Runners’ responses to a biofeedback intervention aimed to reduce tibial acceleration differ within and between individuals

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Runners' responses to a biofeedback intervention aimed to reduce tibial acceleration differ within and between individuals

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ABSTRACT

An increment in peak tibial acceleration (PTA) may be related to an increased risk of running-rated injury. Many authors believe that reducing PTA through improved shock-absorption could, therefore, help prevent injury. The aim of the current study was, therefore, to investigate the individual responses of participants to a biofeedback intervention aimed at reducing PTA. 11 participants (two females, nine males; 43 ± 10 years; stature: 1.74 ± 0.07 m; body mass: 74 ± 11 kg; distance running a week: 19 ± 14 km; 5 km time: 24 ± 3 min) received an intervention of six sessions of multisensory biofeedback aimed at reducing PTA. Mean PTA and kinematic patterns were measured at baseline, directly after the feedback intervention and a month after the end of the intervention. Group as well as single-subject analyses were performed to quantify differences between the sessions. A significant decrease of 26 per cent (effect size: Hedges' g = 0.94) in mean PTA was found a month after the intervention. No significant changes or large effect sizes were found for any group differences in the kinematic variables. However, on an individual level, shock-absorbing solutions differed both within and between participants. The data suggest participants did not learn a specific solution to reduce PTA but rather learned the concept of reducing PTA. These results suggest future research in gait retraining should investigate individual learning responses and focus on the different strategies participants use both between and within sessions. For training purposes, participants should not focus on learning one running strategy, but they should explore several strategies.

1. Introduction

Worldwide, running is one of the most popular recreational exercise activities in terms of participation. The popularity of running is probably due to: being relatively inexpensive, easy to practise, and its health-related benefits. Unfortunately, dropout rates are high due to running-related injuries (Videbæk et al., 2015). Chan et al. (2018) showed in a large prospective study that gait retraining to decrease vertical loading rate reduced the one-year incidence of overall running injuries in novice runners by 62% compared to a control group. Johnson et al. (2020) also showed that higher instantaneous vertical loading rates were associated with overall running injuries. It is impractical to measure loading rates in the field, but peak tibial acceleration (PTA) has been measured outside of the laboratory (Van den Berghe et al., 2022) and has been shown to be correlated with vertical loading rate for level running (Hennig and Lafortune, 1991; Hennig et al., 1993; Laughton et al., 2003). Thus it is plausible that reducing PTA may reduce the likelihood of running injuries. This relationship between PTA and vertical loading rate is absent in Yong et al.'s (2018) study where forefoot-striking is compared to rear-foot striking, but it is plausible that reducing PTA will reduce vertical loading rate for the same gait type, and thus may reduce the likelihood of running injury.

Interventions focussing on decreasing PTA, such as gait retraining using biofeedback, might help to reduce the prevalence of injuries and aid rehabilitation in injured runners. Previous studies have shown gait retraining using biofeedback reduced mean PTA by 22 to 44 %, which was maintained at one-month (Clansey et al., 2014; Crowell and Davis, 2011; Sheerin et al., 2020) and one-year post-intervention (Bowser et al., 2018).

Understanding the way runners change running patterns in response to feedback might help gait retraining. Clansey et al. (2014) reported a reduction in PTA was accompanied by group changes in foot strike

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Table 1
Overview of the feedback intervention, where the first 6 sessions were within 3.5 weeks.

	Ses 1	Ses 2	Ses 3	Ses 4	Ses 5	Ses 6	One-month follow-up
Warming-up	6 min	6 min	6 min	6 min	6 min	6 min	6 min
Baseline	2 min	NA	NA	NA	NA	NA	NA
Feedback	15 min	16 min	17 min	18 min	19 min	20 min	NA
Retention	1 min	1 min	1 min	1 min	1 min	2 min	2 min

Ses = session, min = minutes, NA = not applicable.

