.9±2.8 g) or control groups (n=10, 39.1±10.4 yrs., 13.0±3.9 g). They performed six running sessions in an athletic training environment. A body-worn system collected axial tibial acceleration and provided real-time feedback. The retraining group received music-based biofeedback in a faded feedback scheme. Pink noise was superimposed on tempo-synchronized music when the peak tibial acceleration was ≥70% of the runner's baseline. The control group received tempo-synchronized music, which acted as a placebo for blinding purposes. Speed feedback was provided to obtain a stable running speed of ~2.9 $m \cdot s^{-1}$. Peak tibial acceleration and running cadence were evaluated.

Results: A significant group by feedback interaction effect was detected for peak tibial acceleration. The experimental group had a decrease in peak tibial acceleration by 25.5% (mean: 10.9±2.8 g versus 8.1±3.9 g, p=0.008, d=1.08, mean difference = 2.77 [0.94, 4.61]) without changing the running cadence. The control group had no change in peak tibial acceleration nor in running cadence.

Conclusion: The retraining protocol was effective at reducing the peak tibial acceleration in high-impact runners by reacting to music-based biofeedback that was provided in real-time per wearable technology in a training environment. This reduction magnitude may have meaningful influences on injury risk.

Introduction

Alteration to running technique or gait retraining may help to manage the risk of injury in distance runners (Barton et al., 2016). Reducing the peak instantaneous vertical loading rate through gait retraining has resulted in fewer running-related injuries in novice runners (Chan et al., 2018). There have been several examples of running gait retraining programs that have proven effective in healthy subjects with impact loading evaluated in a lab setting (Chan et al., 2018; Clansey et al., 2014; Crowell and Davis, 2011; Napier et al., 2019; Willy et al., 2016). For example, real-time feedback derived from an instrumented treadmill has been provided in a lab and its effectiveness was evaluated in the same location (Chan et al., 2018; Napier et al., 2019). Willy et al. (Willy et al., 2016) brought the practice of gait retraining out of the lab and into the field by providing feedback on running cadence (i.e., steps per minute). Although this study has been executed as randomized controlled trial in a field setting, the evaluation of the impact loading still happened on a treadmill in the lab (Willy et al., 2016). So far, gait retraining with the use of real-time feedback on an impact measure has been conducted or evaluated in the laboratory (Barton et al., 2016; Bowser et al., 2018; Chan et al., 2018; Clansey et al., 2014; Crowell and Davis, 2011; Napier et al., 2015; Willy et al., 2016). A challenge is to transfer both the practice and the evaluation of its effectiveness from a treadmill in the laboratory to an over-ground environment outside of the traditional laboratory (Willy et al., 2016). The running cadence itself is no impact measure (Futrell et al., 2018), thus another input for real-time feedback might be favourable. The axial peak tibial acceleration (PTA_a) is of interest as it has been correlated with the peak vertical loading rate in the laboratory and has been proven reliable within- and between sessions during over-ground level running (Laughton et al., 2003; Van den Berghe et al., 2019b). Multiple studies have reported a reduction in PTA_a and other impact measures at the end and even following the completion of a treadmill-based retraining program with the use of real-time feedback on axial tibial acceleration (Bowser et al., 2018; Clansey et al., 2014; Crowell and Davis, 2011). Importantly, real-time feedback on the PTA_a is deliverable during over-ground running (Van den Berghe et al., 2021b, 2020). There is proof-of-concept for music-based feedback on the PTA_a to stimulate a substantial and perhaps clinically meaningful reduction in PTA_a (-27% or 2.96 *g*) in runners who exhibited high PTA_a (Van den Berghe et al., 2021b). However, a controlled trial is wanted because a control group was lacking and the intervention was limited to a single session of gait retraining.

Gait retraining protocols involve multiple sessions of running (Bowser et al., 2018; Clansey et al., 2014; Crowell and Davis, 2011; Willy et al., 2016). We hypothesize that music-based biofeedback can be effective for running with lower impact (i.e., PTA_a) during a multi-session protocol when motor learning principles are applied and self-discovery strategies are elicited. To achieve these design criteria, we used faded feedback and music that is tempo-synchronized. We previously developed a biofeedback module to reduce the PTA_a of running in a single session with the use of continuous feedback delivered by a prototype wearable system (Van den Berghe et al., 2021b). In the current study, we aimed to develop and test a wearable system for impact reduction by providing music-based biofeedback that is tempo-synchronized and faded over time. A major advantage of running with tempo-synchronized music is for its pleasing effect and possibility to increase the adherence of the participants (Alter et al., 2015; Moens et al., 2014). The beats of the music were synchronized in real time to the step frequency (Lorenzoni et al., 2019b; Van den Berghe et al., 2021b), meaning the auditory feedback does not interfere with the running cadence. Hence, the user may choose to alter his or her cadence in an attempt to achieve impact reduction and the beats per minute of the music will instantaneously follow the cadence of the runner. The faded feedback encourages internalization of the altered running form (Davis and Futrell, 2016), implying the retraining may further benefit from fading the feedback on PTA_a in time. Hence, incorporating a faded feedback scheme is desired to stimulate motor learning and will consist of a variable volume of biofeedback across the running sessions.

When carrying out over-ground gait retraining, it is important to control the external factors that might influence PTA_a. For instance, the running speed can influence PTA_a during indoor running (Van den Berghe et al., 2019b). Hence, adequate speed control is needed to study the isolated effects of biofeedback targeting PTA_a reduction. The monitoring and controlling of the running speed are more daunting over-ground than on a treadmill, especially in sports facilities located indoors. In such case, accurate indoor localization is realizable by ultra-wideband technology (Macoir et al., 2019b, 2019a; Ridolfi et al., 2018). The wearable system has a mobile tag on a trail run backpack to localize the runner using ultra-wideband in an athletic facility tailored to running.

