The effectiveness of real-time haptic feedback gait retraining for reducing resultant tibial acceleration with runners.

Authors

Kelly R. Sheerin[a], Duncan Reid[a], Denise Taylor[b] , Thor F. Besier[a,c]

Affiliations

[a] Sports Performance Research Institute New Zealand (SPRINZ), School of Sport and Recreation, Auckland University of Technology, New Zealand

[b] Health & Rehabilitation Research Institute, Faculty of Health & Environmental Sciences, Auckland University of Technology, Auckland, New Zealand

[c] Auckland Bioengineering Institute & Department of Engineering Science, University of Auckland, New Zealand

Corresponding author

Kelly Sheerin

Sports Performance Research Institute New Zealand (SPRINZ), School of Sport and Recreation, Auckland University of Technology, New Zealand

Postal Address: Auckland University of Technology, Private Bag 92001 Auckland Mail Centre, Auckland, New Zealand.

Phone: +64 9 921 9999 Ext 7354

Email: kelly.sheerin@aut.ac.nz

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Abstract

Objectives: To examine the effectiveness of real-time haptic feedback gait retraining for reducing resultant tibial acceleration (TA-R) with runners, the retention of changes over four weeks, and the transfer of learning to overground running.

Design: Case control

Setting: Biomechanical laboratory treadmill, and track-based overground, running.

Participants: 18 experienced uninjured high tibial acceleration runners.

Main outcome measures: TA-R measured while treadmill and overground running assessed at pre-, post- and 4-weeks post-intervention.

Results: Across the group, a 50% reduction in TA-R was measured post-intervention (ES: 0.9, z=-18.2, p<.001), and 41% reduction at 4-weeks (ES: 0.8, z=-12.9, p<.001) with treadmill running. A 28% reduction (ES: 0.7, z=-13.2, p<.001), and a 17% reduction in TA-R were measured at these same time points when runners ran overground (ES: 0.7, z=-11.2, p<.001). All but two runners responded positively to the intervention at the post-intervention assessment. Eleven runners were categorised as positive responders to the intervention at the 4-week post-intervention.

Conclusions: Haptic feedback based on TA-R appears to be as effective, but less invasive and expensive, compared to other more established modalities, such as visual feedback. This new approach to movement retraining has the potential to revolutionise the way runners engage in gait retraining.

Keywords

running; gait retraining; haptic feedback; tibial acceleration

Introduction

There are clear health and fitness benefits that come from regular participation in running (Hoffman & Hoffman, 2008; Lee et al., 2014), however running is also associated with a higher rate of overuse injury than other aerobic training (Bertola, Sartori, Correˆa, Zotz, & Gomes, 2014; Hauret et al., 2015; van Gent et al., 2007). Bony fatigue fractures (frequently termed stress fractures) are a common running injury (Francis, Whatman, Sheerin, Hume, & Johnson, 2018), with the tibia being the most common site (Burr, 1997; Grimston et al., 1994). The causal mechanism of fatigue fractures is related to an imbalance between mechanical loading and an accumulation of damage of the tissue and the remodeling of the bone (Warden, Davis, & Fredericson, 2014). Various mechanical loading variables have been correlated to the chronicity and recurrence of tibial fatigue fractures, including surrogates such as tibial acceleration (TA) and instantaneous vertical force loading rates (Milner, Davis, & Hamill, 2006a; Milner, Ferber, Pollard, Hamill, & Davis, 2006b; Napier, MacLean, Maurer, Taunton, & Hunt, 2018; Warden et al., 2014). Previous studies have demonstrated that with appropriate feedback and guidance, running biomechanics can be successfully altered to reduce biomechanical injury risk factors in relatively short periods of time (Clansey, Hanlon, Wallace, Nevill, & Lake, 2014; Creaby & Smith, 2016; Crowell & Davis, 2011; Noehren, Scholz, & Davis, 2011; Willy et al., 2016). There is also some evidence that these changes can translate to injury reductions, at least in novice runners (Chan et al., 2018). Within the context of changing injury-related biomechanical risk factors, it is not sufficient for runners to demonstrate a change in their running performance; they should be able to consistently reproduce an altered technique in the long-term, such that they have relearned this motor skill (Davis & Futrell, 2016).

Several gait retraining interventions have used biofeedback from tibial mounted accelerometers to modify lower extremity biomechanics (Clansey et al., 2014; Creaby & Smith, 2016; Crowell & Davis, 2011; Crowell, Milner, Hamill, & Davis, 2010; Wood & Kipp, 2014). Compared to force plates, the benefit of using this surrogate measure of impact is that it enables measurement outside the laboratory (Giandolini, Pavailler, Samozino, Morin, & Horvais, 2015). Additionally, accelerometers are also considerably less expensive, and therefore more accessible for clinical applications (Higginson, 2009).

