# Learning effects in over-ground gait retraining: A 6-month follow-up of a quasi-randomized controlled trial

**Original research article**

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## Abstract

*Objectives*: Real-time feedback on peak tibial acceleration is used in gait retraining programs to reduce impacts. Although the immediate effects of impact reduction in these programs have been evaluated in running, the learning and recall effects are typically neglected. Therefore, the current study aimed to evaluate learning and recall effects six months after a feedback-based retraining program.

*Design*: A 6-month follow-up of a quasi-randomized controlled trial with and without recall.

Method: Twenty runners with high peak tibial acceleration were assigned to either the experimental or the control group and completed a 3-week running program. A body-worn system collected axial tibial acceleration and provided real-time feedback for six running sessions in an athletic training facility. The experimental group received music-based biofeedback in a faded feedback scheme. The controls received tempo-synchronized music as a placebo for blinding purposes. The peak tibial acceleration and vertical loading rate of the ground reaction force were determined in a lab at baseline and six months after the end of the intervention to assess retention and recall.

*Results*: No statistically significant changes were found regarding the retention of the impact variables. The impacts of the experimental group substantially decreased at follow-up following a simple verbal recall (i.e., run as at the end of the program): PTAa:-32%, p=0.018; VILR: -34%, p=0.006. The impact magnitudes did not change over time in the control group. *Conclusions*: Although the biofeedback-based intervention did not induce clear learning at follow-up, a substantial impact reduction was recallable through simple cueing in the absence of biofeedback.

**Keywords**: motor learning, biofeedback, biomechanics, motor control, music

## Practical implications

- The impact reduction induced by our feedback device and protocol was not clearly retained after half a year. The provision of additional feedback in refreshing sessions is likely needed for motor learning.
- Practitioners can use simple verbal cueing to recall feedback-induced gait adaptations for impact reduction long time after runners have completed a gait retraining program.
- The distractive task of the running Stroop test appears advantageous to differentiate between retention and recall conditions when learning effects are evaluated.

## Introduction

The notion of gait retraining in human running has recently been studied in relation to the objective of impact reduction [1,2] and, relatedly, to injury risk management [3,4]. It has been known that runners can reduce the axial peak tibial acceleration ($PTA_a$) with the simple use of real-time feedback on $PTA_a$ [2,5]. For example, $PTA_a$ has been reduced by about 30% following a 3-week retraining program in a laboratory setting [2]. More recently, a feedback-based retraining program has been completed in a controlled training environment [5], which also resulted in a clear reduction in the $PTA_a$ upon its completion. However, the learning effects following the use of real-time biofeedback for impact reduction have only recently received substantial scientific attention [2,6–9].

Gait-retraining studies often focus implicitly or explicitly on the immediate effects of impact reduction and on variables potentially related to injury risk such as ground reaction forces [8,10,11]. This approach is useful for examining the acute sensitivity of running-related variables to feedback interventions, but neglects long term motor learning that may occur. Altering a motor pattern that has been reinforced over millions of cycles might be possible if guidance and practice are provided [9,12]. Data from a recent report on gait retraining suggests that impact reduction can be achieved and maintained up to one year [9], but the retraining program was performed in a lab environment and without control group. More recently, feedback-based gait retraining targeting a reduction in $PTA_a$ in a controlled training center has been studied in a quasi-randomized controlled trial [5]. Furthermore, the impact reduction achieved while receiving the real-time, music-based feedback on $PTA_a$ was relatively reproducible through simple verbal cueing without requiring this feedback [5,7]. Although the studies performed by Van den Berghe and Derie et al. have been performed in a controlled trial design [5,7], they are limited to the short-term influence of the biofeedback. Thus, an evaluation should be carried forward to examine if the impact reduction persists over time.

In this study, we took an extended approach to evaluating learning effects and asked whether low-impact running is retained and recallable half a year after completing the biofeedback-based retraining program. This question is well suited to the use of retention testing, which is our primary method. Based on the few studies that included some form of retention testing [1,2,9], we hypothesized that motor learning occurs and the impact reduction would persist.

## Methods

*Experimental design*. This follow-up of a parallel, quasi-randomized controlled trial is part of a study series [5,7]. Hence, the study cohort is identical to preceding studies in which the immediate effects on impact reduction and running biomechanics have been documented [5,7]. Reporting of the study followed the CONSORT statement (Figure 1). The institutional ethics committee reviewed and approved the experimental procedure. We carried out the methods following their guidelines and regulations. Interested volunteers completed an online questionnaire and made an appointment with the research team.