The present study goes beyond previous work by focusing on an over-ground, biofeedback-driven gait retraining protocol that was executed on an athletic track in a controlled trial design. To that end, a lab-in-the-field was set up with ultra-wideband technology for the provision of high-fidelity feedback on the running speed. The research question was whether, instantaneous music-based feedback on PTA_a is decreasing the PTA_a in a population of runners with high PTA_a compared with a placebo given to controls in a gait retraining protocol. The effect of increasing running cadence on the PTA_a has been reviewed and is limited (Barton et al., 2016). Few studies have found a decrease in PTA_a when the habitual cadence was heavily increased (Busa et al., 2016; Clarke et al., 1985; Derrick et al., 1998). In our proof-of-concept study we found no clear change in running cadence despite a substantial change in PTA_a. Here, we wished to collect more evidence on whether an increase in running cadence would be a main motor strategy to decrease PTA_a. Therefore, we evaluated whether running cadence systematically changed between the baseline measurement and the end of the running protocol.

Methods

Experimental Design

This parallel, quasi-randomized controlled trial recruited people who engaged in distance running. Reporting of the study followed the CONSORT statement (Fig. 1, table S1). The trial can be classified as rather explanatory (Loudon et al., 2015). A risk-of-bias assessment was performed (Table S2) (Sterne et al., 2019). The institutional ethics committee reviewed and approved the experimental procedure. We carried out the methods following their guidelines and regulations. Extended methods were made available (supplementary materials).

Participants

Recreational runners between 18–60 years of age were recruited. Participants were physically healthy and required to have been regularly engaged in running (minimally 2 sessions/week and 15 km/week). They were excluded if they engaged in prior gait retraining, were wearing minimalist footwear during practice, or sustained a lower extremity injury in the previous 6 months. Participants provided written informed consent for participation. The extended methods further describe the data collection of the screening phase performed in a sports laboratory. The habitual footwear of each runner was inspected to confirm use of conventional athletic footwear during practice. Following the eligibility check and in line with Clansey and Crowell and colleagues (Clansey et al., 2014; Crowell and Davis, 2011), the runners experiencing a high PTA_a were targeted for the intervention. The sample size was based on primary and secondary justifications (Lakens, 2021). Primary, previous research involving gait retraining programs with the use of real-time feedback on axial tibial acceleration have recruited at least 10 participants in the experimental group (Clansey et al., 2014; Crowell and Davis, 2011). Secondary, resource constraints due to the limited number of battery-powered biofeedback devices, the availability of the athletic facility, and the manpower for instrumentation and supervision on site. The first 20 eligible volunteers started the running protocol (Table 1). They were assigned to either the retraining group or the control group. The test leaders generated an allocation sequence and quasi-randomly assigned 10 participants to the experimental group and

10 to the control group (extended methods). The sample size corresponded with previous interventions that provided multiple sessions of real-time feedback on PTA_a to runners who exhibited high PTA_a (Clansey et al., 2014; Crowell and Davis, 2011).

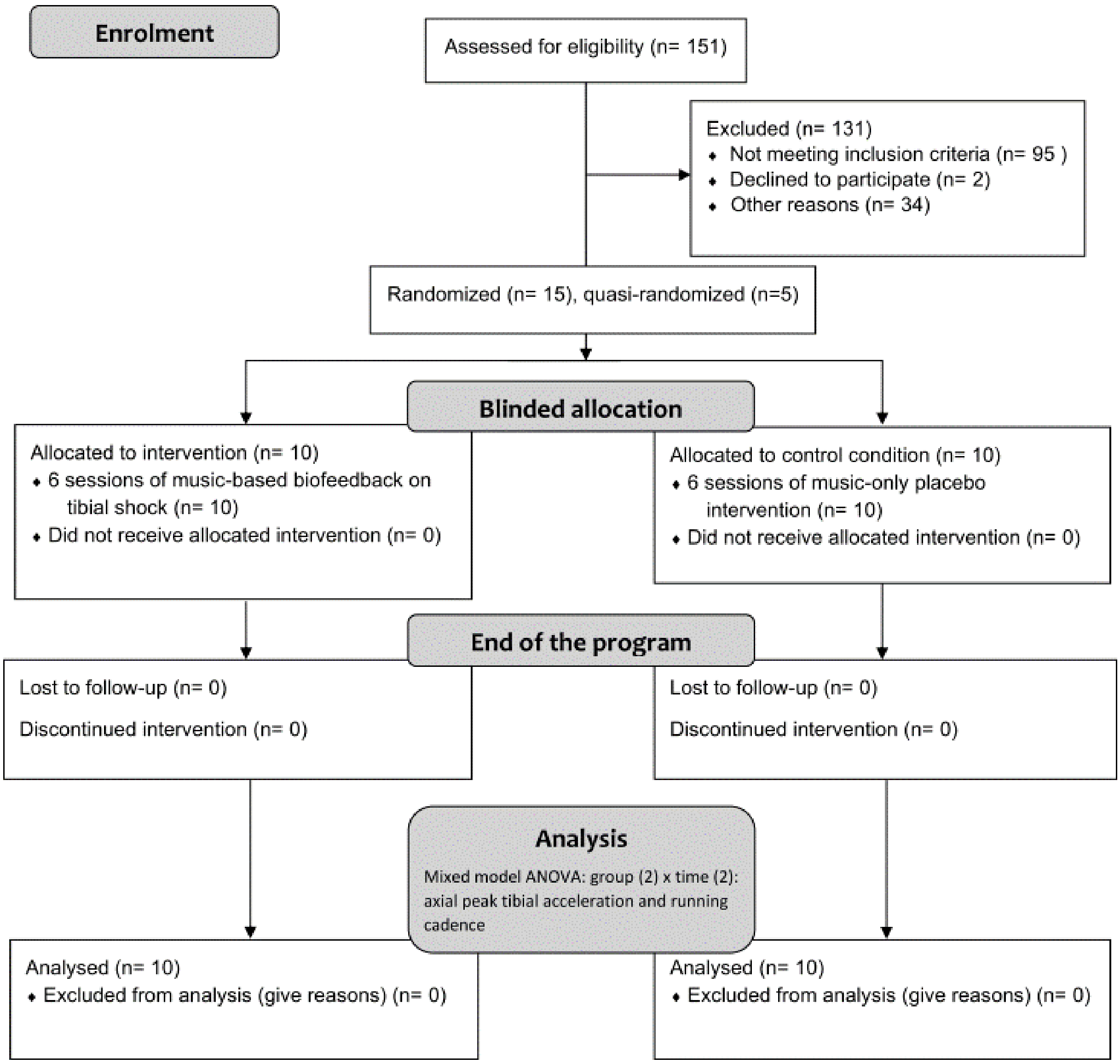

Figure 1. CONSORT 2010 flow diagram.