To date, many real-time feedback systems used with runners have been designed in a way that lack ecological validity, and ultimately restrict the potential for their use in a normal training environment. For example, while visual feedback displays have been successfully used (Baggaley, Willy, & Meardon, 2016; Crowell & Davis, 2011), this approach requires runners to remain indoors on a treadmill. While audio feedback, presented as either amplified impact sound (Phan et al., 2016) or different audible pitches (Clansey, Hanlon, Wallace, & Lake, 2012;

Wood & Kipp, 2014), are options that offer improved mobility, audio feedback has important safety considerations specifically when headphone use by pedestrians has been implicated in serious injury and death (Lichenstein, Smith, Ambrose, & Moody, 2012; Mwakalonge, Siuhi, & White, 2015). Tactile and kinesthetic feedback conveyed through vibrations on the skin (haptic feedback) is an option that has not yet been explored in this area (Chen, Haller, & Besier, 2017). Motivation for the use of wearable haptic devices is that they lend themselves to use in normal training environments, while also leaving vision and hearing free for other tasks (Van Erp, Saturday, & Jansen, 2006). Haptic feedback has been used more widely in walking gait retraining to reduce knee adductor moments in healthy individuals, those with osteoarthritis (Shull, Shultz, et al., 2013a; Shull, Silder, et al., 2013b), and to provide independent feedback about multiple gait parameters within a single session (Shull, Lurie, Cutkosky, & Besier, 2011; Uhlrich, Silder, Beaupre, Shull, & Delp, 2018). However, its use with runners is limited to providing feedback on directional information (Tsukada & Yasumura, 2004), rhythmic breathing patterns (Valsted, Nielsen, Jensen, Sonne, & Jensen, 2017), and TA, where haptic stimuli was paired with simultaneous visual and auditory feedback (van Gelder, Barnes, Wheat, & Heller, 2018).

In sports medicine and biomechanics it is rare that a one-size-fits-all intervention is successful for each individual, however this is only occasionally acknowledged, and not often discussed, in running gait retraining literature (Crowell et al., 2010; Zhang, Chan, Au, An, & Cheung, 2019). In order to appropriately determine the effectiveness of an intervention, the acknowledgement and analysis of non-responders must occur alongside those who positively respond. Additionally, within the context of motor learning, consideration should also be given not only to whether participants immediately changed their performance after receiving feedback, but also the retention of these changes over a period with no feedback, as well as the ability to transfer changes to different environments (Winstein, 1991). The aim of this study was to examine the effectiveness of a real-time haptic feedback gait retraining system for reducing resultant tibial acceleration with individual runners. A secondary aim was to assess the retention of changes over four weeks, and the transfer of learning to overground running.

Methods

Participants

Runners between the ages of 18 and 65 years of age were invited to participate in this study if they were injury free, and had consistently run three or more times, to a combined weekly distance of at least 20 km for greater than six months. Procedures were approved by institutional human research ethics (AUTEC #15181), and participants signed written informed consent.

Using TA data from Zhang, et al.(2019), an *a priori* power analysis (alpha=0.05, power=0.8) was conducted with G*Power (v3.1.9.3). Fifteen subjects were needed to adequately power the study. To account for potential drop-out, 19 runners were enrolled in the study.

Study Design

To avoid a floor effect of the retraining intervention, participants were screened to determine their baseline resultant tibial acceleration (TA-R) (Figure 1). Runners were invited to participate in the intervention where the TA-R from either limb exceeded the threshold corresponding to their nominated training pace. Runners who accepted the invitation to participate in the intervention underwent a 3-week 'control' period to confirm the stability of their baseline TA-R. During this period runners continued with their typical training, before returning for the pre-intervention assessment. TA-R data measured during both treadmill and overground running was recollected at this time point, as well as immediately post-intervention, and 4-weeks post-intervention. During the four weeks that followed the intervention, runners reverted to their typical training. They received no feedback, guidance or oversight from the research team during this period. Injuries and adverse incidents were also monitored for the duration of the study.