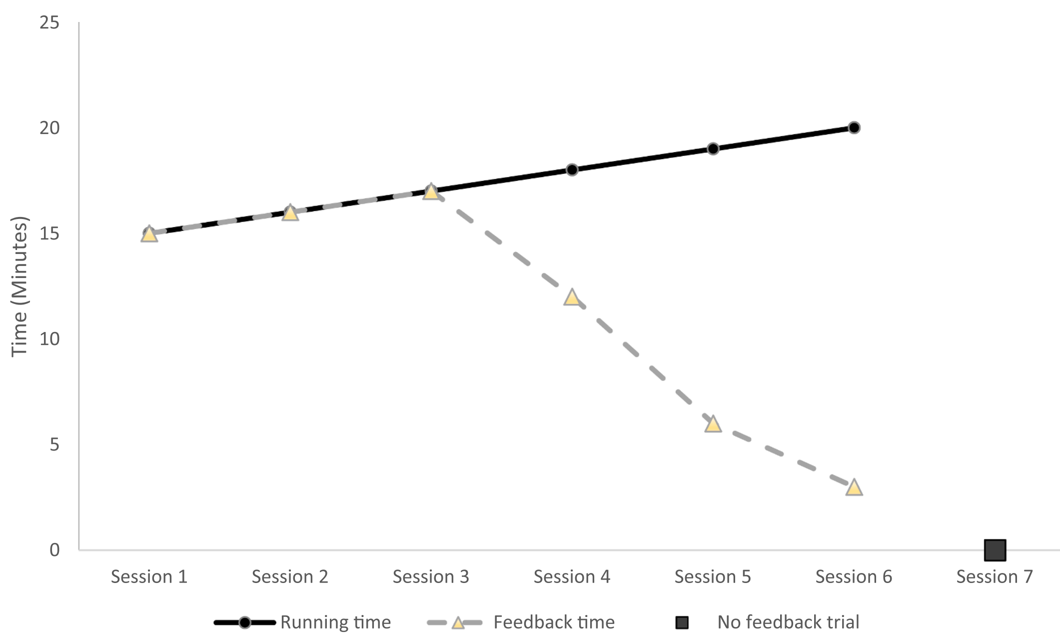

Fig. 1. Schedule of running time and feedback time of the 6 feedback sessions. The feedback was gradually removed after the third session. In the seventh session no feedback trial was given. Session 1–6 occurred over 2–3.5 weeks, session 7 occurred a month after.

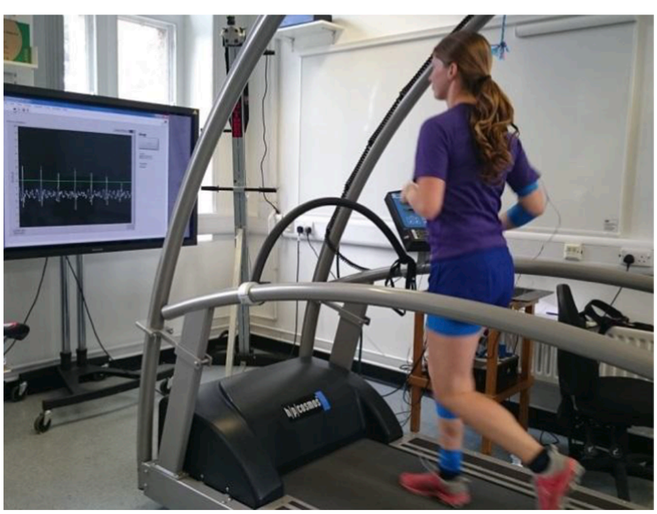

Fig. 2. Participant receiving feedback on tibial acceleration. The screen shows the tibial acceleration signal (white peaks) together with the target (green straight line). This is a recording without motion capture. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

angle, with participants changing from rearfoot to midfoot strike pattern, increasing ankle plantarflexion, and decreasing in heel vertical velocity at initial contact. Although Clansey et al. (2014) found a significant trend towards midfoot strike patterns, they did not find the accompanying increased knee flexion angle at initial contact, shorter stride length, increased stride frequency (cadence), and decreased knee flexion excursion, to be expected with a change in foot strike angle (Almeida et al., 2015). A large standard deviation was reported for footstrike angle in the post-intervention session, which could indicate participants used different strategies to decrease mean PTA. Different strategies can be adopted to reduce loading rates (e,g, extreme rear-foot or fore-foot initial contact (Stiffler-Joachim et al., 2019)). These different strategies may cancel each-other out when calculating the mean over a group and, broaden a response or demonstrate no group difference (Bates et al., 2004). Thus the aim of the current study was to investigate the individual responses to a biofeedback intervention aimed at reducing PTA. The first objective was to investigate the individual effects of a six-session multisensory feedback intervention on mean PTA. The second objective was to establish the kinematic strategies participants used to reduce PTA.

2. Methods

2.1. Participants

An a-priori statistical power calculation indicated a minimum of twelve participants were required for a repeated measures ANOVA from three time points (Baseline of first session, B; retention test taken directly after the intervention, R1; and retention measurement taken after one month, R2), with a power of 0.80, an alpha level of 0.05 and effect size of 0.40 (Faul et al., 2013). With the retention test being a 2 min run without feedback to measure the learning effect of the

Table 2
Kinematic and spatiotemporal results for all participants.