Table 1. Participants' group characteristics. Mean ± SD.

	Experimental group (n = 10)		Control group (n = 10)	
Demographics				
Sex	5 Males, 5 Females		3 Males, 7 Females	
Age (years)	32.1	7.8	39.1	10.4
Body height (m)	1.74	0.11	1.74	0.11
Body mass (kg)	71.5	18.3	69.9	12.1
Impact characteristics in the screening session performed at 3.2 m·s⁻¹				
Axial peak tibial acceleration (g)	13.16	1.91	10.95	1.34
Peak inst. vert. loading rate (BW/s)	137.8	32.7	111.9	23.3
Self-reported training habits				
Typical running speed ($m \cdot s^{-1}$)	2.91	0.27	2.93	0.42
Typical running volume (km/week)	27	10	36	18
Listen to music while running	3 always, 5 sometimes, 2 never		2 always, 2 sometimes, 6 never	
Self-reported injury history				
Running-related injury in the past 3 years	5 Yes, 5 No		4 Yes, 6 No	
History of tibial stress injury	4 Yes, 6 No		7 Yes, 3 No	

Measurement equipment

The runner wore a wearable biofeedback system that could provide real-time feedback on PTA_a while also informing about the running speed (Fig. 2). The technology is embedded in commonly used running accessories. For example, the textile component of the wearable system is a slim running sleeve worn on the lower leg. A lightweight accelerometer is patched in the sleeve that has a separate enclosure for wireless data transfer (Fig. 2, fig.S2-4). The mass of all components was about 1.8 kg.

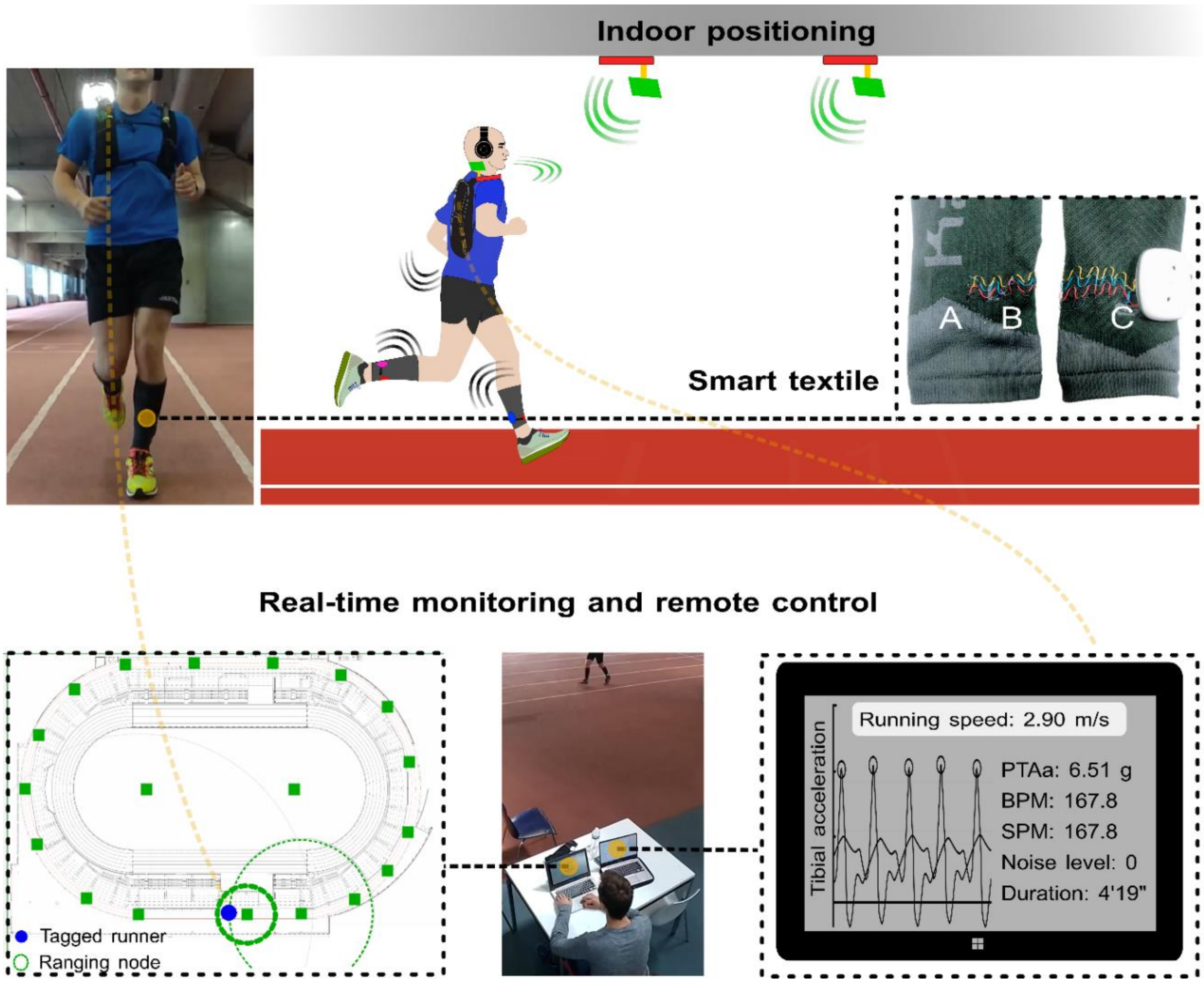

Figure 2. Schematic set-up of a participant running over-ground at 2.9 m·s^{-1}. The running speed and tibial acceleration data were transmitted over a wireless network for real-time monitoring by a test leader. The accelerometer was hidden in (A) a patch in a compression sleeve and connected by (B) wires woven into the sleeve to read-out electronics in (C) an enclosure at the other side of the leg. The mobile tag on the running vest was enregistered by the anchor nodes of the indoor positioning system.