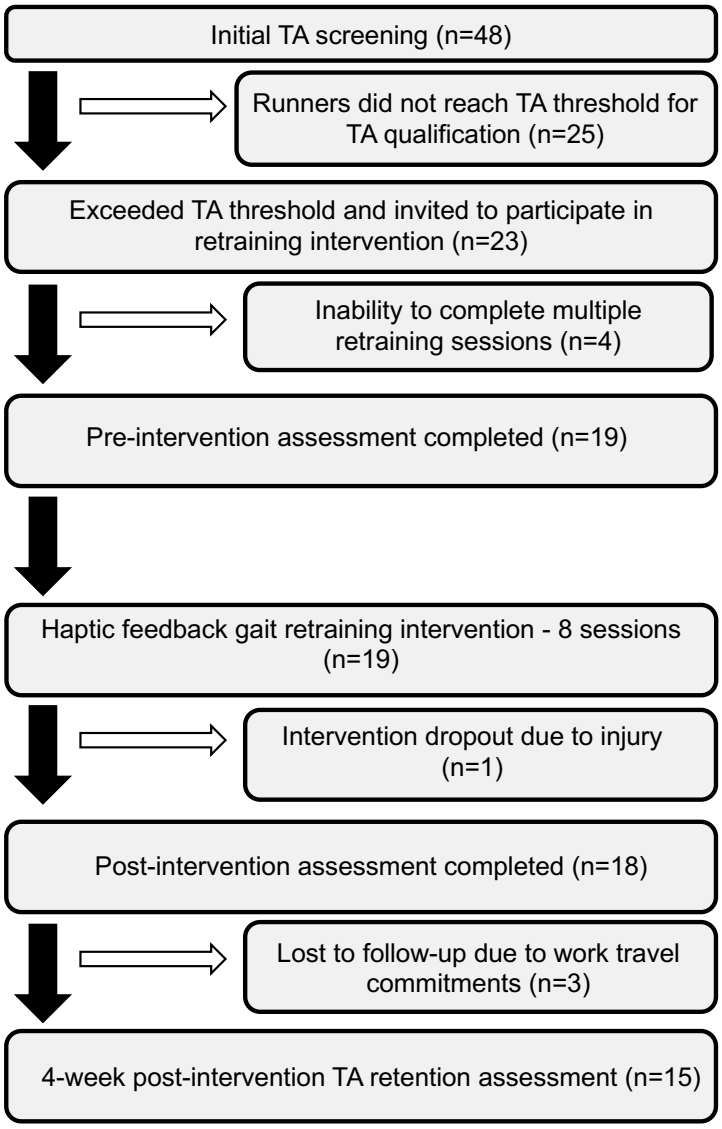

Figure 1: Flow chart describing the study recruitment screening and study design.

Procedures

Acceleration data were collected via inertial measurement units (IMeasureU, Auckland, New Zealand) securely attached to the antero-medial tibiae, at a sample rate of 1000 Hz. In all instances, 30s of TA data were extracted for processing. TA-R data were processed and analysed according to previously described procedures (Sheerin, Besier, Reid, & Hume, 2018b). Runners wore standardised neutral running shoes (Asics Kudrow, Kobe, Japan) and ran on an instrumented treadmill (Bertec, Columbus, OH, USA) that provided minimal shock absorption.

Following a 5-minute warm-up at a self-selected pace, participants ran at the velocities of 2.7, 3.0, 3.3 and 3.7 m/s, during which time their TA was recorded. Runners were free to adopt their natural running technique and no feedback was provided. After the screening assessment

each runner nominated a speed from the four options, which matched closest to their comfortable 10 km training pace. Owing to the relationship between faster running velocity and increased TA-R, different threshold levels were set for each velocity, corresponding to >1SD of a healthy group of runners at this speed (Table 1) (Sheerin, Besier, & Reid, 2018a). Only runners who exceeded the threshold TA-R at their nominated training velocity were invited to participate in the intervention. If both limbs exceeded the threshold, the limb with the higher TA-R was used for the retraining portion of this study (hereafter referred to as the 'target limb').

Table 1:Resultant tibial acceleration screening thresholds

Running velocity (m/s)	2.7	3.0	3.3	3.7
Resultant tibial acceleration (g)	12.5	14.0	15.2	16.6

With tibial accelerometers still in place, additional overground running assessments were conducted on a standard athletics track during the pre-intervention, post-intervention and 4-weeks post-intervention assessments. Participants ran two complete full laps (corresponding to 800m) at a self-nominated pace, as close as possible to their nominated training velocity. Pace was recorded via a GPS watch (Garmin Forerunner 235, Garmin Ltd, Schaffhausen, Switzerland). Overground running pace during the post-intervention and 4-week post-intervention assessments were deemed acceptable when they were within ±5% of the pre-intervention pace (Clansey et al., 2014).

Gait retraining intervention

Prior to each retraining session a custom accelerometer (SparkFun 9DoF Razor IMU, SparkFun Electronics, CO, USA) was securely attached to the target limb while the controlling electronics were attached more proximally on the lower calf (Figure 2). A haptic feedback device previously described by Chen, Haller & Besier (Chen et al., 2017) was fitted into a watch, and attached to the wrist corresponding to the side of the target limb. Vibration actuators were located in the watch, while the controlling electronics were attached more proximally on the forearm. An integrated Arduino MICRO development board served as a controller driving four eccentric rotating mass motors to illicit a vibration.