Variable	Baseline	Reten direct	Reten month	ANOVA		Hedges' g	
	Mean (SD)	Mean (SD)	Mean (SD)	F	p	1—6	1—7
Peak tibial accel (g)	7.8 (1.9)	6.3 (2.3) *	5.79 (2.3) *	4.07	**0.03**	0.70	0.94
Foot strike angle (°)	14.7 (8.7)	16.6 (9.2)	13.2 (11.9)	1.10	0.35	0.18	0.10
Ankle dorsiflex IC (°)	2.4 (4.4)	1.2 (4.7)	−0.6 (6.1)	1.53	0.24	0.21	0.52
Knee flexion IC (°)	17.5 (5.6)	16.3 (7.0)	18.9 (5.6)	1.07	0.36	0.14	0.22
Knee flexion excurs (°)	25.2 (4.8)	25.3 (5.9)	23.6 (5.8)	0.88	0.43	−0.03	0.26
Hip flexion IC (°)	40.3 (6.3)	38.5 (5.4)	39.2 (4.6)	0.80	0.46	0.27	0.17
Hip adduction excurs (°)	5.8 (3.5)	7.0 (3.7)	5.9 (3.8)	1.36	0.28	0.28	−0.02
Ankle evers excurs (°)	10.1 (3.3)	115 (5.2)	12.4 (7.6)	1.22	0.41	0.28	0.36
Landing distance (m)	0.25 (0.06)	0.27 (0.05)	0.25 (0.06)	2.16	0.17	0.26	0.05
Cadence (steps/s)	1.42 (0.06)	1.45 (0.07)	1.45 (0.10)	1.83	0.20	0.45	0.39
Heel velocity IC (m/s)	0.37 (0.11)	0.27 (0.10)	0.30 (0.19)	4.19	0.06	0.89	0.38
Peak hip adduction (°)	19.7 (6.8)	19.5 (5.2)	19.2 (4.0)	0.03	0.97	−0.02	0.04
Peak ankle eversion (°)	5.5 (2.9)	8.8 (6.2)	8.4 (5.9)	0.14	0.18	0.65	0.58

Reten direct = retention measurement taken directly after the feedback intervention, Reten month = retention measurement taken after a month, SD = standard deviation, F = F-value, p = p-value,1–6 = comparison baseline to retention measurement taken directly after the feedback intervention, 1–7 = comparison baseline to retention measurement taken after a month, accel = acceleration, dorsiflex = dorsiflexion, IC = initial contact, excurs = excursion, * = significant different to baseline, $p < 0.05$, **Bold** = significant, $p < 0.05$.

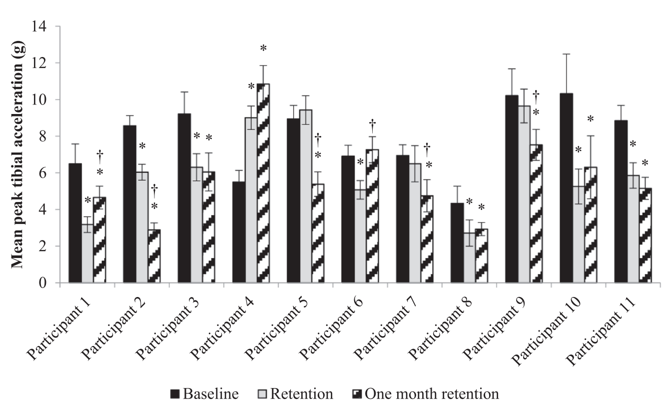

Fig. 3. Mean peak tibial acceleration for the participants for the different measurements displayed with one standard deviation. * = real difference between retention measurement and baseline measurement, † = real difference between retention measurement taken directly after the measurement and retention taken after a month.

Table 3
Adaptations to a six-session biofeedback intervention. In the table, shock-absorbing mechanisms are shown participants found using comparing the session (direct after the intervention or a month after the intervention) to the baseline measurement. If no decrease in mean peak tibial acceleration was found the differences between the two sessions were not reported (n.a.).

PP	Direct after intervention	A month after intervention
1	ankle plantarflexion↑ cadence↑ heel velocity↓	ankle plantarflexion↑ knee flexion excursion↑ ankle eversion excursion↑
2	knee flexion excursion↑ heel velocity↓	foot strike angle↓ knee flexion↑ landing distance↓ heel velocity↓
3	ankle eversion excursion↑ heel velocity↓	knee flexion excursion↑ heel velocity↓
4	n.a.	n.a.
5	n.a.	foot strike angle↓ knee flexion↑ hip adduction excursion ↑landing distance↓
6	knee flexion↑ hip adduction excursion↑ cadence↑ heel velocity↓	n.a.
7	n.a.	foot strike angle↓ plantarflexion↑ knee flexion↑ hip adduction excursion ↑landing distance↓
8	cadence↑ heel velocity↓	knee flexion↑ ankle eversion excursion↑ cadence↑ heel velocity↓
9	n.a.	knee flexion excursion↑ ankle eversion excursion↑ cadence↑ heel velocity↓
10	hip adduction excursion↑ ankle eversion excursion↑ cadence↑ heel velocity↓	hip adduction excursion↑ankle eversion excursion↑ cadence↑ heel velocity↓
11	heel velocity↓	heel velocity↓ cadence↑ knee flexion↑

