



## Impact loading during distracted running before and after auditory gait retraining

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Abstract:	<p>Visual feedback gait retraining has been reported to successfully reduce impact loading in runners, even when the runners were distracted. However, auditory feedback is more feasible in real life application. Hence, this study compared the peak positive acceleration (PPA), vertical average (VALR) and instantaneous (VILR) loading rate during distracted running before and after a course of auditory feedback gait retraining in 16 runners. They were asked to land with softer footfalls with and without auditory feedback. Low or high sound pitch was generated according to the impact of particular footfall, when compared with the preset target. Runners then received a course of auditory gait retraining program and after the gait retraining, runners completed a reassessment. Runners before gait retraining exhibited lower PPA, VALR, and VILR with augmented auditory feedback (<math>p &lt; 0.049</math>). We found a reduction in PPA, VALR, and VILR after gait retraining, regardless of the presence of feedback (<math>p &lt; 0.018</math>). However, runners after gait retraining did not demonstrate further reduction in PPA and VALR with auditory feedback (<math>p &gt; 0.104</math>). A trivial effect of auditory feedback on VILR in runners after gait retraining was observed (<math>p = 0.032</math>). Real time auditory feedback gait retraining is effective in impact loading reduction, even when the runners were distracted.</p>

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## Impact loading during distracted running before and after auditory gait retraining

### Abstract

Visual feedback gait retraining has been reported to successfully reduce impact loading in runners, even when the runners were distracted. However, auditory feedback is more feasible in real life application. Hence, this study compared the peak positive acceleration (PPA), vertical average (VALR) and instantaneous (VILR) loading rate during distracted running before and after a course of auditory feedback gait retraining in 16 runners. They were asked to land with softer footfalls with and without auditory feedback. Low or high sound pitch was generated according to the impact of particular footfall, when compared with the preset target. Runners then received a course of auditory gait retraining program and after the gait retraining, runners completed a reassessment. Runners before gait retraining exhibited lower PPA, VALR, and VILR with augmented auditory feedback ( $p < 0.049$ ). We found a reduction in PPA, VALR, and VILR after gait retraining, regardless of the presence of feedback ( $p < 0.018$ ). However, runners after gait retraining did not demonstrate further reduction in PPA and VALR with auditory feedback ( $p > 0.104$ ). A **small** effect of auditory feedback on VILR in runners after gait retraining was observed ( $p = 0.032$ ). Real time auditory feedback gait retraining is effective in impact loading reduction, even when the runners were distracted.

**Keywords:** Wearable sensor; Accelerometer; Vertical loading rate; Dual task; Kinetics

## Introduction

Impact loading parameters, such as vertical average loading rate (VALR), vertical instantaneous loading rate (VILR), and peak positive acceleration (PPA), have been associated with the development of overuse musculoskeletal injuries in distance runners [11,35]. A series of studies have reported successful impact loading reduction by real time biofeedback gait retraining [8,9,31,32,34]. More importantly, a recent large scale randomized controlled trial suggests such gait retraining may reduce injury risk in novice runners by 62% [6].

Among different running gait retraining protocols, vision is the most common tool used to convey feedback information [1], which is possibly due to a more convenient laboratory setup (i.e., participants looking at a screen placed in front of a treadmill). However, running with visual feedback in real life is not very practical. Therefore, previous studies have adopted auditory feedback such that participants adjust the running gait according to verbal instructions [13] and different sound pitches [34]. With the advancement of wearable sensors and smart garments, along with the fact that many runners listen to music during training, auditory feedback may allow a more feasible gait retraining outside laboratory environment.

Most of the current evidence in gait retraining was based on tests when the participants were only focused on the running task [11]. Since gait is not completely autonomous [12] and acquiring a new motor pattern after gait retraining may require certain level of attentional capacity, a recent study has examined the effectiveness of visual biofeedback gait retraining by challenging the participants with an additional