Music-based feedback

The biofeedback system consisted of a 7" tablet strapped to a backpack, several sensors, and a pair of headphones. The tablet was connected to a microcontroller in connection with two lightweight accelerometers to non-invasively collect acceleration data. Tibial acceleration was continuously collected while a java-implemented peak detection algorithm on tablet unceasingly, bilaterally, and repetitively detected the PTA$_a$ (Van den Berghe et al., 2019b). The magnitude and timing of each peak were directly transmitted by the java app to a MAX/MSP patch (Lorenzoni et al., 2019b). That application acted as an interactive music player, provided the music-based feedback, and regulated the music-to-movement synchronization (Lorenzoni et al., 2019b). The smart music player was based on D-Jogger technology, which permits movement adaptation in locomotor tasks (Moens et al., 2014; Van Dyck et al., 2015). Manipulating the musical tempo slightly by use of D-Jogger has resulted in a subconscious adjustment of the running cadence to match the musical tempo (Van Dyck et al., 2015). Take the example of someone who is running with a habitual running cadence of 170 steps per minute at the given running speed. If a song would start playing at a slightly different musical tempo (e.g., 174 beats per minute), this runner would probably adjust the running cadence spontaneously to match the musical tempo (Van Dyck et al., 2015). Changes in running cadence have shown to influence the axial peak tibial acceleration (Busa et al., 2016; Clarke et al., 1985; Derrick et al., 1998), however, we wanted to test the effectiveness of the auditory biofeedback on the axial peak tibial acceleration in isolation. Thus, subconscious entrainment of one tempo with another was controlled for. In our case, we continuously adjusted the tempo of the music to match the cadence of the runner. More specifically, the beats per minute of were matched to the steps per minute on a step by step basis. The steps per minute were derived from the timing of the detected peaks in real time (Lorenzoni et al., 2019b; Van den Berghe et al., 2020). It is important to note that the instantaneous tempo-synchronization of the music permitted cadence-induced changes if desired by the user. Further, aligning the musical tempo (i.e., beats per minute) with that of the running gait (i.e., steps per minute) might result in a rewarding coupling between movement and music. The music database contained commercially available songs with a clear beat in the tempo range of running. Songs with an appropriate tempo were selected by the smart music player that instantaneously adjusted for slight and major changes in the running cadence (extended methods). Real-time biofeedback was provided by converting the level of the PTA_a into an audible signal that was passed to the runner via headphones. The audible signal was a perceptible pink noise that was superimposed on the music (Lorenzoni et al., 2019b). The loudness level of pink noise was directly linked to the level of PTAa of the targeted leg. The conversion was done based on an experimentally established relationship between perceived and imposed noise levels (Lorenzoni et al., 2019b). This pre-defined relationship informed the participant to reduce the superimposed noise associated with the momentary level of PTA_a by adjusting his or her running form. A momentary level of PTA_a below -30% of a runner's baseline value resulted in clear and enjoyable music (Van den Berghe et al., 2020), implying tempo-synchronized music without superimposed noise. As such, there was a rewarding solution to unpleasant musical feedback (Lorenzoni et al., 2019b). Based on the biofeedback, the experimental group may adjust the running form such that the noise gets reduced and the music becomes clearer with less punishment. Learning a new motor program is likely enhanced by providing biofeedback in two phases (Davis and Futrell, 2016). During the first, which was the acquisition phase, biofeedback was continuously provided and helped to develop the connection between the extrinsic feedback and the internal sensory cues associated with the desired target behaviour (Davis and Futrell, 2016). During the second, which was the transfer phase, the biofeedback was systematically removed. The fading of the biofeedback prevents the reliance on it, and enhances the internalization, and thus learning, of the new motor pattern (Davis and Futrell, 2016). We designed a two-phased faded feedback scheme (Fig. 3). The first two sessions of running comprised of 20 minutes of continuous biofeedback. The time of biofeedback provision gradually decreased in the last four sessions. None of the experimentals were told about the faded feedback scheme of biofeedback on PTA_a. Two backpack models were developed with identical software and were employed depending on the availability at the time of testing. These models are detailed in the extended methods.

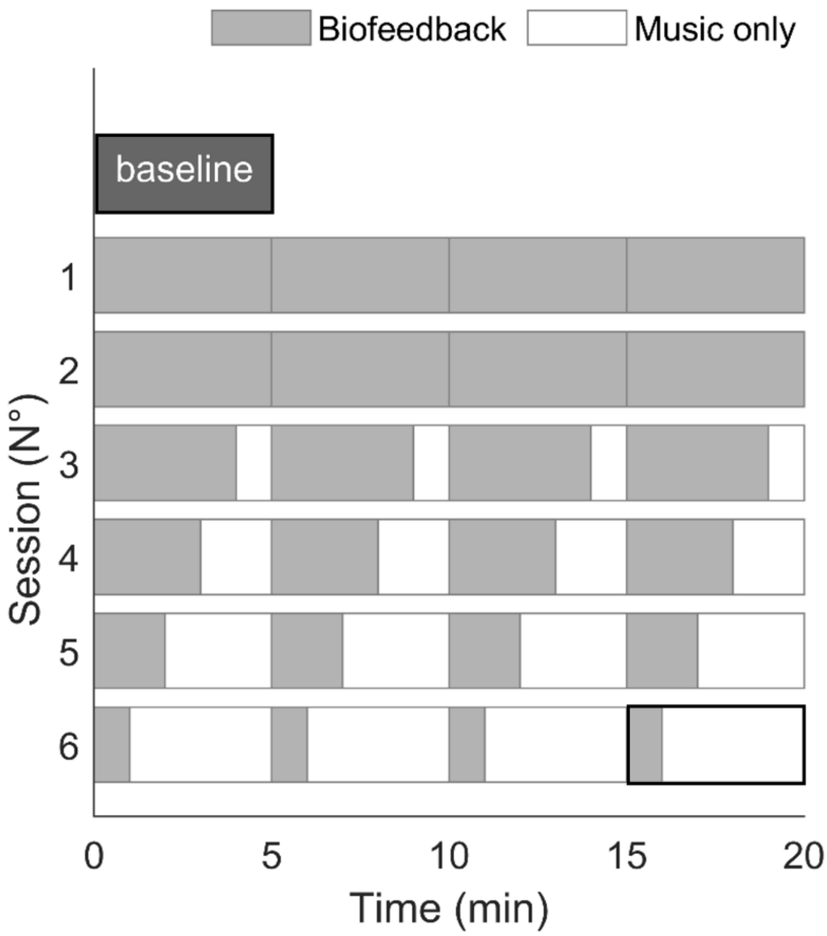

Figure 3. The faded-feedback scheme of the running retraining protocol. The amount of biofeedback was gradually removed in the final four sessions. Music played for 20 minutes in each running session. The tempo of the music continuously synchronized with the cadence of the runner. The frame borders indicate the 5-minute period used for the statistical comparison between the baseline and the end of the running protocol.