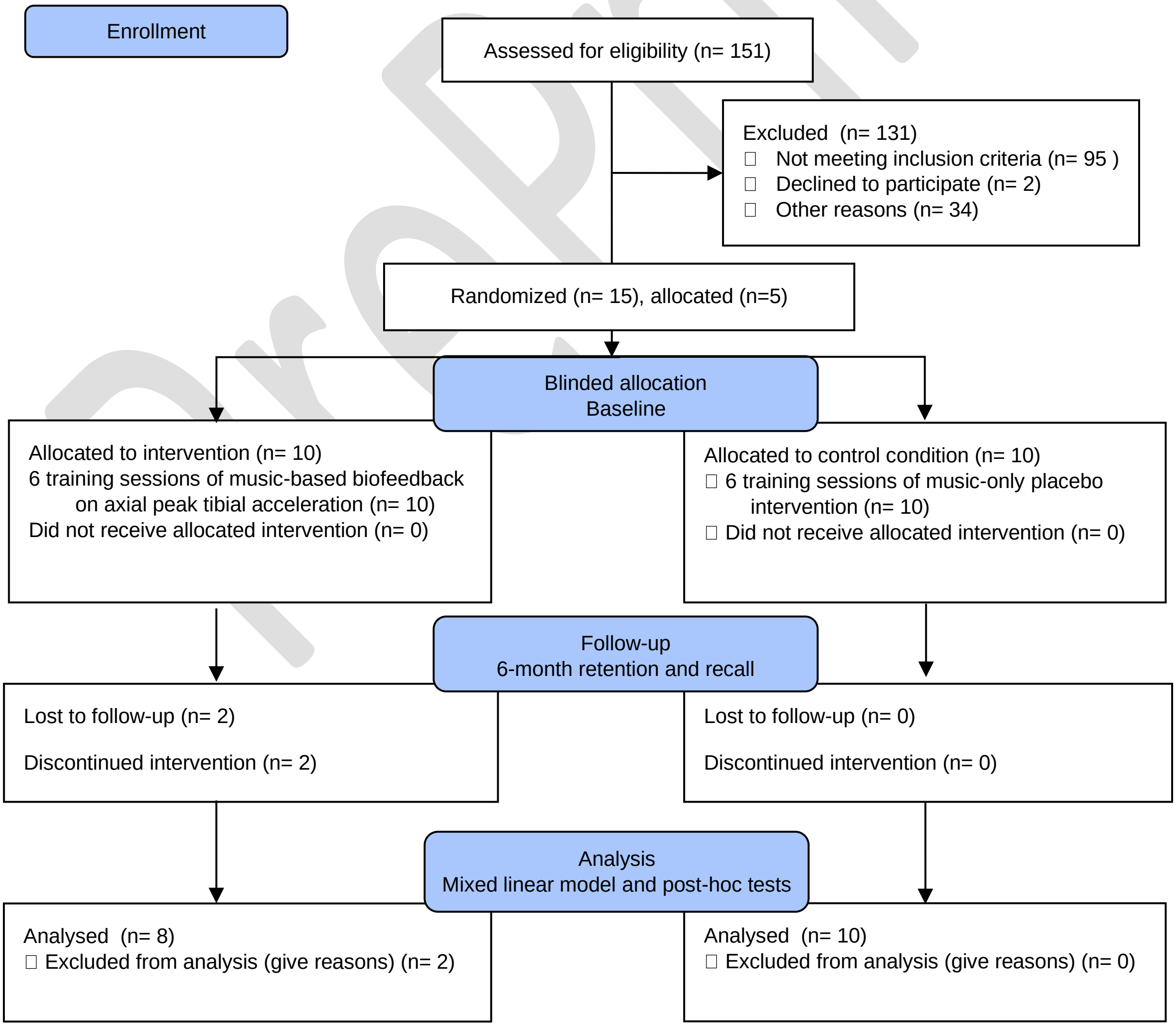

Figure 1. CONSORT 2010 diagram: flow chart of study participants and conditions.

Participants enrolled in the first (screening) phase were invited to participate in the second (intervention) part of the study if they fulfilled the following inclusion criteria: aged 18–60 years, no contraindication to performing running activity, typically running 15 km per week or more spread over at least two weekly sessions and experiencing high $PTA_a$ while running at ~3.2 m/s. To fully qualify, participants were required to attend a brief running impact screening in a sports laboratory in which only tibial acceleration was collected. Extended methods have been made available and further describe the data collection of the screening phase performed [5]. Runners experiencing high $PTA_a$ relative to a pool of 151 screened runners were re-invited and the first twenty volunteers proceeded to the intervention phase [5,7]. These participants were assigned to either the retraining group (n = 10, age: 32.1±7.8 years, body mass: 71.5±18.3 kg, body height: 1.74±0.11 m, weekly running volume: 27±10 km, self-reported training speed: 2.9±0.3 m/s, Males/females: 5/5) or the control group (n = 10, age: 39.1±10.4 years, body mass: 69.9 ±12.8 kg, body height: 1.74±0.11 m, weekly running volume: 37±18 km, self-reported training speed: 2.9±0.4 m/s) and were blinded to the group assignment. The sample size was chosen so that short-term effects in impact reduction could be observed in a quasi-randomized controlled design through the application of music-based biofeedback [5,7].