↑ = real increase between the session and the baseline measurement, ↓ = real decrease between the session and the baseline measurement.

intervention. 14 participants were recruited following institutional ethical approval. The inclusion criteria required participants to run at least once a week, be injury-free during testing, and be aged 18 or over. Participants were selected based on having a high PTA (Clansey et al., 2014; Crowell and Davis, 2011; Sheerin et al., 2020). 132 runners were measured during a recreational, mass start, five-kilometre run. The top 30 % of participants with a mean PTA of at least 11 g, measured over the whole run, were invited to take part in the study. 14 runners participated in the study. 11 of the 14 participants completed the intervention (two females, nine males; 43 ± 10 years; stature: 1.74 ± 0.07 m; body mass: 74 ± 11 kg; distance running a week: 19.09 ± 13.58 km; 5 km time: 23.61 ± 3.08 min). Participants completed a pre-screening questionnaire (Appendix 1) and provided written informed consent before participating in the study.

2.2. Study design

Participants were required to attend the laboratory for six biofeedback sessions, occurring over a 2 to 3.5 week time period, and a follow-up session at least one month after the intervention had finished (Table 1). During the sessions participants wore their own footwear, which was the same for each participant over the seven sessions. To create a representative design (Araújo et al., 2007), for all sessions treadmill speed was set to 95 % of participants' five-kilometre current best speed. Running time in the feedback trials increased, while feedback was faded over the feedback sessions (Fig. 1), to prevent participants becoming dependent on feedback, facilitating improved learning (Crowell and Davis, 2011; Winstein, 1991). The participants were instructed on how the feedback system worked, but were not given any instruction on what the feedback represented or how to change their gait pattern (Bates, 1996; Newell, 1986). This approach was chosen to allow participants to explore possible shock-absorbing solutions rather than being prescriptive about any one strategy. PTA was recorded for all sessions. Kinematic and spatiotemporal data were collected during the first, sixth, and seventh sessions.

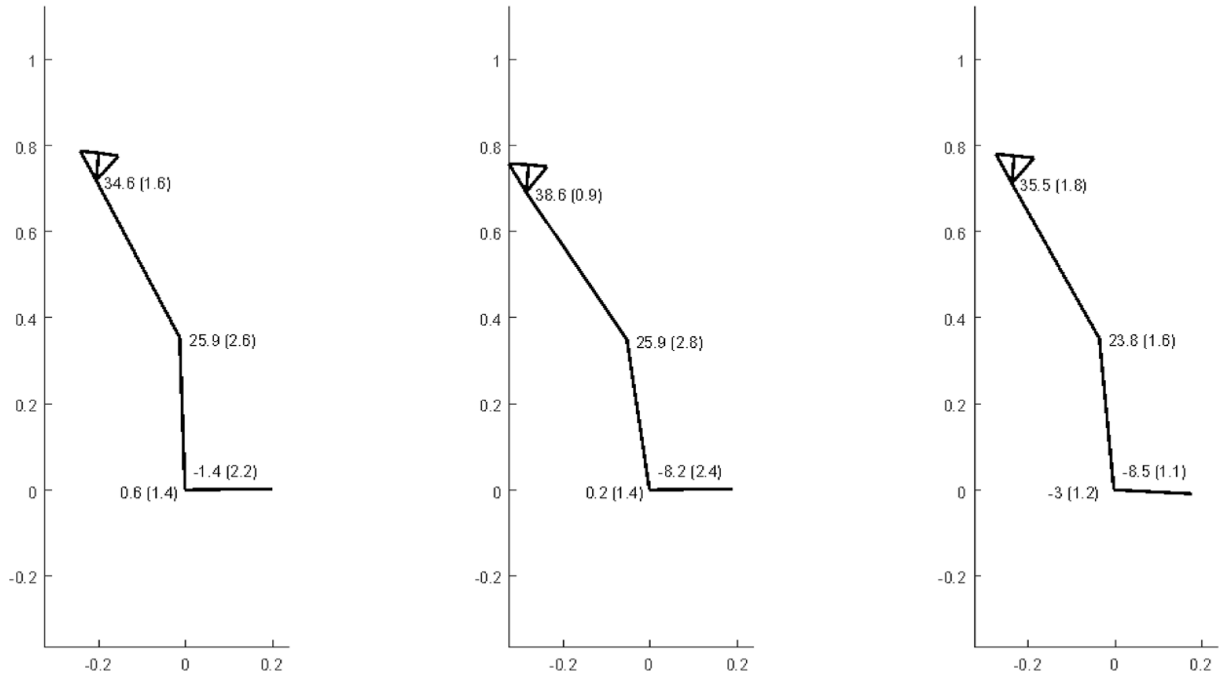

Fig. A1. Stick figures displaying the foot contact, ankle, knee and hip angle. From left to right: baseline measurement, retention test direct after the feedback intervention, and retention test after a month.