Indoor speed feedback

Individual feedback on the running speed was considered essential to avoid a speed-induced influence on PTA_a. Indoor training facilities are typically shielded from the outside by metal and reinforced concrete, which hampered localization from commercially available GPS devices. Therefore, we installed an indoor positioning system in a lab-in-the-field to achieve feedback on the running speed with negligible delay (extended methods). A mobile tag was placed on the backpack at shoulder height to track the position of the runner (Macoir et al., 2019a). The tag broadcasted an ultra-wideband signal that was captured by anchor nodes (Fig. 2, fig. S4). We refer to previous studies for a technical system description (Macoir et al., 2019b, 2019a; Ridolfi et al., 2018; Van Herbruggen et al., 2019). Verbal feedback ("faster" or "slower") was automatically transmitted through the headphone when deviating ±0.27 $m \cdot s^{-1}$ from the instructed speed of 2.9 $m \cdot s^{-1}$. An indoor sports hall was used when the athletic training facility was inaccessible because of external events ($n_{sessions}$ = 9/120) (extended methods).

Running program

The running protocol was supervised and took place in an indoor sports facility (Movie S1). All sessions involved over-ground running while wearing the wearable system. The instructed running speed of 2.9 $m \cdot s^{-1}$ approximated the average of the self-reported training speed. Both groups were subjected to six running sessions of twenty minutes (Clansey et al., 2014). Two weekly sessions were scheduled over a three-week calendar period (Clansey et al., 2014). The participants were blinded to the group assignment and the existence of the opposite group for the duration of the study. Both groups always received music synchronized to their running cadence. The experimental group received real-time feedback on PTA_a. The control group received the blind delivery of a sham treatment that consisted of tempo-synchronized music only. Before the running protocol started, each subject performed a 5-minute run without biofeedback nor music to determine his or her PTA_a at a controlled speed. During the baseline measurement, the leg with the greatest average value in PTA_a was targeted in the experimental group (Crowell and Davis, 2011). Each participant chose their preferred sound volume. The participants were then told to run while the wearable system provided them with individualized music. The experimentals were familiarized with discrete and perceivable levels of pink noise. They listened to the categorical noise levels, going from the minimum to the maximum and vice versa. The experimental group received verbal instructions in their mother tongue: "This may be very difficult, but I would like you to try concentrating on the task throughout the entire intervention. Listen carefully to the noise-distorted music. Try to run with the music as clearly as possible by modifying your running technique. The amount of distortion is linked to your tibial shock." No instructions on running gait were given to elicit self-discovery strategies (Clansey et al., 2014; Wood and Kipp, 2014). Participants were asked to wear the same footwear from the first run for the remainder of the sessions. A running session was terminated when the music stopped playing after the set period. Participants were allowed to run outside the training sessions (Clansey et al., 2014). Participants were free to choose whether to maintain the modifications outside the lab-based training sessions during their regular training routine in the community.

Statistical Analysis

Descriptive analyses were performed to summarize the screening data of the twenty enrolled participants. The main and secondary outcomes of this study were the influence of performing the running protocol respectively on the PTA_a and the running cadence as continuous variables. The data files of each participant were inspected. Previous studies about gait modification with the use of biofeedback on PTA_a have selected up to 20 values per participant per condition (Bowser et al., 2018; Clansey et al., 2014; Crowell et al., 2010; Crowell and Davis, 2011). In the present study, the detected values of PTA_a and running cadence were taken from the entire 5-minutes baseline measurement to ascertain a representative magnitude of PTA_a per participant. An equal time frame was used at the end of each session of the running protocol while music was still playing. Specific to the experimental group, biofeedback of a variable volume over time was encapsulated due to the faded feedback scheme. Subjects were not aware of data being collected for analysis in these time periods. The individual values were averaged to obtain a subject mean for these variables per condition (Data S1). The variables of interest were analysed via separate two-way, mixed-design analyses of variances. Our choice of analysis was similar to previous studies on running gait retraining (Chan et al., 2018; Willy et al., 2016). The within-subject factor of time was set across two levels (before and near completion of the running protocol). The between-subject factor was set across two levels (experimental group and control group). Following significant group-by-time interactions, pairwise comparisons were conducted to analyse the effects of the running protocol on the outcomes over time. Statistical tests were performed in JASP (v0.12.2, JASP Team, Amsterdam, the Netherlands), with the level of significance set as P value of less than 0.050. Effect sizes were calculated for the ANOVA (generalized and partial eta squared) and pairwise comparison analyses (Cohen's d) (Fritz et al., 2012). Levene's test and Shapiro-Wilk test of normality were carried out. Percentage differences, 95% confidence intervals for the mean difference, and the effect size before and near the end of the running protocol were computed for the outcome variables. The average running speed of each session was calculated. The individual data were made available in the supplementary datasheet.