Two lab visits were scheduled, prior to and after the intervention, during the 6th month of the follow-up. Both tests were performed while running continuously on an indoor track (Figure 2) at a pace of $2.9 \pm 0.2\ m{\cdot}s^{-1}$ in mimicked pairs of the participants' habitual running footwear. An overview of the subjects' habitual footwear and matching laboratory footwear has been made available [7]. The first visit comprised a 5-min warm-up that served as a familiarization to the setup, and a continuous run of about 25 minutes to determine baseline values. The second visit also comprised a warm-up which was followed by two running conditions to assess learning: the retention condition and the recall condition. In case of retention testing, participants may intentionally produce the desired gait pattern during assessments, making it difficult to discern if motor learning and retention have truly occurred [13]. Therefore, to avoid response bias, participants were intentionally distracted in the retention condition. They performed a cognitive distraction task each time when passing the lab's measurement zone. Specifically, a modified Stroop test started each time a participant would enter the measurement zone (Figure 2, video S1). We projected a written name of a color, in which the name of the color and the color of the text not necessarily matched (video S1). They were instructed to say the color of the text out loud, but not the word itself. Participants were asked to say the word accurately and as fast as possible. For the recall condition, the participants were asked to reproduce the running technique from the intervention six months earlier. We used a simple verbal instruction for all subjects: *"Try running* *as you did in the final session of the retraining program. "* The instructed running speed was in agreement with that of the running program [7].