Table A1
Mean and standard deviation for the parameters of interest for the different measurements.

Variable	Baseline	Retention after intervention	Retention after month
	Mean (SD)	Mean (SD)	Mean (SD)
Peak tibial acceleration (g)	6.5 (1.1)	3.2 (0.4) *	4.7 (0.6) *†
Foot strike angle (°)	0.6 (1.4)	0.2 (1.4)	−3.0 (1.3)
Ankle dorsiflexion IC (°)	−1.4 (2.2)	−8.2 (2.4) *	−8.5 (1.1) *
Knee flexion IC (°)	25.9 (2.6)	25.9 (2.9)	23.8 (1.6)
Knee flexion excursion (°)	18.2 (2.7)	17.9 (2.3)	20.2 (2.0) *†
Hip flexion IC (°)	34.6 (1.6)	38.6 (1.0)	35.5 (1.8)
Hip adduction excursion (°)	4.8 (1.0)	5.5 (1.0)	3.3 (0.8) *†
Ankle eversion excursion (°)	8.4 (3.4)	10.4 (3.2)	12.0 (1.5) *
Landing distance (m)	0.15 (0.02)	0.17 (0.01) *	0.17 (0.01) *
Cadence (steps/s)	1.46 (0.02)	1.48 (0.02) *	1.44 (0.02) †
Heel velocity IC (m/s)	0.53 (0.08)	0.43 (0.06) *	0.67 (0.06) *†
Peak hip adduction (°)	15.9 (1.3)	16.1 (1.0)	22.4 (1.2) *
Peak ankle eversion (°)	5.0 (0.9)	6.9 (0.9)	4.3 (1.2)

IC = Initial contact, SD = standard deviation, * = real difference between retention measurement and baseline measurement, † = real difference between retention measurement taken directly after the measurement and retention taken after a month, IC = initial contact.

2.3. Systems

Tibial acceleration was measured using a uniaxial accelerometer (PCB Piezotronics, Stevenage, UK, Model: 352C22), with its sensitive axis visually aligned with the long axis of the right tibia. The accelerometer was mounted on a small piece of thermoplastic (total mass: 1.65 g), which was attached with double-sided tape to the anteromedial aspect of the right tibia, five centimetres above the medial malleolus and wrapped in cohesive bandage. The accelerometer was connected via a cable to a PCB signal conditioner (PCB Piezotronics, Stevenage, UK, model: 480E09; gain = 10) and sampled at 1000 Hz by an analogue to digital converter (USB-6009, National Instruments, Austin, TX).

The multisensory feedback was delivered using a custom-written LabVIEW™ program (National Instruments, Austin, TX, USA). Visual feedback consisted of a real-time chart of the acceleration displayed on a screen, together with a target line (Fig. 2). Based on pilot studies and to keep participants motivated, the initial target was set at the tenth percentile of the PTA recorded during the baseline measurement and adjusted automatically to the participant's performance. Participants received both vibrotactile feedback on the wrist (Precision Microdrives, London, UK, model: 307–103) and auditory feedback through a speaker when the measured PTA was greater than the target acceleration. The intensity of the vibration and pitch of the sound were scaled to the magnitude of the difference between the measured PTA and the target acceleration, participants were made aware of this prior to undertaking the intervention.

Kinematic and spatiotemporal data were collected using a 14-camera optoelectronic motion capture system sampling at 240 Hz (12 × Raptor and 2 × Eagle, Motion Analysis Corporation, CA, US). The cameras were placed around the treadmill with a capture volume of 2.25 m, a width of 0.75 m, and a height of 1.5 m, which included the legs and pelvis. The system was calibrated in two steps. The averages of the 3D residuals