2.5.1 Results

A total of 151 individuals underwent eligibility screening (Fig. 1). The twenty enrolled participants completed the running protocol between April and July 2019 in 18 ± 4 days without concomitant running-related injuries. Our application was directed to a method for gait retraining of runners with high peak tibial acceleration at a controlled running speed and was investigated in a quasi-randomized controlled trial. Individual demographics, training habits, other regular sports activities, and the training footwear of the twenty enrolled participants are retrievable in the supplementary datasheet. The latter resulted in an analysis by original assigned groups and the assumptions were met for the executed tests. There were significant group x time interactions for PTA_a ($F=4.675$, $p=0.044$, $\eta_P^2=0.206$, $\eta_G^2=0.031$), but not for running cadence ($F=0.867$, $p=0.364$, $\eta_P^2=0.046$, $\eta_G^2=0.004$) (Fig. 4). Subsequent pairwise comparisons in PTA_a over time revealed a clear decrease in the experimental group (n=10, mean±SD: 10.9±2.8 versus 8.1±3.9 g, $t=3.418$, $p=0.008$, $d=1.08$ [0.27, 1.85], mean difference = 2.77 g [0.94, 4.61]), without a significant change in the control group (n=10, mean±SD: 13.0±3.9 versus 12.8±3.9 g, $t=0.343$, $p=0.739$, $d=0.11$ [-0.52, 0.73], mean difference = 0.28 g [-1.57, 2.13]). We observed no significant main effect of time on running cadence ($F=1.113$, $p=0.305$, $\eta_P^2=0.058$, $\eta_G^2=0.005$), meaning the group of participants had no statistical difference in average scores of steps per minute before and near completion of the running protocol. There was also no significant main effect of group ($F=0.117$, $p=0.736$, $\eta_P^2=0.007$, $\eta_G^2=0.006$) on the running cadence, meaning we found no statistical evidence for a difference in step frequency between the experimental and control groups. Figure 5 shows the evolution in PTA_a and running cadence throughout the sessions. The running speed was within the a-priori permitted boundary for each session in each group (Fig. 5).

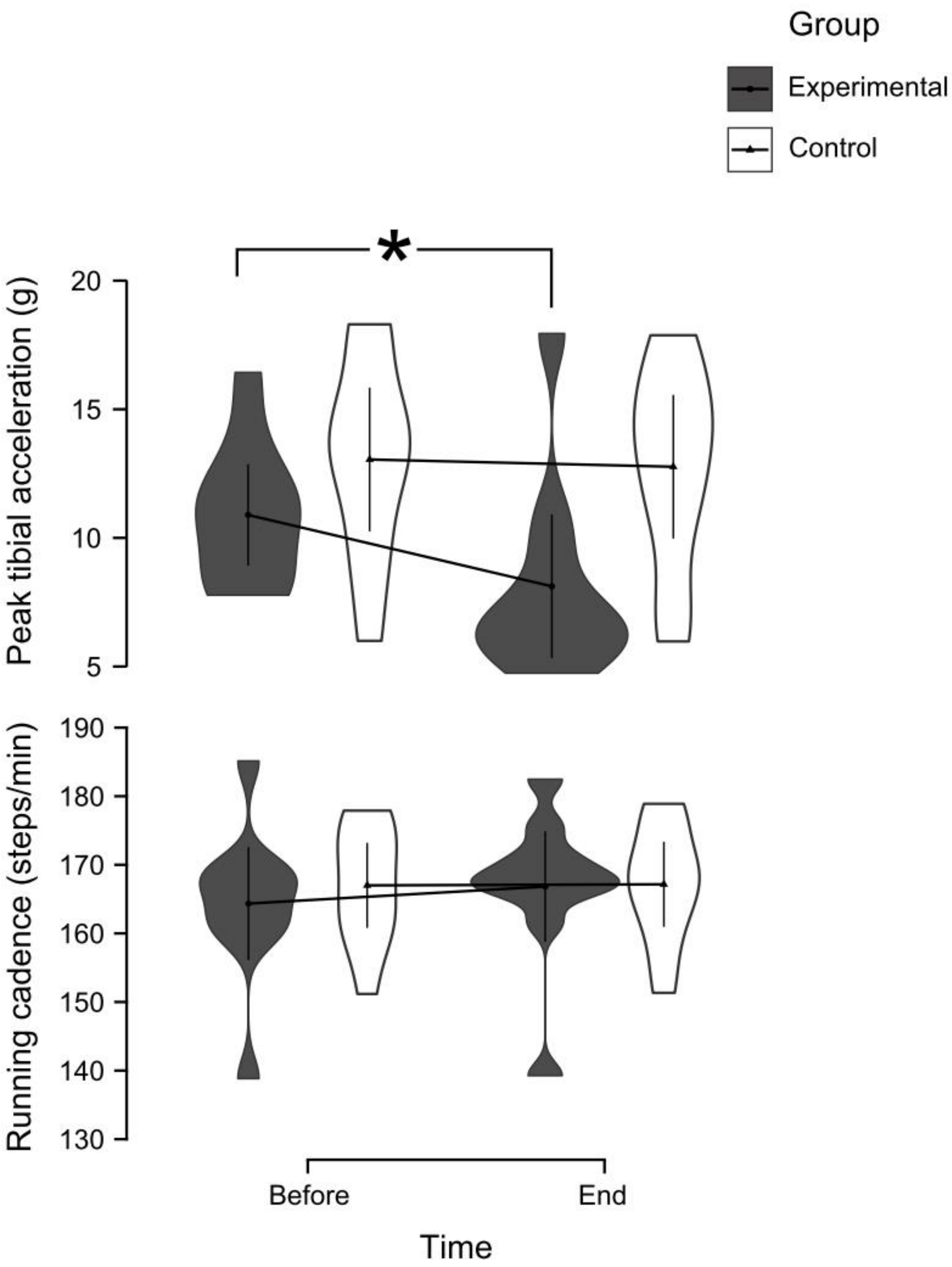

Figure 4. Results of the analysis of variance for the assessment of the axial peak tibial acceleration and the running cadence. A violin plot of the variables shows the estimated means (circles), 95% confidence intervals (error bars), and the kernel probability density of the data at different values. * indicates $p < 0.05$.