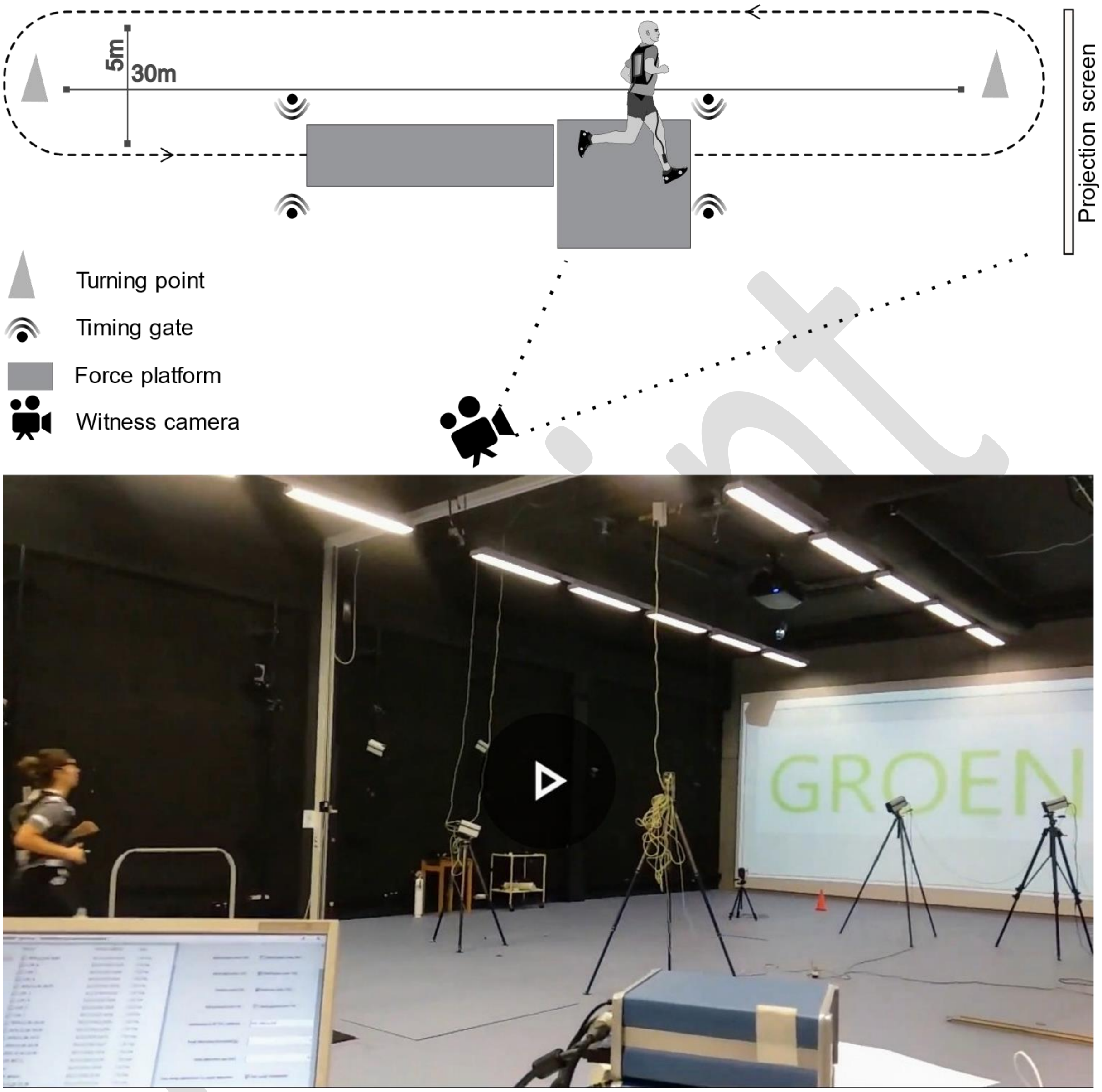

Figure 2. Experimental setup. The running course is illustrated on top. The picture shows a participant during the Retest condition at follow-up. A Stroop test was presented to participants in front of the runway while they ran laps on an indoor track. The projection screen was positioned approximately 15 m away from the center of the measurement zone. The associated video clip is supplemented (Video S1).

*Running program.* Both groups were subjected to a 3-week running program in a supervised training facility [5]. The 3-week schedule and the six sessions were similar to the program design made by Clansey and colleagues [2]. Each running session consisted of twenty minutes of running with music. Participants were told to run with specifically selected music tailored to them. The music-only group listened to music tracks that were suited for synchronization to the individual's running cadence. As such, the smart music player adjust and could mirror the beats per minute of the music to the steps per minute of the runner. The experimental group additionally received real-time feedback on $PTA_a$. This feedback was music-based wherein the music was distorted at medium and high $PTA_a$ [5,10]. This impact measure was converted into noise that is perceptible by the runner, wherein the conversion is done based on a predefined relationship between perceived distortion levels and imposed distortion levels [14]. Specifically, pink noise was superimposed on the music if the peak tibial acceleration was ≥70% of the runner's starting $PTA_a$ [5]. This starting value was determined during the 5-minute warming-up run without any musical feedback [5]. The limb exhibiting the highest mean $PTA_a$ in this period was considered dominant and used further. It has been postulated that a faded feedback approach is superior to continuous feedback for retaining motor skills [15]. Fading of the feedback encourages internalization of the altered running form, [12] implying the motor skill learning may benefit from fading the feedback on $PTA_a$ in time. Therefore, we implemented a two-phased feedback scheme desired to stimulate motor learning [5]. The fading of the biofeedback prevents the reliance on the feedback and enhances the internalization, and thus learning, of the new motor pattern.[12] In the first (acquisition) phase, feedback was continuously provided which helps to develop the connection between the extrinsic feedback and the internal sensory cues associated with the desired target behavior.[12] So, the first two sessions of running comprised of 20 min of continuous biofeedback. In the second (transfer) phase, the feedback was systematically removed, meaning the time of biofeedback provision gradually decreased in the last four sessions. We did not inform the experimental group about this faded feedback scheme in which the volume of the feedback varied. The running speed was steered to approximately 2.9 $m{\cdot}s^{-1}$ throughout these sessions [5], which corresponded to the mean self-reported endurance training speed of the participants. Please see reference [5] for a detailed description of the retraining protocol. In this 3-week program, participants were free to choose whether to maintain the gait modifications during their regular training routine. Following completion of the program, participants were advised to adopt their new gait pattern in their regular running practice [3].

*Materials and lab-based measurements.* Participants were equipped with a portable body-worn measurement device. Its main components were two accelerometers (LIS331, Sparkfun, Colorado, USA, sampling rate: 1000Hz/axis) wired to a microcontroller. This microcontroller was connected to a 7-inch tablet strapped to a stripped backpack [16,17]. Sensor weight and the method of attachment plays an important role in data quality according to a systematic review [18]. The accelerometers were lightweight with a mass of less than 3 grams per unit. Our method of attachment was similar to an approach that has been proven reliable within and between sessions of over-ground, level running [16]. Each sensor was firmly taped to the skin at eight centimeters above the malleolus medialis on the anteromedial aspect of a lower limb. Prior to this action, the skin in the vicinity of the selected sensor location got pre-stretched with sports tape to ensure a rigid coupling. Then, a test leader visually aligned the vertical axis of each accelerometer with the longitudinal axis of the tibia. Thus, we assumed the acceleration collected corresponds to the acceleration of the tibial bone. The body-worn sensors permitted participants to run continuously along a 30-m instrumented running track [7]. Two pairs of photo gates were positioned in the measurement zone 6 meter apart. Two force platforms (AMTI, Watertown MA, USA; dimensions: 2.1·0.5-m and 1.2·1.2-m; sampling rate: 2000Hz) were situated in the center of the measurement zone. These platforms had covers on top which were flush with the running track. Acceleration and force plate data were synchronized in time up to millimeter accuracy by applying a synchronization protocol described elsewhere [16].