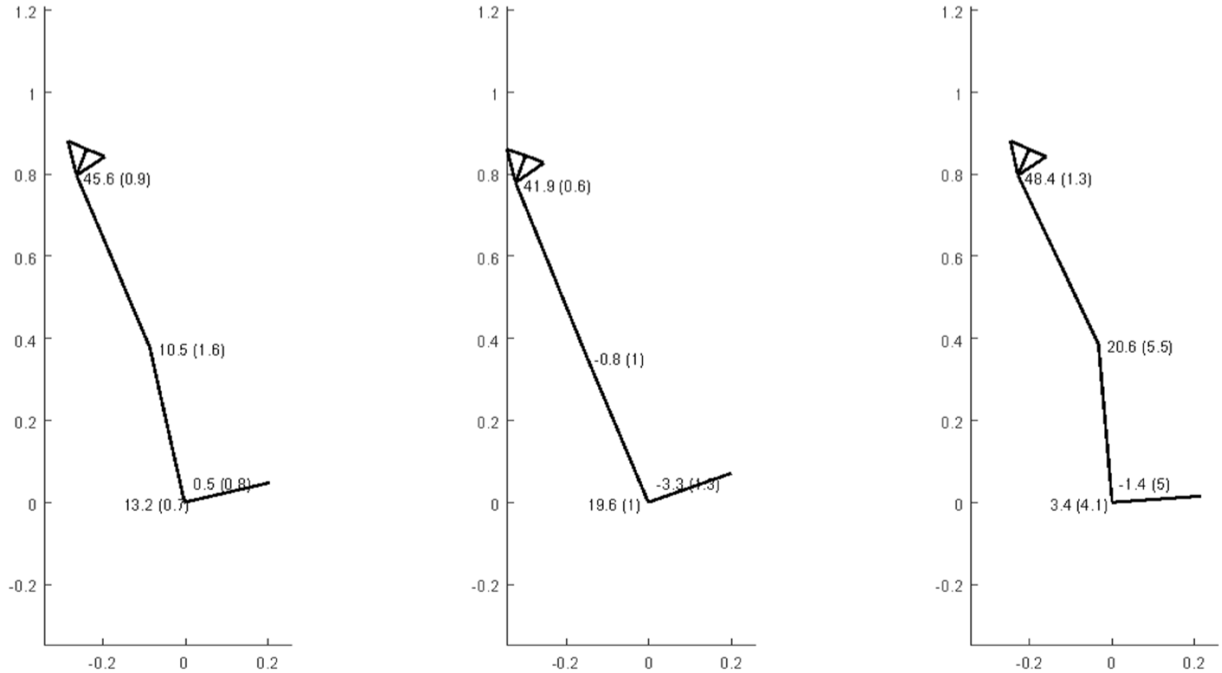

Fig. A2. Stick figures displaying the foot contact, ankle, knee and hip angle. From left to right: baseline measurement, retention test direct after the feedback intervention, and retention test after a month.

Table A2
Mean and standard deviation for the parameters of interest for the different measurements.

Variable	Baseline	Retention after intervention	Retention after month
	Mean (SD)	Mean (SD)	Mean (SD)
Peak tibial acceleration (g)	8.6 (0.6)	6.0 (0.4) *	2.9 (0.4) *†
Foot strike angle (°)	13.2 (0.7)	19.6 (1.0) *	3.4 (4.1) *†
Ankle dorsiflexion IC (°)	0.5 (0.8)	−3.3 (1.3)	−1.4 (5.0)
Knee flexion IC (°)	10.5 (1.6)	−0.8 (1.0) *	20.6 (5.5) *†
Knee flexion excursion (°)	26.9 (1.6)	30.8 (1.0) *	15.7 (5.9) *†
Hip flexion IC (°)	45.6 (0.9)	41.9 (0.6)	48.4 (1.3) †
Hip adduction excursion (°)	3.5 (0.5)	4.1 (0.7)	4.3 (0.7)
Ankle eversion excursion (°)	11.3 (1.1)	10.7 (2.3)	4.3 (5.6) *†
Landing distance (m)	0.26 (0.01)	0.27 (0.01)	0.26 (0.04) *†
Cadence (steps/s)	1.48 (0.02)	1.44 (0.02) *	1.45 (0.06) *
Heel velocity IC (m/s)	0.16 (0.04)	0.07 (0.02) *	0.11 (0.09) *
Peak hip adduction (°)	13.9 (0.3)	14.2 (0.5)	20.0 (0.5)
Peak ankle eversion (°)	5.0 (0.7)	15.2 (0.6) *	11.8 (1.1)

IC = Initial contact, SD = standard deviation, * = real difference between retention measurement and baseline measurement, † = real difference between retention measurement taken directly after the measurement and retention taken after a month, IC = initial contact.

were under 0.4 mm for each calibration. The positive x-axis was directed mediolateral, pointing perpendicular to the treadmill; the positive y-axis was directed anterior, while the positive z-axis was directed upwards. Retro-reflective, spherical markers (12.5 mm diameter) were placed on the right foot, shank, thigh, and pelvis: anterior superior iliac spines, posterior superior iliac spines, medial and lateral femoral condyles, medial and lateral malleoli, back of the calcaneus (heel), and the first and fifth distal metatarsal heads. Clusters with 4 markers were placed on the shank and thigh. To allow for segment coordinate systems to be defined using proximal and distal segment markers, a static trial of a few seconds was recorded in which participants were asked to stand in the anatomical position, after which markers were removed from medial and lateral femoral condyles and malleoli. Next, a dynamic trial to calculate the functional hip joint centre was recorded (Begon et al., 2007), followed by the running trials (Table 1).