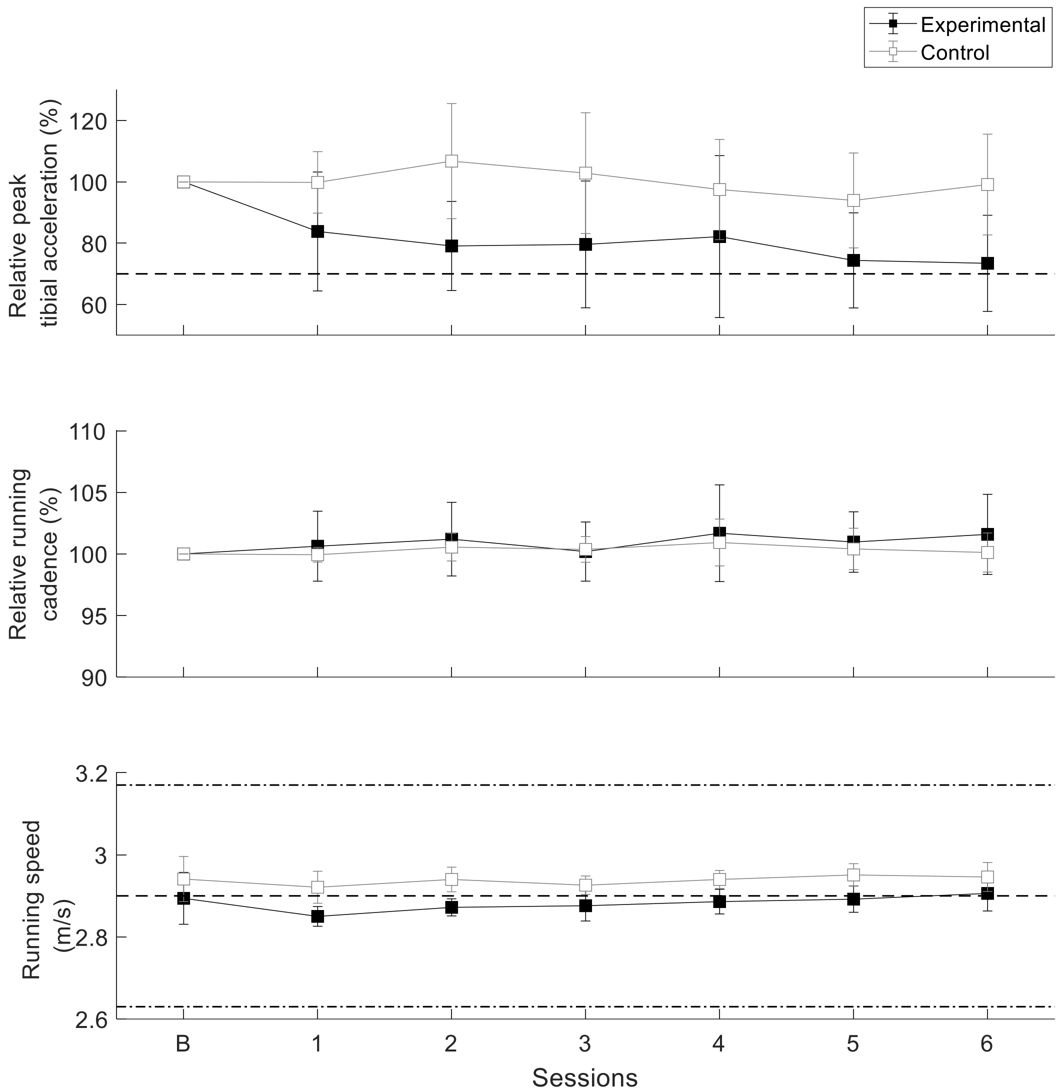

Figure 5. Mobile monitoring of the peak tibial acceleration, the running cadence, and the running speed for the experimental (black square) and control (white square) groups. The peak tibial acceleration and the running cadence are shown relative to the baseline value (%). The black horizontal line (--) shows the target value of -30% in peak tibial acceleration relative to baseline B in the upper panel. In the lower panel it indicates the targeted running speed of 2.9 m/s. The other horizontal lines (-• -) indicate the speed boundaries. Mean ± mean absolute deviation.

Discussion

Main effect on peak tibial acceleration

This single-blinded, quasi-randomized controlled trial evaluated the effectiveness of an over-ground and biofeedback-driven gait retraining protocol in runners who exhibited high PTA_a.

The auditory biofeedback comprised music synchronized to the running cadence with superimposed noise scaled to the level of PTA_a. We hypothesized that runners reacting to the biofeedback would achieve a substantial change in PTA_a, compared to the controls, near completion of the retraining protocol. Indeed, the biofeedback effectively stimulated a reduction in PTA_a (-25.5%, -2.77 g) outside the traditional biomechanics laboratory. The corresponding effect size was large and aligned with a previous single-session study (Van den Berghe et al., 2021b), which has been attributed to the use of a steering paradigm that was inspired by reinforcement learning (Lorenzoni et al., 2019b, 2019a; Silvetti and Verguts, 2012). The decrease in PTA_a of the experimental group appears to have already been achieved in the acquisition phase (Fig. 5), thereby under scribing the reinforcement learning paradigm where participants strive for a rewarding effect (i.e., clear music) from the start. The implemented faded-feedback scheme allowed a gradual decrease in the volume of biofeedback per session to enhance the internalization of a new motor pattern associated with less severe PTA_a. The evaluation of the biofeedback was encapsulated in a faded feedback scheme, wherein the volume of biofeedback diminished over time. We cannot exclude that fading of the biofeedback over time may have influenced the mean PTA_a in the analysis window. The 3-week running program with synchronized music as a sham treatment did not affect the impact measure and additionally confirms the between-session reliability of PTA_a on a group level (Sheerin et al., 2016; Van den Berghe et al., 2019b). This result further supports the reliability of peak tibial accelerations over time (Sheerin et al., 2017; Van den Berghe et al., 2019b). The findings of this blinded, quasi-randomized, controlled trial are a robust appraisal of the effectiveness of biofeedback-driven gait retraining on reducing PTA_a.

Secondary effect on running cadence

Based on the biofeedback, the runner could reduce the PTA_a by adjusting his or her running form. Self-induced changes in running cadence were possible because the musical tempo constantly synchronized with the cadence of one's running gait. Similar to our proof-of-concept study, no clear change in running cadence was observed for the given running speed. Hence, the data of the experimental group confirm the outcome of that study (Van den Berghe et al., 2021b). The indoor positioning system helped in controlling the running speed successfully, suggesting the step length also remained unchanged within-groups. The greatest descriptive change of a subject was +7.8% in running cadence. This subject-specific value is below the average increase of 8.6% in running cadence that was accompanied by reduction in peak instantaneous vertical loading rate in healthy high impact runners (Willy et al., 2016). Contrarily, real-time feedback on the vertical loading rate did not result in a significant increase in running cadence (Baggaley et al., 2017). Napier and colleagues (Napier et al., 2019) provided real-time feedback on the peak braking force and the reduction in braking force was accompanied by a statistically significant increase of 7% in recreational runners (Napier et al., 2019). The results at hand suggest the response in running cadence depends on the impact characteristic selected for biofeedback.