*Statistical analysis.* Baseline demographic data were analyzed with independent t-tests to determine presence of differences between the experimental and control groups. Running variables of interest were PTA$_a$ and the vertical loading rate. The PTA$_a$ was defined as the maximal positive axial acceleration of the lower leg while the foot contacted the ground. The events of foot-ground contact were derived from the vertical ground reaction force. This force was filtered using a 2nd order, zero-lag low-pass Butterworth filter with a 60Hz cut-off frequency. The force threshold was set at 20 N. The vertical loading rate was calculated as the maximum value of the first derivative of the ground reaction force in the first 0.050s of stance. These variables were analyzed via linear mixed model with an $\alpha = 0.05$ (JASP 0.16.3). The fixed effect variables we entered were Group (experimental, control) and Conditions (baseline, retention, recall) and the subjects as random effects grouping factor. In the case of a significant group × time interaction, post-hoc comparisons were conducted with a Bonferroni correction. Cohen's d was calculated to determine the magnitude of the effect. Handling missing data is an important, yet difficult and complex task when analyzing results of randomized trials. Therefore, in a post-hoc analysis, missing values were replaced using single imputation of the mean [19]. In simple mean imputation, missing values are replaced by the mean for the variable of interest.

## Results

Two experimental subjects were lost because of an injury or due to a personal reason after the retraining phase was completed. The follow-up happened after 183 ± 9 days (mean ± standard deviation). There were no significant differences between groups. There were significant group × time interactions for PTA$_a$ (F=3.369, p=0.047) and vertical loading rate (F=4.345, p=0.021). Subsequent pairwise comparisons revealed only a significant change from Baseline-Recall for the experimental group: PTA$_a$ (Mean difference=-2.43 *g* or -31%, t=3.905, p=0.007, d=1.295) and vertical loading rate (Mean difference=-30.5 BW/s or -34%, t=4.231, p=0.003, d=1.195) (Figure 3, Table S1).

For the control group, no significant changes occurred at 6-month follow-up in either the Retention or Recall compared with Baseline levels. The post-hoc analysis with imputed missing data revealed that the change between Baseline and Retention in the experimental group became statistically significant for $PTA_a$ (|Mean difference| = -1.96 g, $t = 3.429$, $p = 0.023$, $d = 1.065$) (Table S1).