2.4. Data processing

The sampled signal from the accelerometer was exported to MATLAB (Mathworks, R2016a) and filtered with a 400th order, Hamming windowed, FIR band-pass filter with lower and upper cut-off frequencies of 8 and 60 Hz, respectively, since the low frequencies associated with voluntary leg movement were found to be below 8 Hz and resonant frequencies were found to be above 60 Hz. After filtering, the mean of the signal was subtracted from the signal to standardize the data and the peaks of the signal were identified to define PTA.

The data recorded from the motion capture system were processed in Cortex software (version 5.3, Motion Analysis Corporation, Santa Rosa, CA, USA) by filling any gaps in the data shorter than 10 samples. The exported data were then filtered in Visual 3D software (C-Motion Inc., Germantown, USA) with a low-pass, fourth order, zero-phase-shift, Butterworth filter with a cut-off frequency of 14 Hz or 18 Hz, for

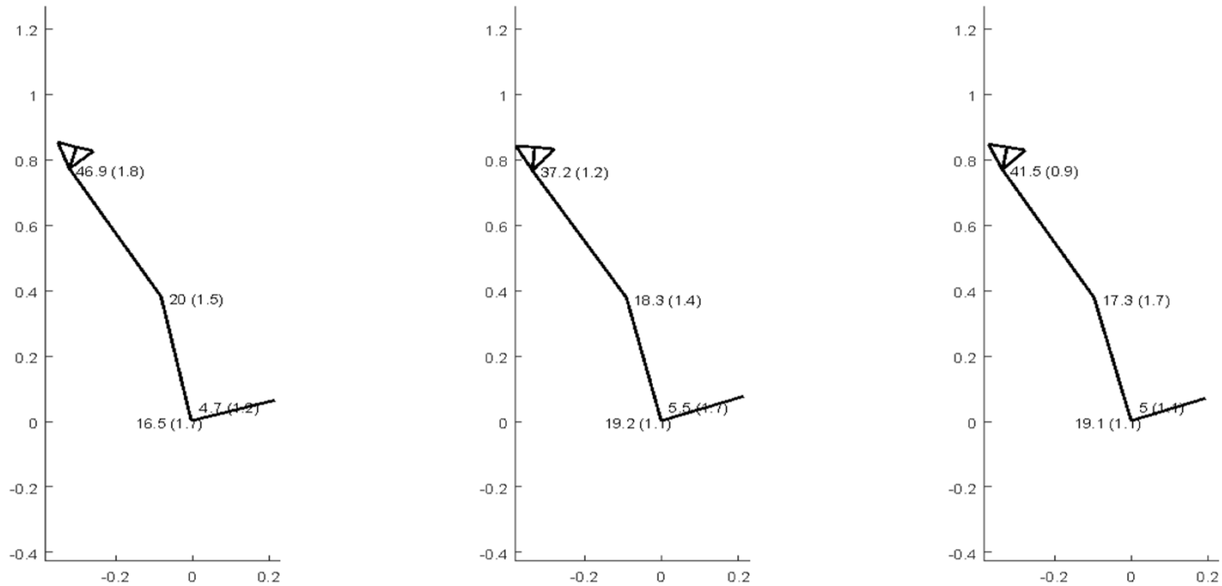

Fig. A3. Stick figures displaying the foot contact, ankle, knee and hip angle. From left to right: baseline measurement, retention test direct after the feedback intervention, and retention test after a month.

Table A3
Mean and standard deviation for the parameters of interest for the different measurements.

Variable	Baseline	Retention after intervention	Retention after month
	Mean (SD)	Mean (SD)	Mean (SD)
Peak tibial acceleration (g)	9.2 (1.2)	6.3 (0.7) *	6.1 (1.0) *
Foot strike angle (°)	16.5 (1.7)	19.2 (1.1)	19.1 (1.1)
Ankle dorsiflexion IC (°)	4.7 (1.2)	5.5 (1.7)	5.0 (1.1)
Knee flexion IC (°)	20.0 (1.5)	18.3 (1.4)	17.3 (1.7)
Knee flexion excursion (°)	20.8 (1.7)	22.7 (1.4)	24.8 (1.5) *
Hip flexion IC (°)	46.9 (1.8)	37.2 (1.2) *	41.5 (0.9)
Hip adduction excursion (°)	10.9 (0.9)	5.8 (1.8) *	9.9 (0.8) †
Ankle eversion excursion (°)	11.8 (1.6)	20.4 (4.3) *	12.7 (1.2) †
Landing distance (m)	0.27 (0.01)	0.29 (0.01) *	0.29 (0.01) *
Cadence (steps/s)	1.42 (0.02)	1.41 (0.03)	1.39 (0.03) *
Heel velocity IC (m/s)	0.30 (0.06)	0.21 (0.04) *	0.22 (0.04) *
Peak hip adduction (°)	28.2 (1.1)	19.7 (0.8) *	18.6 (0.6) *
Peak ankle eversion (°)	3.7 (1.0)	11.6 (1.1) *	11.0 (0.7)

IC = Initial contact, SD = standard deviation, * = real difference between retention measurement and baseline measurement, † = real difference between retention measurement taken directly after the measurement and retention taken after a month, IC = initial contact.

calculation of acceleration and position, respectively. These cut-off frequencies were defined by a residual analysis. The filtered positions were used to calculate hip, knee, and ankle joint angles (Grood and Suntay, 1983). Joint angles and filtered marker data were exported from Visual 3D and dependent variables were calculated using Matlab (Mathworks, R2016a). Identification of initial foot contact was based on the acceleration of foot markers (Maiwald et al., 2009).