Plausible motor strategies to run with less PTA_a

Understanding motor strategies of running with less PTAa would improve our knowledge of low(er) impact running. A systematic review on gait modification concluded that runners tend to employ a distal strategy unless given specific cues (Napier et al., 2015). We suspect it also applies to real-time feedback on PTA_a in conjunction with the self-discovery approach. In habitual rearfoot strikers experiencing high PTA_a, two distal kinematic adaptations have potential for lowering the PTA_a during level running. One of the possible motor strategies is a more pronounced heel strike. This kinematic adaptation is supported by evidence from studies of between- and within-subject design (Bowser et al., 2011; Van den Berghe et al., n.d.), and is in agreement with most comments on the perceived adaptation from participants of the present study. Our research group has found a significant trend of lesser PTA_a in rearfoot strikes with a smaller strike index, which means first ground contact occurs more towards the back of the heel (Van den Berghe et al., n.d.). Results from a conference proceeding showed a smaller foot strike index following gait retraining on treadmill with the use of visual feedback aimed at reducing PTA_a (Bowser et al., 2011). The authors reported on two movement adaptations as the other half of participants changed to a non-rearfoot strike pattern (Bowser et al., 2011). Despite the mixed results on PTA_a between rearfoot and non-rearfoot strike patterns (Glauberman and Cavanagh, 2014; Gruber et al., 2014; Laughton et al., 2003; Van den Berghe et al., 2019a), gait retraining studies aimed at reducing PTA_a do have elicited a change to a non-rearfoot strike pattern from a rearfoot strike pattern (Bowser et al., 2011; Clansey et al., 2014; Van den Berghe et al., 2021b). The observed change was applicable to a whole group or part of it, or was commented on by one of the participants (Bowser et al., 2018; Clansey et al., 2014; Van den Berghe et al., 2021b). Next to a decrease in foot strike index, an increase in foot strike index might thus be an option for lowering PTA_a in people who exhibited high PTA_a during level running. It should be clear to the reader that multiple movement patterns can exist to reach the same goal. The goal was lowering PTA_a with the use of auditory biofeedback and we observed high inter-subject variability in the change of PTA_a, which ranged from +9.2% to -49.2% between subjects. Heterogeneity in the response is inherent to training (Ahtiainen et al., 2020). Interindividual heterogeneity has already been observed in the time of response to the music-based biofeedback during a single session of running retraining(Van den Berghe et al., 2020). Interindividual heterogeneity in the movement adaptation to the music-based biofeedback is likely also present. This heterogeneity should not be neglected because a different motor strategy may lead to a similar response in tibial acceleration, but a different response in internal loading (e.g., tibial stress).

Over-ground, music-based gait retraining for injury reduction?

Similar to other biofeedback-driven retraining programmes in trained runners (Bowser et al., 2018; Clansey et al., 2014), our protocol did not appear to cause any injuries within the scheduled programme of running. Analogues to Clansey and Bowser and colleagues (Bowser et al., 2018; Clansey et al., 2014), several experimentals reported muscle soreness or acute discomfort that progressively disappeared during the retraining process. These previous studies have targeted rearfoot strikers who exhibited high PTA_a (Bowser et al., 2018; Clansey et al., 2014). In the present study, the participants who received the biofeedback had high PTA_a and were also categorized as rearfoot strikers before entering the intervention (Fig. S6). The medium-term success of our musical approach is encouraging as both groups completed the structured running programme. These results add to the evidence that tempo synchronization of music can aid in adhering to a structured exercise program (Alter et al., 2015). The high compliance in a supervised setting is promising for clinical interventions that aim to reduce running-related injuries (Barton et al., 2016; Nielsen et al., 2020). The relative decrease in PTA_a observed in the present study might be clinically significant as Milner and colleagues (Milner et al., 2006) have reported that the likelihood of female rearfoot strikers to have a history of tibial stress fracture decreased by a factor of 1.4 for every 1 *g* decrease in PTA_a. The PTA_a has been correlated with the vertical instantaneous loading rate in a level over-ground running environment (Laughton et al., 2003; Van den Berghe et al., 2019b). This loading rate has been reduced in the experimental group who reported less running-related injuries compared to the control group in a randomized controlled trial with a one-year follow-up (Chan et al., 2018). The successful implementation of the biofeedback system in runners who exhibited high PTA_a opens opportunities for implementation in training and rehabilitation sessions to potentially manage or alter the injury risk in distance runners. Further investigation is needed to determine if the presented protocol has application in the risk management of impact-related running injuries. Replication of the present study is also warranted in larger studies including a follow-up period to determine if the changes in PTA_a are maintained after the retraining phase is stopped.

Perspective

Previous studies have utilized biofeedback in gait retraining programs to reduce impact loading with evaluation in the laboratory. Real-time biofeedback provided per wearable technology can stimulate a substantial and perhaps clinically relevant reduction in impact loading, with high compliance and without changing cadence. Our data and analyses provide a new pathway to a better understanding of feedback-driven running retraining for injury risk management in the field. The technology described is a viable way to collect large amounts of tibial acceleration and spatio-temporal data outside the traditional biomechanics laboratory. Wearable technology embedded in commonly used running accessories (e.g., running sleeves) lets sportspersons engage in gait retraining independent of their training environment. Miniaturisation of processing units and integration in commonly worn devices will eliminate the need of a backpack to house the processing power. Proven efficacious for lower impact running at a steady state running speed indoors, the step towards outdoor running practice is obvious as a lot of runners already use wearable accessories during running.

Conclusion

An over-ground gait retraining protocol using music-based biofeedback with faded feedback was effective at decreasing the PTA_a by a quarter. This form of biofeedback-driven gait retraining had high adherence and could be relatively easily and safely implemented in a training environment by embedding feedback technology in running accessories.