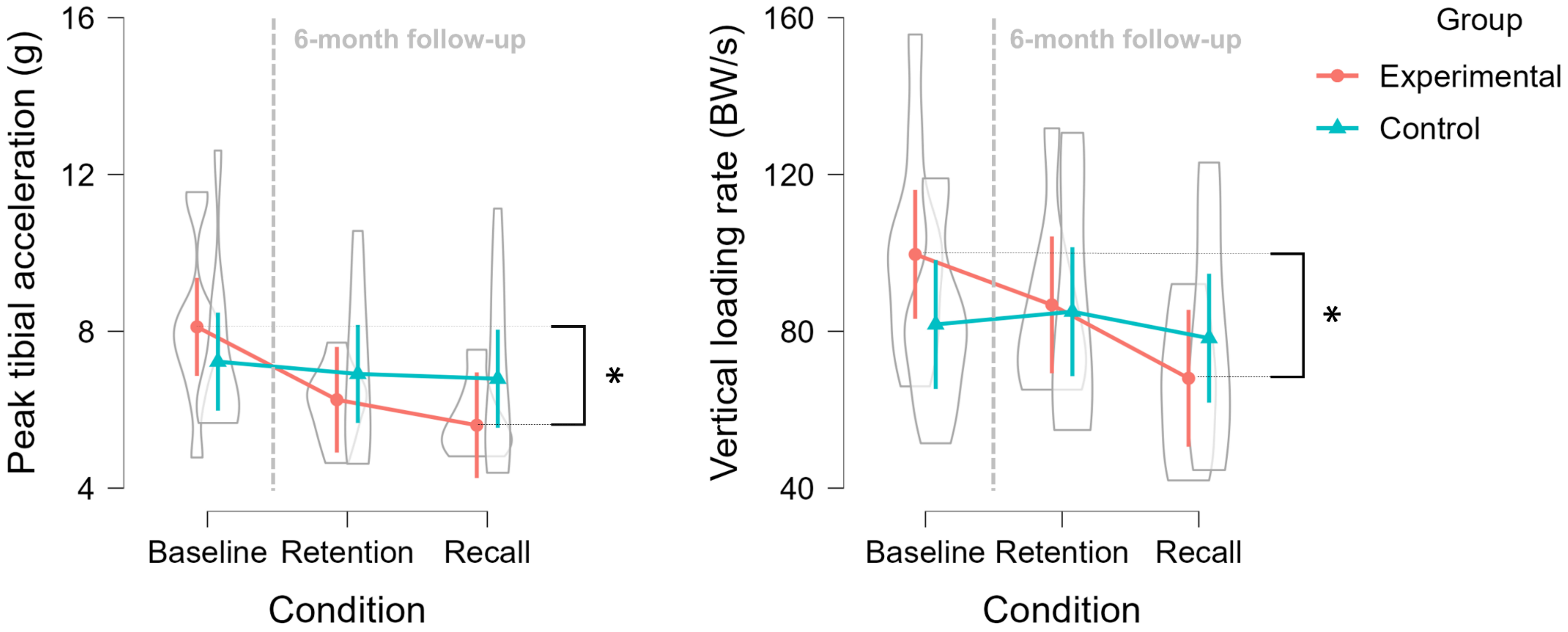

Figure 3. Peak axial tibial acceleration and vertical loading rate for the experimental and control groups at each of the time points throughout. Error bars represent 95% confidence interval. * indicates a statistical difference from the post-hoc comparisons.

## Discussion

The current study evaluated retention and recall effects of a biofeedback-based program targeting impact reduction in level running. The hypothesis was that learning would occur, which was only partially supported. We addressed learning from the perspective of retention first, and found no significant change in impact magnitudes after six months compared to baseline testing. Then, from the perspective of recall, the experimental group who received the biofeedback did achieve an impact reduction of large effect with a Cohen's d effect size of 1.295 at follow-up. This result was found when a test leader explicitly asked to reproduce the running form from the last running retraining session. This finding also suggests that the motor adaptation to achieve impact reduction is recallable long time after completing a 3-weeks intervention. Interestingly, the magnitude of impact reduction by the recall after half a year (mean difference in PTA: -2.43 *g;* vertical loading rate: -30.5 B/W) is in line with that of low-impact running at post-intervention (mean difference in PTA: -2.55 *g;* vertical loading rate: -31.5 B/W) in the same testing environment [7]. So, those who self-discovered impact reduction while having used the auditory biofeedback device remain aware how to run low-impact without spontaneously performing it in the long term.

Contrary to our expectations, the reductions in $PTA_a$ and vertical loading rate previously observed upon completion of the retraining program were not maintained in this rather small cohort after half a year. Data from a report by Bowser et al. (2018) on gait retraining suggests that impact reduction can be achieved and maintained up to one year. Our original research data also countermand a recent systematic review suggesting that real-time tibial acceleration feedback can reduce $PTA_a$ for periods to 12 months when the feedback is removed [20]. A possible explanation for this discrepancy is situated in in the training and testing environments. Previous studies have conducted the intervention and the follow-up testing in the same environment. Their participants must have spent a considerable time in an artificial lab setting during the retraining. At follow-up these participants re-appeared in the same lab, which arguably increases the chances of an instinctive recall and in response bias. In the present study, the retraining program and the learning evaluation were conducted at different locations, meaning the participants performed the learning tests in another environment than they practiced. Another possible explanation is that the participants had insufficient practice time to establish true motor skill learning. Participants received only six practice sessions while the studies reporting a retainment of impact reduction at a follow-up involved eight practice sessions [8,9].

A standardized feedback schedule was applied in the current study. This schedule consisted of two-phases because the learning of a new motor program is likely enhanced by providing biofeedback in two phases.[12] The acquisition phase involved continuous biofeedback and proceeded the transfer phase in which the biofeedback was gradually decreased. A drawback to this schedule is that participants may enter the transfer phase too soon and may benefit from more continuous feedback as provided in the acquisition phase. Therefore, we propose to initiate the fading of the feedback only if the participant has reached a major impact reduction for a certain period of time. This reduction may be qualitatively analyzed by a supervisor while monitoring the participant from a distance or may be quantitatively analyzed through a change-point analysis [17]. Another recommendation based on our observations is to tailor the number of sessions in the retraining program. A statistically non-significant reduction in the impact magnitudes at Retention suggests that participants need more sessions than initially foreseen. Also, they may benefit from earlier refresher training or recall sessions to achieve true motor learning. Although a new motor pattern was not yet ingrained at Retention with distraction, we find it encouraging that reproduction of a specific motor skill is possible through a simple verbal recall at six months follow-up after just six times twenty minutes of practice. Looking at the control group, the $PTA_a$ remained stable after half a year. This finding extends to a simple test-retest in which the $PTA_a$ in level, over-ground running was deemed reliable on the group level [16].