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3 cognitive task [7]. Interestingly, they found beneficial influences of the augmented visual  
4 feedback not only before, but also after gait retraining during dual-tasking. As  
5 participants after gait retraining may still rely on external cues for performing optimal  
6 motor pattern, such findings provide an argument that current visual gait retraining  
7 program may not be sufficient to lead to a stable modified gait pattern.  
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15 There is considerable evidence that human sensitivity and attention to purely  
16 temporal information is greater in the auditory than in the visual modality [14,16–  
17 20,23,26]. Previous experiments have demonstrated that temporal discrimination and  
18 reproduction of temporal patterns are poorer in vision than in audition [17–20]. When  
19 auditory and visual stimuli are in conflict with respect to other modality at one of various  
20 phase relationships, participants' judgments are typically more strongly influenced by  
21 the auditory than by the visual temporal information [14,16,23,26]. Therefore, auditory  
22 feedback may be a better modality for gait retraining.  
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34 Hence, a replication of study by Cheung et al. [7] but using auditory feedback may  
35 provide insight on the level of motor learning using different sensory modality in gait  
36 retraining. Specifically, this study sought to compare the impact loading during  
37 distracted running before and after a course of auditory feedback gait retraining. Based  
38 on the previous findings [7], we hypothesized that participants would present a lower  
39 impact loading, as measured by PPA at shoe (PPA<sub>S</sub>), PPA at distal tibia (PPA<sub>T</sub>), VALR  
40 and VILR, at the completion of gait retraining, when they were distracted.  
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## Materials & Methods

### *Study design*

The overall design of the present study referred to Cheung et al. [7]. Specifically, it is a cross-over study involving a laboratory-based gait retraining using auditory feedback. Participants were tested before and after gait retraining in two conditions i.e. with and without auditory feedback. This study meets the ethical standards outlined by the International Journal of Sports Medicine [22].

### *Participants*

Sixteen recreational runners (9 females and 7 males; age= $25.1 \pm 7.9$  years; body height= $1.64 \pm 0.10$  m; body mass= $57.37 \pm 9.21$  kg; running experience= $3.2 \pm 0.9$  years; weekly mileage= $16.0 \pm 1.7$  km) who have been running for at least 12 km per week for a minimum of 12 months were recruited from local running clubs. They were free from any active injury twelve months before the experiment and had received no prior lower extremity surgery. In order to avoid floor effect, participants exhibited  $PPA_S < 8$  g during self-paced running were excluded [7]. Experimental procedures were reviewed and approved by the concerning institutional review board. Written consent was obtained from each participant before being tested.

### *Experimental procedures*

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6 A lightweight tri-axial accelerometer (measurement range=0-50 g, Maestro WB,  
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8 01DB-Stell, Limonest, France) was aligned with the long axis of the participant's tibia,  
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10 and securely affixed onto the posterior aspect of the right shoe. Another identical device  
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12 was placed at the anteromedial right tibia [9] (Figure 1). At first, participants were asked  
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14 to run at a self-selected pace on an instrumented treadmill (AMTI force sensing tandem  
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16 treadmill, Watertown, MA, USA) for five minutes with their usual shoes. The running  
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18 speed was kept constant within each participant throughout all of the tests. We set the  
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20 target for gait retraining according to a previous study [7]. Specifically, participants were  
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22 asked to soften their footfalls such that the  $PPA_S$  was below 80% of the mean  $PPA_S$   
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24 from the last minute of the baseline assessment.  
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30 After establishing the target for gait retraining, participants were asked to land softer  
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32 with and without auditory feedback in a randomized sequence generated by an online  
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34 program ([www.random.org](http://www.random.org)). Simultaneously, they were required to conduct a cognitive  
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36 and verbal counting task (i.e., addition of two to a random 3-digit integer) continuously  
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38 for the entire 5-minute running trial [7]. Real time auditory feedback was given using a  
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40 pair of stereo speakers located in front of the treadmill. Using customized LabVIEW  
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42 code (National Instruments, TX, USA), a middle C (261.6 Hz) tone and a high-pitch C  
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44 (4,186.0 Hz) of equal sound intensity were generated at a footfall below and above the  
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46 preset loading target respectively. Participants were asked to modify their running gait in  
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48 order to avoid the high-pitched sound. Running kinetics was measured during the last  
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50 minute of the five-minute running bout in each condition [28]. A ten-minute rest was  
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52 given between two trials in order to avoid fatigue.  
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3 Participants then received a two-week gait retraining for impact loading reduction  
4 according to the protocol employed in Cheung et al. [7]. This gait retraining program  
5 was also employed by other previous studies [3,6,9,25,33]. In brief, they participated in  
6 eight sessions of gait modification over two weeks (four sessions per week). During the  
7 gait retraining, participants were asked to run with softer footfalls at the previous test  
8 speed on a treadmill. Similar to previous studies [6], participants were allowed to use  
9 their preferred strategies to achieve the goal. The same target and auditory feedback  
10 were used in the gait retraining. The gait retraining time was gradually increased from  
11 15 minutes to 30 minutes over the eight sessions and auditory feedback was  
12 progressively removed in the last four sessions [9]. No verbal counting task was  
13 required during the gait retraining program. After the gait retraining, participants  
14 returned to complete a post-training assessment, which was identical to the pre-training  
15 assessment. Additionally, we asked if the participants experienced any symptoms or  
16 any other adverse effect related to the gait retraining. The overall study design is  
17 presented in Figure 2.  
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#### 41 *Data acquisition and processing*