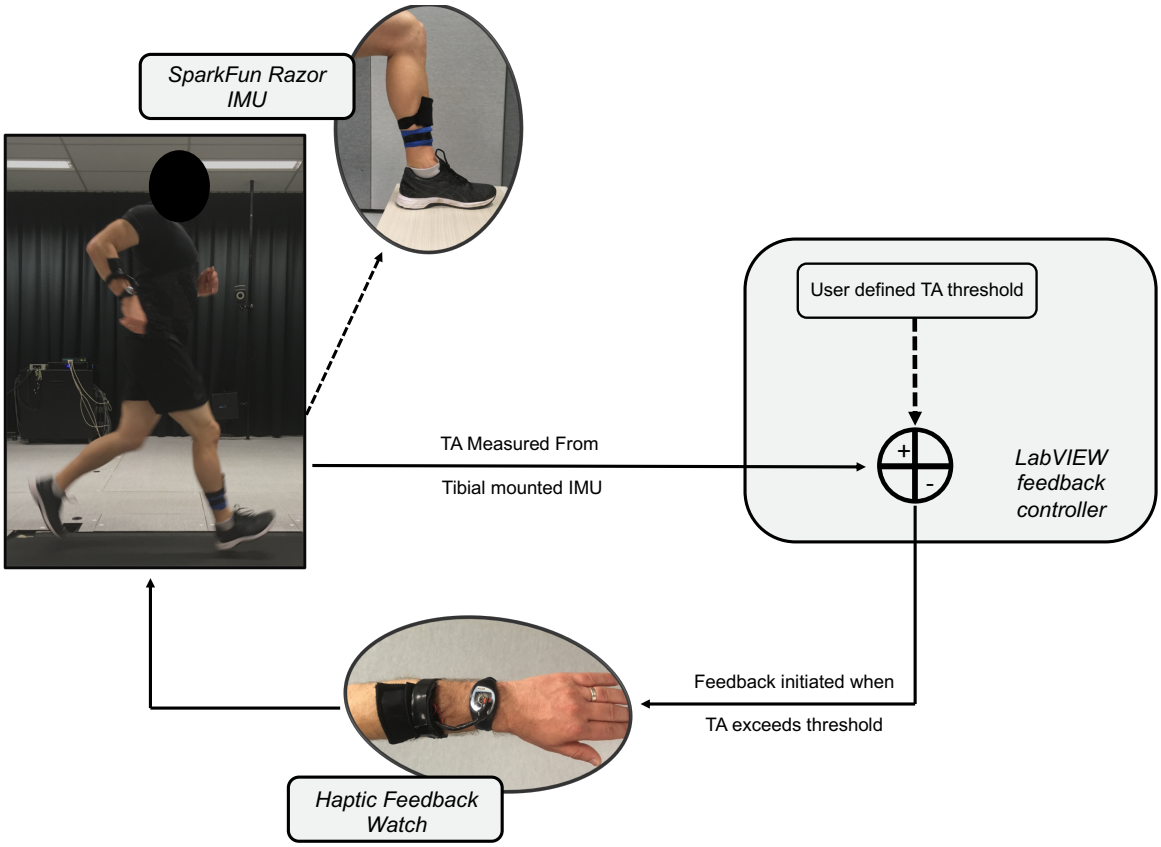

Figure 2: Block diagram of real-time haptic feedback system.

The acceleration measured from a SparkFun IMU sensor was transmitted via Bluetooth to a computer running a custom LabVIEW programme (National Instruments Corp.; Austin, Texas, USA) which captured the raw signal and calculated TA-R (Figure 3). Where peaks in the TA-R (corresponding to foot-ground impact) exceeded the target threshold, an output signal was transmitted via Bluetooth to the haptic feedback watch. The feedback system was set without a delay on the haptic feedback, and the stimulus duration was set at 200ms. Within the LabVIEW programme was a function to switch off the feedback watch, so that users could measure from the accelerometer without providing feedback to runners.

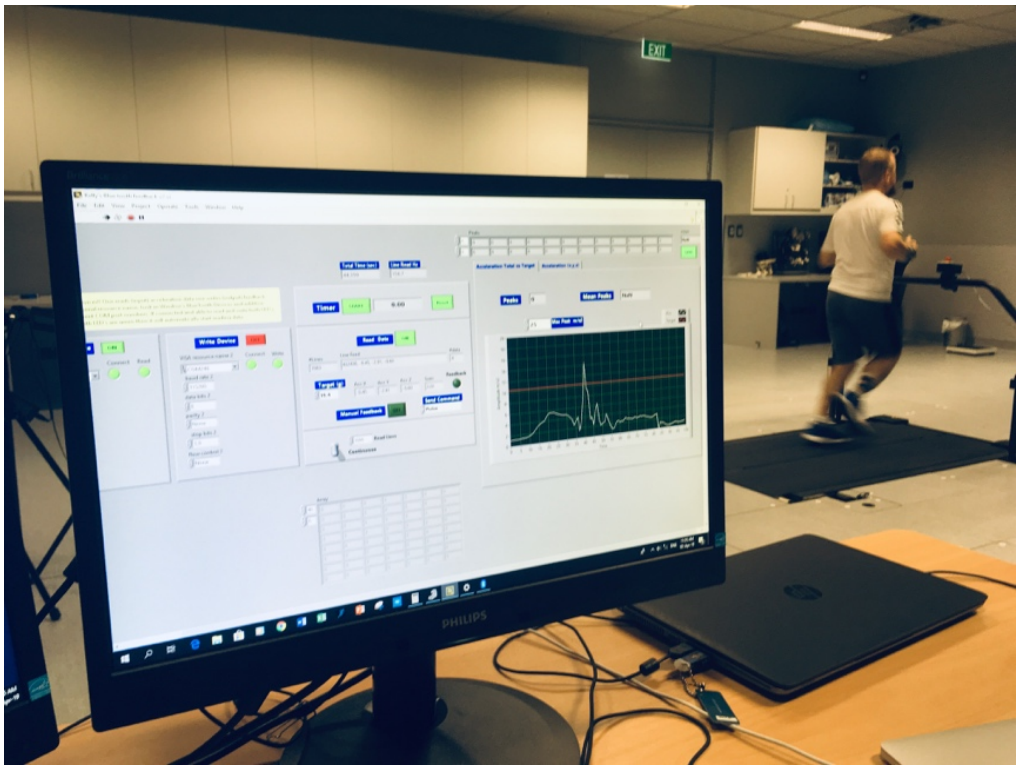

Figure 3: Typical participant running on the treadmill while receiving real-time haptic feedback via custom software.

In accordance with the challenge point framework (Guadagnoli & Lee, 2004), to ensure a challenging yet achievable target, runners' TA-R was re-assessed prior to each retraining session. The target threshold was then set 10% below the session baseline. This proportional target has previously been successfully used with an audio intervention (Wood & Kipp, 2014), and was re-confirmed through pilot testing with haptic feedback. During the intervention period, step-by-step peak TA-R were calculated, and a pulse was provided to the wrist by the feedback watch when the runner exceeded the session target threshold. Runners were instructed to make their footfalls softer and eliminate the vibration feedback (Bowser, Fellin, Milner, Pohl, & Davis, 2018).