A first and main limitation of the current study is the small sample size. Simulating experiments in small sample sizes has revealed that despite clear results with the original large samples, the results with smaller subsamples were highly variable, yielding both false positive and false negative outcomes [21]. Therefore, future research on motor learning in gait retraining should try to increase the sample size. A second limitation is the issue of incomplete data, which is inherent to longitudinal study designs. If performing mean imputation, the interpretation would have been different; as in this case, a retention effect could be detected for the feedback variable. However, using single imputation often result in an underestimation of the variability because unobserved values carry the same weight in the analysis as the known, observed values [5]. The decrease in variability was apparent in the small experimental group, so increasing the sample size in future research is advised. A third limitation is that although the intervention was performed in a training environment [5], follow-up testing was performed in a laboratory setting. Follow-up testing in the field with monitoring wearables is warranted to validate the results of these gait-retraining interventions.

## Conclusion

The biofeedback-based intervention to alter the gait of high-impact runners did not induce a clear learning effect after half a year. Interestingly, a substantial impact reduction was recallable at the six-month follow up through simple verbal cueing wherein subjects were asked to recall and replicate low-impact running in the absence of feedback on $PTA_a$. In the absence of additional feedback sessions between the end of the intervention and a follow-up, a verbal recall by a supervisor or coach appears effective to evoke the impact reduction achieved during the intervention.

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## References

1 Creaby MW, Franettovich Smith MM. Retraining running gait to reduce tibial loads with clinician or accelerometry guided feedback. *J Sci Med Sport* 2015. Doi: 10.1016/j.jsams.2015.05.003.

2 Clansey AC, Hanlon M, Wallace ES, et al. Influence of Tibial shock feedback training on impact loading and running economy. *Med Sci Sports Exerc* 2014; 46(5):973–981. Doi: 10.1249/MSS.0000000000000182.

3 Chan ZY, Zhang JH, Au IP, et al. Gait Retraining for the Reduction of Injury Occurrence in Novice Distance Runners: 1-Year Follow-up of a Randomized Controlled Trial. *Am J Sports Med* 2018; 46(2):388–395. Doi: 10.1177/0363546517736277.

4 Morris JB, Goss DL, Miller EM, et al. Using real-time biofeedback to alter running biomechanics: A randomized controlled trial. *Transl Sport Med* 2020; 3(1):63–71. Doi: 10.1002/tsm2.110.

5 Van den Berghe P, Derie R, Bauwens P, et al. Reducing the peak tibial acceleration of running by music-based biofeedback: A quasi-randomized controlled trial. *Scand J Med Sci Sports* 2022; 32(4):698–709. Doi: 10.1111/sms.14123.

6 Wood CM, Kipp K. Use of audio biofeedback to reduce tibial impact accelerations during running. *J Biomech* 2014; 47(7):1739–1741. Doi: 10.1016/j.jbiomech.2014.03.008.

7 Derie R, Van den Berghe P, Gerlo J, et al. Biomechanical adaptations following a music-based biofeedback gait retraining program to reduce peak tibial accelerations. *Scand J Med Sci Sports* 2022; 32(7):1142–1152. Doi: 10.1111/sms.14162.

8 Crowell HP, Davis IS. Gait retraining to reduce lower extremity loading in runners. *Clin Biomech* 2011; 26(1):78–83. Doi: 10.1016/j.clinbiomech.2010.09.003.

9 Bowser BJ, Fellin R, Milner CE, et al. Reducing impact loading in runners: A one-year follow-up. *Med Sci Sports Exerc* 2018; 50(12):2500–2506. Doi: 10.1249/MSS.0000000000001710.

10 Van den Berghe P, Lorenzoni V, Derie R, et al. Music-based biofeedback to reduce tibial shock in over-ground running: a proof-of-concept study. *Sci Rep* 2021; 11(1):4091. Doi: 10.1038/s41598-021-83538-w.

11 Baggaley M, Willy RW, Meardon SA. Primary and secondary effects of real-time feedback to reduce vertical loading rate during running. *Scand J Med Sci Sport* 2017; 27(5):501–507. Doi: 10.1111/sms.12670.

12 Davis IS, Futrell E. Gait Retraining: Altering the Fingerprint of Gait. *Phys Med Rehabil Clin N Am* 2016; 27(1):339–355. Doi: 10.1016/j.pmr.2015.09.002.

13 Futrell EE, Gross KD, Reisman D, et al. Transition to forefoot strike reduces load rates more effectively than altered cadence. *J Sport Heal Sci* 2020; 9(3):248–257. Doi: 10.1016/j.jshs.2019.07.006.

14 Lorenzoni V, Van den Berghe P, Maes P-J, et al. Design and validation of an auditory biofeedback system for modification of running parameters. *J Multimodal User Interfaces* 2019; 13(3):167–180. Doi: 10.1007/s12193-018-0283-1.