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44 The accelerometer data was sampled at 1,000 Hz and filtered using a second order  
45 Butterworth low-pass filter at 50 Hz.  $PPA_S$  and  $PPA_T$  were defined as the maximum  
46 positive vertical acceleration that measured from the shoe-mounted sensor and the  
47 tibial sensor within the first 50 ms of foot-ground contact [10]. Synchronized vertical  
48 ground reaction force was recorded at 1,500 Hz. Ground reaction force data was filtered  
49 using a fourth order Butterworth low-pass filter at 100 Hz and body weight normalized.  
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3 The VALR and VILR were calculated as per the method described previously [2]. In  
4 brief, VALR is the slope of the line from the 20% point to the 80% point of the impact  
5 peak. VILR is the maximum slope of the vertical ground reaction force curve between  
6 the successive data points in the same region. In case of a non-clearly discernible  
7 impact peak, a set time point of 13% stance was used as a surrogate measure of the  
8 impact peak [4]. All the data were extracted and averaged across all the footfalls with  
9 the final one-minute of the trials.  
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### 23 *Statistical analysis*

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26 A two-way repeated measures ANOVA was used to measure within-subject  
27 difference of  $PPA_S$ ,  $PPA_T$ , VALR, and VILR between conditions (pre- and post-training;  
28 with and without feedback) during distracted running. All statistical tests were performed  
29 by SPSS software (Version 23, SPSS Inc., Chicago, IL, USA), with global alpha at 0.05.  
30 In addition, differences between conditions were also illustrated by Cohen's d, where  
31 values **greater than** 0.2, 0.5 and 0.8 are considered as 'small', 'medium' and 'large'  
32 effect sizes respectively [30].  
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### 46 **Results**

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48 All the participants completed gait retraining without any adverse effect reported.  
49 The self-selected running speed was **2.08 ± 0.23 m/s**. The  $PPA_S$ ,  $PPA_T$ , VALR, and  
50 VILR before and after gait retraining are presented in **Table 1**. There was only  
51 significant interaction effect between gait retraining and feedback on  $PPA_S$  ( $F=16.129$ ;  
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3  $p=0.001$ ), while the interaction effects on  $PPA_T$  ( $F=1.428$ ;  $p=0.266$ ), VALR ( $F=3.438$ ;  
4  $p=0.083$ ), and VILR ( $F=2.799$ ;  $p=0.115$ ) were not significant.  
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8 Participants presented a reduction in  $PPA_S$ ,  $PPA_T$ , VALR, and VILR after gait  
9 retraining, regardless of the presence of feedback ( $p<0.018$ ; Cohen's  $d=0.42-1.23$ ;  
10 moderate to large effect; see **Table 2**). Runners before gait retraining exhibited lower  
11  $PPA_S$ ,  $PPA_T$ , VALR, and VILR with augmented auditory feedback ( $p<0.049$ ; Cohen's  
12  $d=0.27-0.55$ ; moderate to large effect; see **Table 3**). However, runners after gait  
13 retraining did not demonstrate further reduction in  $PPA_S$ ,  $PPA_T$ , and VALR with auditory  
14 feedback ( $p>0.104$ ). We observed a **small** effect of auditory feedback on VILR in  
15 runners after gait retraining ( $p=0.032$ ; Cohen's  $d=0.15$ ; **Table 3**).  
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## 30 **Discussion**