A faded feedback design was used to encourage internalisation of the new running pattern, and the retraining schedule was as described by other research groups (Chan et al., 2018; Crowell & Davis, 2011). Runners participated in eight feedback sessions, which were carried out on a treadmill at the runner's nominated training velocity. The duration of each session increased step-wise from 15-minutes for the first session, to 30-minutes in the final session (Figure 4). Participants received feedback for 100% of the time during the first four sessions, and it was progressively withdrawn over the final four sessions, such that only three minutes of feedback was provided in the final session, with one minute at the start, middle and end of the session. Participants had a minimum of one day off after two consecutive days of running,

and they were required to complete all running retraining sessions within a three-week period. During this time, participants were allowed to continue with their normal training.

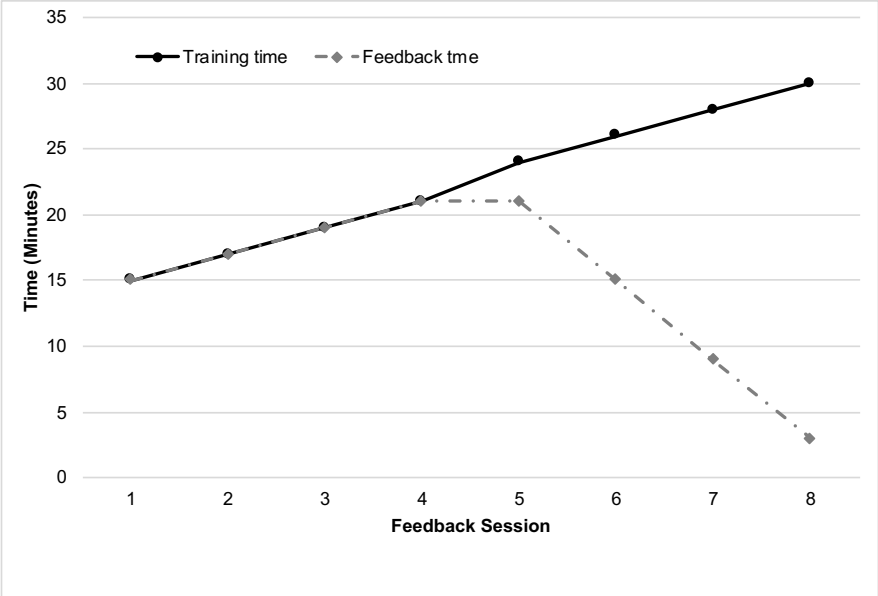

Figure 4: Gait retraining schedule

Statistical Analysis

Statistical analyses were performed using SPSS statistics package version 24 (IBM Corporation, Armonk, NY, USA) with the level of significance set at $p<0.05$ throughout. Data normality and variance homogeneity were tested using the Shapiro-Wilk test. Group and individual statistics including medians (Md) and interquartile range (IQR) were calculated. The difference between TA-R measured pre- and post-intervention, as well as pre-intervention and 4-week follow-up, were analysed using a Wilcoxon Signed-Rank Test. Probability of Superiority Effect Sizes (ES) were calculated as: ES = $\mathrm{ZScore}/\sqrt{\mathrm{n}}$, and ranged from 0 to 1. An ES of 0.5 indicated a 50% probability that there was no difference,1.0 indicated absolute certainty there was a difference, between the scores being compared. An ES of 0.9 indicate almost certainty, 0.7-0.8 likely probably, and 0.6 only slightly greater than an even chance of a difference between scores (Barnes, 2016). A multi-point criterion was used to define runners who positively responded, and therefore the intervention was only considered successful where an individual runner achieved each of the three criteria outlined in Table 2.

Table 2: Multi-point criteria to define positive responders to intervention.

1. Target threshold TA-R for the selected training velocity was achieved during treadmill running.
2. A statistically significant reduction (p<0.05), and a likely probable ES (>0.7) when pre-intervention TA-R was compared to both post-, and 4-week post-intervention during treadmill running.
3. A statistically significant reduction (p<0.05), and a likely probable ES (>0.7) when pre-intervention TA-R was compared to both post-, and 4-week post-intervention during overground running.

Results

Forty-eight runners were screened for eligibility (Figure 1), of which 23 demonstrated TA-R measures that exceeded the pre-defined threshold (Table 1). Nineteen runners agreed to participate in the gait retraining intervention, and therefore completed the pre-intervention assessment. One participant dropped out of the study after the first intervention session due to an injury unrelated to running. The remaining 18 participants (7 female, 11 male; age: 35.2 ±9.6 years) completed all intervention sessions and the post-intervention assessment (Table 3). Participants had regularly participated in running for an average of 8.5 ±9.5 years, and ran 42.4 ±22.2 km over 4.2 ±1.2 weekly training sessions. Three participants were lost to follow up due to being overseas with work commitments (n=2), or moving from the study region (n=1). All 18 runners who completed the haptic feedback gait retraining, and the runners who returned for the 4-week follow-up, did so without any injuries or adverse effects.

Table 3: Participant characteristics.