15 Winstein CJ. Knowledge of results and motor learning - Implications for physical therapy. *Phys Ther* 1991. Doi: 10.1093/ptj/71.2.140.

16 Van den Berghe P, Six J, Gerlo J, et al. Validity and reliability of peak tibial accelerations as real-time measure of impact loading during over-ground rearfoot running at different speeds. *J Biomech* 2019; 86:238–242. Doi: 10.1016/j.jbiomech.2019.01.039.

17 Van den Berghe P, Gosseries M, Gerlo J, et al. Change-Point Detection of Peak Tibial Acceleration in Overground Running Retraining. *Sensors* 2020; 20(6):1720. Doi: 10.3390/s20061720.

18 Norris M, Anderson R, Kenny IC. Method analysis of accelerometers and gyroscopes in running gait : A systematic review 2014; 228(1):3–15. Doi: doi.org/10.1177/1754337113502472.

19 Jakobsen JC, Gluud C, Wetterslev J, et al. When and how should multiple imputation be used for handling missing data in randomised clinical trials – a practical guide with flowcharts. *BMC Med Res Methodol* 2017; 17(1):162. Doi: 10.1186/s12874-017-0442-1.

20 Li X, Yu J, Bai J, et al. The Effect of Real-Time Tibial Acceleration Feedback on Running Biomechanics During Gait Retraining: A Systematic Review and Meta-Analysis. *J Sport Rehabil* 2023:1–13. Doi: 10.1123/jsr.2022-0279.

21 Oakes LM. Sample Size, Statistical Power, and False Conclusions in Infant Looking-Time Research. *Infancy* 2017; 22(4):436–469. Doi: 10.1111/infa.12186.

**Supplementary materials**

Table S1. Impact variables for the experimental and control groups. Descriptives are presented as mean (±SD).

| Variable | Group | Baseline | Retention | Recall | Baseline-Retention | Baseline-Recall |
|---|---|---|---|---|---|---|
| PTAa<br>*(g)* | Experimental<br>(n = 8) | 7.93<br>(±1.87) | 6.15<br>(±0.95) | 5.50<br>(±1.13) | MD = -1.78<br>P = 0.110<br>d = 0.949<br>t = 2.862 | MD = -2.43<br>P = 0.007*<br>d = 1.295<br>t = 3.905 |
| imputated | (n = 10) | | 6.15<br>(±0.84) | 5.50<br>(±1.00) | MD = -1.96<br>P = 0.023*<br>d = 1.065<br>t = 3.429 | MD = -2.61<br>P < 0.001*<br>d = 1.418<br>t = 4.565 |
| | Control<br>(n = 10) | 7.23<br>(±2.16) | 6.91<br>(±2.07) | 6.79<br>(±2.34) | MD = - 0.31<br>P = 1.000<br>d = 0.167<br>t = 0.561 | MD = - 0.44<br>P = 1.000<br>d = 0.232<br>t = 0.782 |
| VLRi<br>(BW/s) | Experimental<br>(n = 8) | 96.3<br>(±28.0) | 84.4<br>(±22.5) | 65.8<br>(±18.7) | MD = -11.8<br>P = 1.000<br>d = 0.462<br>t = 1.636 | MD = -30.5<br>P = 0.003*<br>d = 1.195<br>t = 4.231 |
| imputated | (n = 10) | | 84.5<br>(±19.8) | 65.8<br>(±16.4) | MD = -15.1<br>P = 0.349<br>d = 0.618<br>t = 2.370 | MD = -33.9<br>P < 0.001*<br>d = 1.383<br>t = 5.302 |
| | Control<br>(n = 10) | 81.7<br>(±22.0) | 85.0<br>(±30.2) | 78.2<br>(±28.6) | MD = 3.3<br>P = 1.000<br>d = -0.128<br>t = -0.505 | MD = -3.5<br>P = 1.000<br>d = 0.137<br>t = 0.542 |

PTAa: Axial Peak Tibial Acceleration. VLRi: Instantaneous Vertical Loading Rate. MD: Mean Difference. d denotes Cohen's d. P-value (Bonferroni) adjusted for comparing a family. Imputated indicates single imputation of the mean for the variable of interest. * Significant independent t-test comparisons. Significance set at P < 0.05.

Video S1. A video clip of data collection during the Retention test. A modified Stroop test is projected on the screen in front of the measurement zone. A colored word appears when a participant entered the measurement zone and disappeared when leaving this zone, which was part of a straight section of the running lap. In the first video clip, the word blue ('blauw' in Dutch) is shown in black text. The participant is shouting 'zwart' which means black in Dutch. In the second clip, the word green ('groen' in Dutch) is colored in green and is shouted accordingly.