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33 The present study evaluated the effect of auditory feedback gait retraining on impact  
34 loading reduction in runners with cognitive distraction. We found that auditory gait  
35 retraining is effective in impact loading reduction. In addition, we found that augmented  
36 auditory feedback only reduces impact loading before gait retraining. Runners after gait  
37 retraining do not exhibit a difference in impact loading with additional feedback.  
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45 In the present study, we employed a cognitive and verbal counting task to distract  
46 the participants and better reflect the motor learning outcome after gait retraining. Such  
47 dual-task paradigm has been applied in some previous gait retraining studies [5,7,27].  
48 According to the learning theory by Fitts and Posner [15], participants after the gait  
49 retraining should be able to perform the newly acquired gait pattern with less cognitive  
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3 demand. Therefore, it is logical to test the effectiveness of gait retraining when the  
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5 participants were distracted.  
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9 Except for the type of biofeedback adopted for gait retraining, our study was highly  
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11 comparable with the work by Cheung et al. [7]. Cheung et al. reported that an  
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13 augmented visual biofeedback after gait retraining may still be effective in lowering  
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15 impact loading. In contrast, our study indicated that after same duration and intensity of  
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17 gait retraining using auditory feedback, trained runners did not present further impact  
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19 loading reduction with additional biofeedback. According to the learning theory by Fitts  
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21 and Posner [15], there are three motor learning stages, namely cognitive stage,  
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23 associative stage, and autonomous stage. It has been shown that augmented feedback  
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25 are highly effective in either cognitive or associative stage [29]. Once the new gait  
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27 pattern is mastered and autonomously performed, additional feedback should not affect  
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29 performance. Given our study and the study by Cheung et al. [7] adopted identical  
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31 duration and intensity of gait retraining protocol, our findings may potentially indicate a  
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33 better motor learning from gait retraining with auditory feedback than visual feedback.  
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40 Previous studies have reported successful reduction in impact loading with moderate  
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42 to large effect by a course of visual feedback gait retraining (Cohen's d ranging between  
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44 0.74 and 1.7) [17–20]. Such effect is highly comparable with our findings. Our study is  
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46 also in accordance with the findings reported by previous auditory gait retraining study  
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48 [34], which indicates that auditory feedback gait retraining is effective in reducing impact  
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50 loading in distance runners. However, some previous studies [8,9] reported greater  
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52 effect (Cohen's d up to 1.7) than our findings, which can be explained by the difference  
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54 in the gait retraining target. Our target was set at 80% of the original PPAs, while the  
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3 other studies used 50% as the target for gait retraining [8,9]. Another possible reason  
4 may be due to the feedback used in the gait retraining. One of the previous studies  
5 used step rate as a feedback [21] and cadence can be measured by runners outside the  
6 laboratory environment. Additional practice may provide further improvement in gait  
7 modification and thus a greater effect was observed.  
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15 Previous experiments have demonstrated that the differentiation and reproduction of  
16 temporal patterns are stronger in audition than vision [17–20], suggesting auditory  
17 sensitivity and attention is greater than that in the visual modality. Some studies also  
18 reported participants' determinations are highly influenced by the auditory than by the  
19 visual temporal information [14,16,23]. Hence, auditory feedback may be a better  
20 modality for gait retraining than visual feedback. In real life, runners may modify their  
21 running mechanics with auditory signals, without losing focus on road conditions.  
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32 The results reported in this study may indicate a preference on the feedback type  
33 employed in gait retraining. On top of more convenient user interface, our findings may  
34 advocate the development of in-field auditory gait retraining with wearable sensors. In-  
35 field gait retraining programs using wearables has been reported as effective in  
36 modifying faulty gait biomechanics, such as lowering knee joint contact force during  
37 running [24,32]. This would allow a longer and more persistent gait retraining in the  
38 community, which may lead to a more persistent change in the motor performance  
39 during gait.  
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51 When interpreting our results, it is important to consider several limitations in our  
52 study. Firstly, only healthy recreational runners were recruited and hence our findings  
53 may not be generalized to runners at different elite levels or injured runners. Secondly,  
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3 we affixed the accelerometer at the heel counter, as it is a common placement site for  
4 commercial biosensors. However, we did not measure participants' footstrike patterns,  
5 which may affect PPA measurement. Besides, some commercial sensors are mounted  
6 onto the lace box and may produce different results to this study. Future study is  
7 warranted to replicate the present experiment with different sensor placement locations.  
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14 Thirdly, we did not measure the effect of gait retraining after each session. Therefore,  
15 the learning curve during the gait retraining program remains unknown. Finally, we did  
16 not measure joint kinematics. Since the participants may use different strategy to soften  
17 the footfalls, further study could explore the relationship between the modified kinetics  
18 and the running kinematics after gait retraining in future studies.  
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27 In conclusion, real time auditory feedback gait retraining is effective in impact  
28 loading reduction during distracted running. Runners after gait training do not benefit  
29 from augmented auditory feedback. When compared with findings reported by a visual  
30 feedback gait retraining study with similar design, auditory feedback gait retraining may  
31 provide better motor learning than gait retraining with visual feedback.  
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42 Acknowledgements