	Male (n=11)	Female (n=7)	Combined (n=18)
Age (years)	38.3 ±8.2	30.4 ±10.4	35.2 ±9.6
Height (m)	1.81 ±0.07	1.67 ±0.06	1.75 ±0.10
Mass (kg)	82.5 ±10.2	58.7 ±4.5	73.3 ±14.5
Running history (years)	6.8 ±8.9	11.2 ±10.4	8.5 ±9.5
Weekly running distance (km)	36.7 ±18.1	51.4 ±26.5	42.4 ±22.2
Weekly running frequency (days / week)	4.0 ±1.3	4.6 ±0.9	4.2 ±1.2

The Shapiro-Wilk test showed that the data were not normally distributed and therefore non-parametric statistics were used for analysis. Comparing pre- to post-intervention TA-R measures from treadmill running, the median decreased by 50% (Table 4). A Wilcoxon Signed-Rank Test revealed a reduction in TA-R following the intervention (z=-18.2, p<.001), with an ES indicating almost certainty of a change (ES=0.9). Comparing TA-R measures at these same time points from overground running, the median decreased by 28% (z=-13.2, p<.001).

Table 4: Group-based resultant tibial acceleration results for treadmill and overground running.

Condition	Assessment Time Points	TA-R (g) Md (IQR)	Md Diff (%Diff)	*Z*	*p*	ES
Treadmill	Pre-intervention	14.8 (12.5, 16.6)				
	Post-intervention	7.4 (6.1, 9.2)	-7.4 (-50%)	-18.2	<0.001	0.9
	4-wk post-intervention	8.7 (7.4, 13.7)	-6.2 (-41%)	-12.9	<0.001	0.8
Overground	Pre-intervention	19.4 (17.3, 20.6)				
	Post-intervention	14.0 (11.8, 17.7)	-5.4 (-28%)	-13.3	<0.001	0.7
	4-wk post-intervention	16.1 (10.5, 18.6)	-3.3 (-17%)	-11.3	<0.001	0.7

For each condition, results from post-intervention and 4-wk post-intervention assessments were compared to the pre-intervention assessment.

When TA-R from treadmill running were compared from pre-intervention to 4-weeks post-intervention, the median TA-R decreased by 41% (Table 4). A Wilcoxon Signed-Rank Test confirmed a reduction in TA-R 4-weeks post-intervention (z=-12.9, p<.001), with an ES indicating a likely probability of a true reduction (ES=0.8). The median reduction in TA-R between these same time points from the overground running was 17%. All but two runners responded initially positively to the intervention, meeting the criteria outlined in Table 2. This reduced to 11 runners at the 4-week post-intervention follow-up (Figures 5 and 6).