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## Figure legends

Figure 1. Sensor locations (indicated by the red boxes) and corresponding fixations

Figure 2. Study flow diagram

## Table legends

Table 1. Peak positive acceleration measured at the shoe ( $PPA_S$ ), peak positive acceleration measured at the distal tibia ( $PPA_T$ ), vertical average loading rate (VALR) and vertical instantaneous loading rate (VILR) before and after gait retraining

Table 2. Differences of peak positive acceleration measured at the shoe ( $PPA_S$ ), peak positive acceleration measured at the distal tibia ( $PPA_T$ ), vertical average loading rate (VALR) and vertical instantaneous loading rate (VILR) before and after gait retraining

Table 3. Effect of augmented auditory feedback on peak positive acceleration measured at the shoe ( $PPA_S$ ), peak positive acceleration measured at the distal tibia ( $PPA_T$ ), vertical average loading rate (VALR) and vertical instantaneous loading rate (VILR)



Table 1. Peak positive acceleration measured at the shoe (PPA<sub>S</sub>), peak positive acceleration measured at the distal tibia (PPA<sub>T</sub>), average vertical loading rate (VALR) and instantaneous vertical loading rate (VILR) before and after gait retraining

Parameters	Pre-training		Post-training	
	Without auditory feedback	With auditory feedback	Without auditory feedback	With auditory feedback
PPA <sub>S</sub> (g)	19.01 ± 7.71	14.78 ± 7.16	12.58 ± 6.91	11.61 ± 7.53
PPA <sub>T</sub> (g)	5.45 ± 1.63	4.91 ± 1.37	4.28 ± 1.50	3.92 ± 1.32
VALR (N/kg/s)	62.66 ± 18.78	56.61 ± 19.72	47.11 ± 15.21	45.39 ± 14.92
VILR (N/kg/s)	74.63 ± 19.96	68.99 ± 20.09	58.34 ± 17.11	55.72 ± 17.12

Table 2. Differences of peak positive acceleration measured at the shoe (PPA<sub>S</sub>), peak positive acceleration measured at the distal tibia (PPA<sub>T</sub>), vertical average loading rate (VALR) and vertical instantaneous loading rate (VILR) before and after gait retraining

Parameters	Cohen's d	P value
PPA <sub>S</sub> without auditory feedback	0.85	<0.001*
PPA <sub>S</sub> with auditory feedback	0.42	0.004*
PPA <sub>T</sub> without auditory feedback	0.95	0.018*
PPA <sub>T</sub> with auditory feedback	1.23	0.012*
VALR without auditory feedback	0.88	<0.001*
VALR with auditory feedback	0.62	0.001*
VILR without auditory feedback	0.85	<0.001*
VILR with auditory feedback	0.69	0.002*

\* indicates significant difference before and after gait retraining

Table 3. Effect of augmented auditory feedback on peak positive acceleration measured at the shoe (PPA<sub>S</sub>), peak positive acceleration measured at the distal tibia (PPA<sub>T</sub>), vertical average loading rate (VALR) and vertical instantaneous loading rate (VILR)

Parameters	Cohen's d	P value
PPA <sub>S</sub> before gait retraining	0.55	<0.001*
PPA <sub>S</sub> after gait retraining	-	0.158
PPA <sub>T</sub> before gait retraining	0.45	0.049*
PPA <sub>T</sub> after gait retraining	-	0.104
VALR before gait retraining	0.30	0.024*
VALR after gait retraining	-	0.195
VILR before gait retraining	0.27	0.014*
VILR after gait retraining	0.15	0.032*