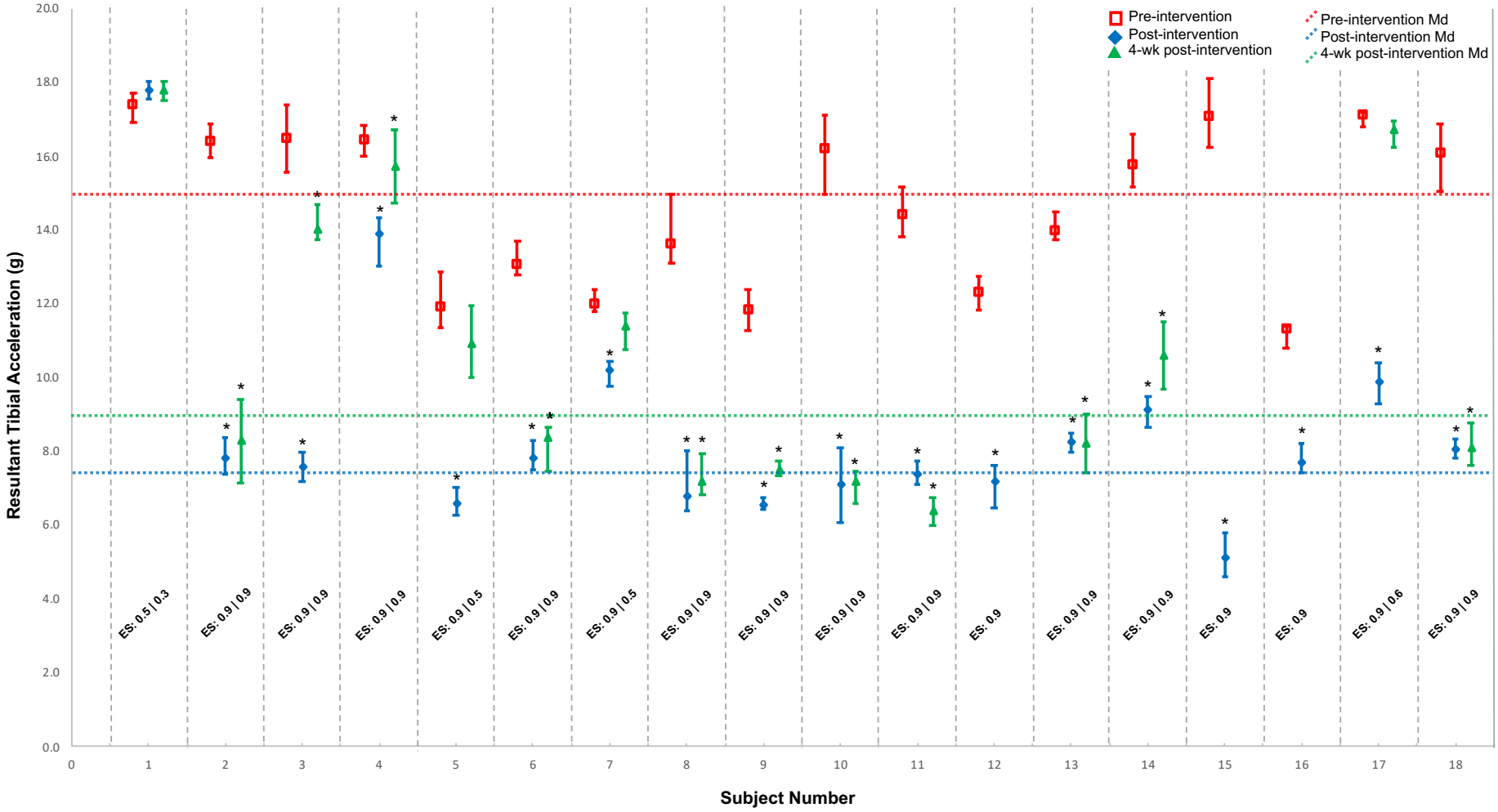

Figure 5: Resultant tibial acceleration during treadmill running at pre-intervention, post-intervention and 4-weeks post-intervention assessments.

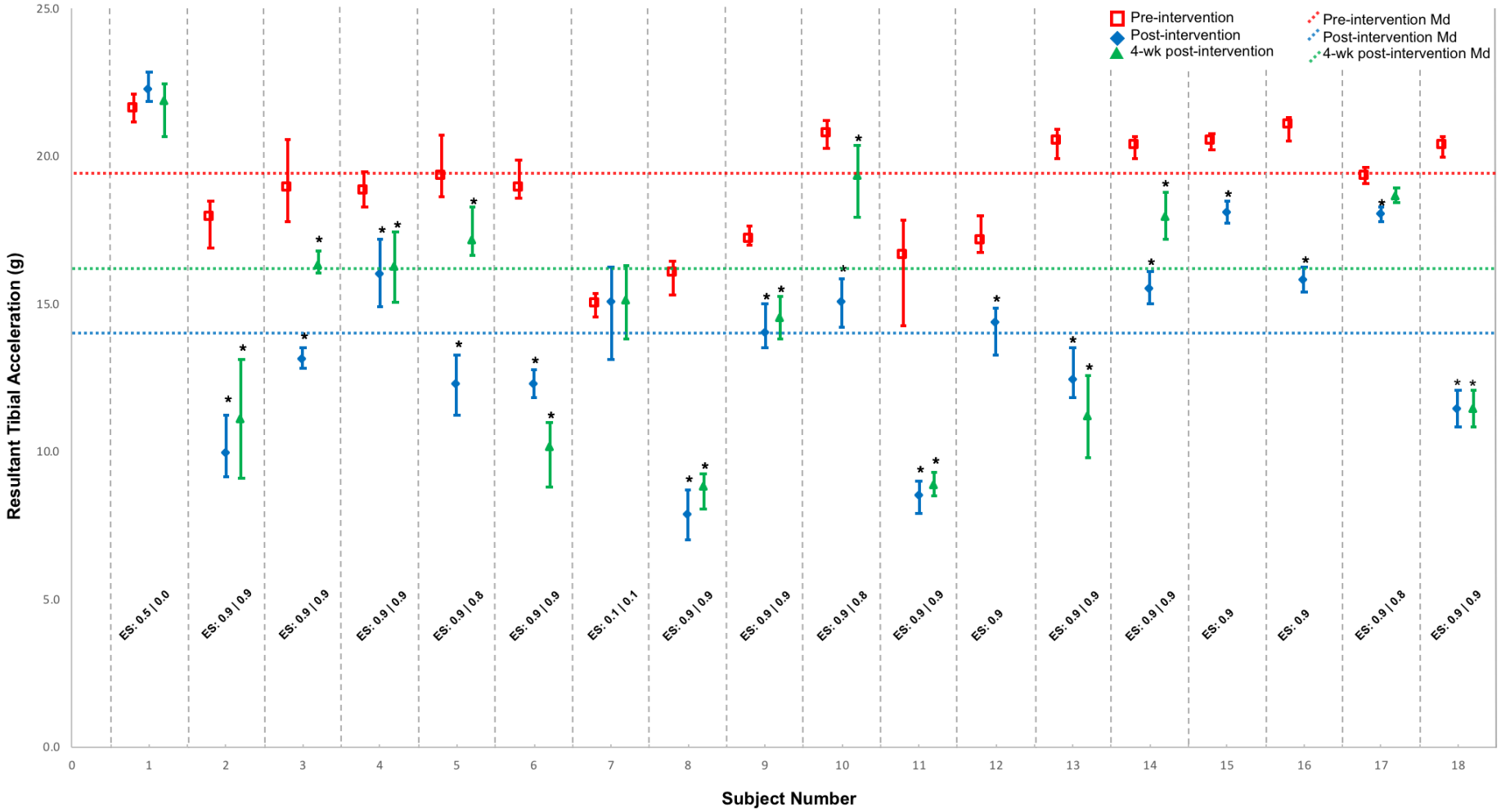

Figure 6: Resultant tibial acceleration during overground running at pre-intervention, post-intervention and 4-weeks post-intervention assessments.