\* indicates significant difference with and without auditory feedback

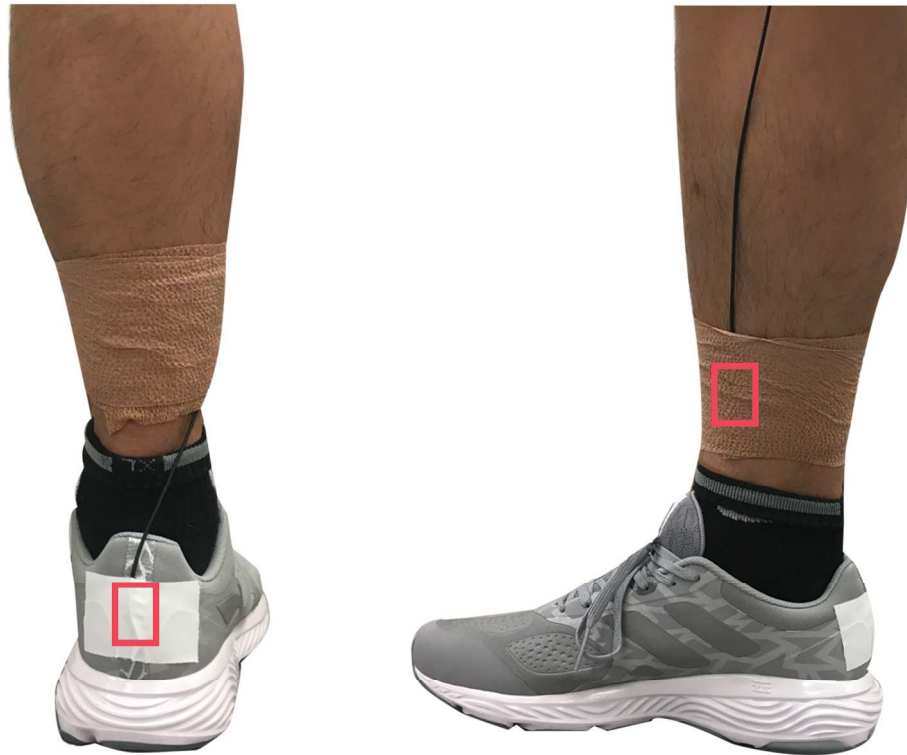


Fig. 1: Sensor locations (indicated by the red boxes) and corresponding fixations

438x339mm (300 x 300 DPI)

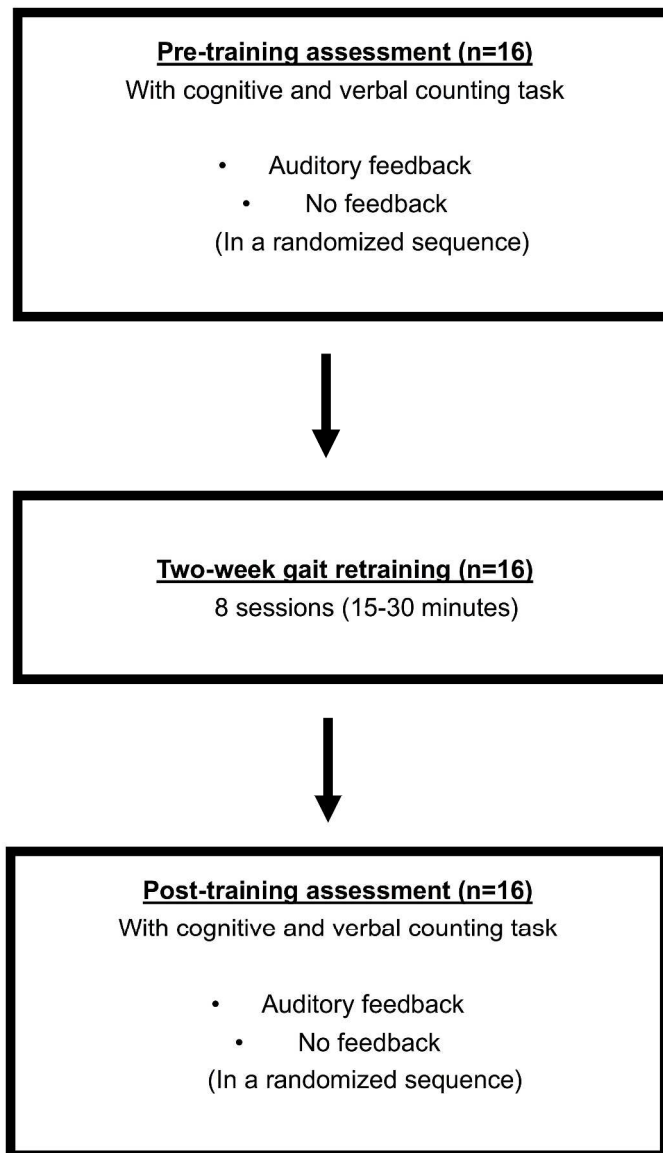


Fig. 2: Study flow diagram

413x669mm (300 x 300 DPI)