Discussion

The primary aim of this study was to examine the effectiveness of a real-time haptic feedback gait retraining system for reducing resultant tibial acceleration with individual runners, with a secondary aim to assess the retention and the transfer of learning to overground running. Across the cohort of runners studied, this intervention was associated with a 50% reduction in TA-R at the cessation of the intervention, and a 41% reduction 4-weeks later. The magnitude of these changes are amongst the highest reported when compared similar designed studies that have measured axial TA (Clansey et al., 2014; Creaby & Smith, 2016; Crowell et al., 2010; Crowell & Davis, 2011; Wood & Kipp, 2014). When overground running, tibial acceleration were in all cases higher in magnitude than treadmill running. Reductions in TA-R were measured at the post- and 4-week post-intervention time points, with these being somewhat smaller than the changes during treadmill running (28% and 17% respectively). This is a consistent trend observed in previous studies (Clansey et al., 2014; Crowell et al., 2010; Zhang et al., 2019). The differences when compared to treadmill running are likely due to a greater inconsistency in running pace and reduced attentional focus due to inherent distractions of a normal training environment.

While the obvious difference in design between this intervention and those previously published is the use of a haptic feedback device, there were other notable differences. With regard to participant recruitment, while most studies conducted screening based on a target biomechanical variables (e.g. TA or AVLR), a number of studies specifically targeted rearfoot strike runners (Baggaley et al., 2016; Chen et al., 2016; Clansey et al., 2014; Crowell & Davis, 2011; Diebal, Gregory, Alitz, & Gerber, 2012). Additionally, other researchers used a single velocity (commonly 3.7 m/s) to screen all potential participants (Chen et al., 2016; Clansey et al., 2014; Creaby & Smith, 2016; Crowell & Davis, 2011; Phan et al., 2016; Willy et al., 2016). Both of these factors could have biased the study recruitment, and as a result, recruitment of participants for this study was not restricted to any other biomechanical criteria other than high TA-R. Screening was also conducted at four different velocities, and runners chose the velocity which most closely matched their 10 km training pace. Participants were only recruited for the intervention where they exceeded the pre-defined TA-R threshold at their individually selected velocity. Subsequent gait assessments and retraining were all carried out at this velocity. These measures ensured that each participant was undertaking the intervention at a comfortable running pace which had the potential to optimise engagement with the feedback.

At the individual level, the ultimate success of the intervention was determined by a multi-point criterion for both treadmill and overground running. Based on these criteria, 61% of runners

who completed the intervention were classified as positive responders. At the post-intervention time point this success rate was similar to that reported when a visual feedback intervention was used (Zhang et al., 2019). A degree of drop-off in retention was noted at the 4-week post-intervention mark, however previous studies have not assessed changes at the individual level for this length in time, so no direct comparisons can be made (Crowell et al., 2010; Zhang et al., 2019).

It has previously been highlighted that flexibility in feedback protocols is important to optimise individual motor learning (Guadagnoli & Lee, 2004; Zhang et al., 2019), and therefore as part of this study, rather than having a set proportional target threshold that remained constant for the duration of the intervention, a 10% target threshold was reset before each intervention session to ensure that runners had a challenging, yet achievable goal. While the reaction from participants to the haptic feedback intervention was largely positive, many runners struggled during initial sessions determining their current TA-R level in relation to the threshold. With the simple feedback design used, runners received the same feedback stimuli if the just exceeded, or greatly exceeded the target threshold. There is substantial evidence to support the 8-session, faded feedback protocol design can be effective (Chan et al., 2018; Cheung & Davis, 2011; Cheung et al., 2018; Crowell & Davis, 2011; Noehren et al., 2011), there is no evidence that this was the optimal design for each individual in this cohort. Superior results may have been achieved with greater or lesser number of sessions, of a shorter or longer duration. These are two areas where there is clearly a need for additional design optimisation and research validation with runners. While we support the identification of non-responders, there is further work required to improve the early identification of these individuals so that the time and effort of clinicians and runners is not needlessly expended.

While this study presents positive findings, at least for a large proportion of high tibial load runners, it is not without limitations. Due to the lack of a control group it was not possible to establish causation in relation to the intervention. Also, only a relatively small sample of healthy participants were recruited and hence our findings may not be generalised to injured runners, or those with differing characteristics. Additionally, the follow-up assessment timeframe was relatively short, and the incidence of subsequent injuries were not recorded or analysed. There is some evidence that changes in biomechanical risk factors from similar interventions can reduce the incidence of injuries in novice runners (Chan et al., 2018), but these findings need to be replicated for a more experienced cohort as in this study. There were also a number of other elements that were not controlled within the study, this included the participants' running training outside the feedback protocol, as well at the footwear the

runners chose to use during feedback sessions. Both of these factors could have impacted on the training, and the translation of the learning effects.

Conclusions

After a 4-week follow up, 61% of high tibial load runners reduced their tibial acceleration both on a treadmill and overground after undertaking a real-time haptic feedback gait retraining intervention. Haptic feedback based on resultant tibial acceleration appears to be as effective, but less invasive and expensive, compared to other more established modalities, such as visual feedback. This new approach to movement retraining has the potential to revolutionise the way runners engage in gait retraining.

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