2.5. Outcome measures

The mean of the final 20 steps of each measurement was used to calculate the dependent variables. The dependent variables were related to different shock attenuating variables (Table 2). Eversion joint angular excursion was defined as the angular displacement between initial contact and the peak value during the stance phase of each step. Foot strike angle was calculated by subtracting the foot angle to the horizontal while standing from the foot angle at initial contact of each step during the running measurements, such that a value of 0° corresponded with a flat foot (Altman and Davis, 2012). The foot angle was defined as the angle, in the lab YZ plane, between the vector from the heel to the first metatarsal head and the anteroposterior axis in the lab coordinate system. A rearfoot strike was defined as foot strike angle $\geq 8.0°$, a midfoot strike as foot strike angle $> -1.6°$ and $< 8.0°$, and a forefoot strike as foot strike angle $\leq -1.6°$ (Altman and Davis, 2012). Landing distance was calculated as the horizontal distance between the sacrum (the virtual midpoint between the left and right posterior superior iliac spine markers) and the heel marker at initial contact.

2.5.1. Single-participant analysis

A single-participant analysis was used to characterise individual kinematic changes (Bates, 1996). For each participant, minimal detectable differences (MDD) were used to characterize “real” individual differences between the measurements (Atkinson and Nevill, 1998). The minimal detectable differences for the dependent variables were based on a previously conducted reliability study and can be found in Appendix 2. Effect sizes were calculated using Cohen’s d comparing the last 20 steps of R2 to B. Cohen’s d above 0.2, 0.5 and 0.8 were considered to represent small, medium, and large differences, respectively.

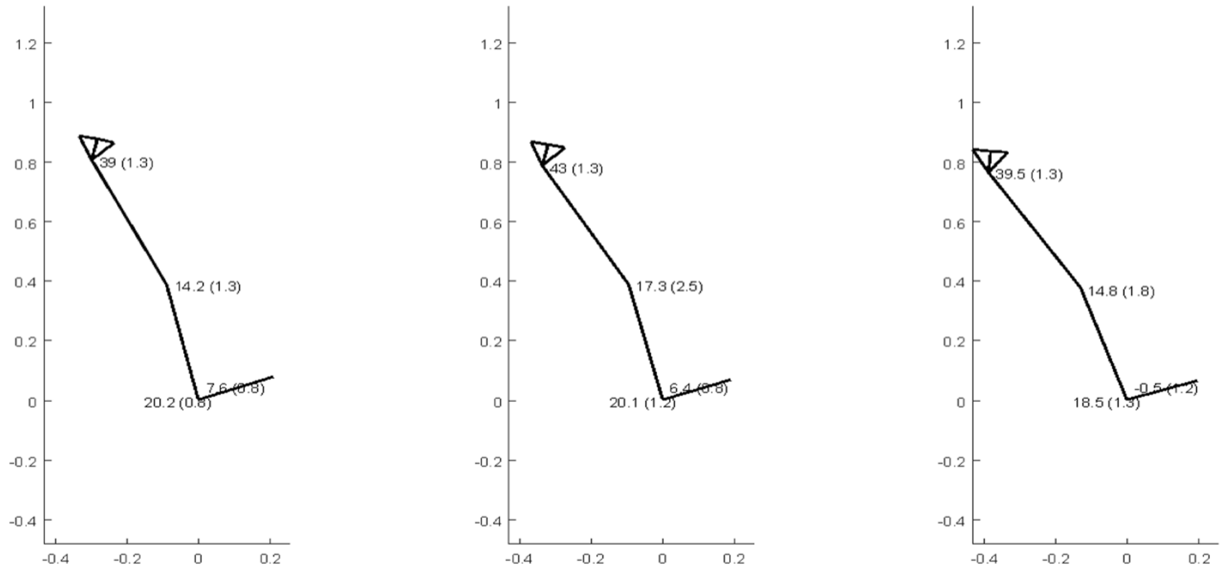

Fig. A4. Stick figures displaying the foot contact, ankle, knee and hip angle. From left to right: baseline measurement, retention test direct after the feedback intervention, and retention test after a month.

Table A4
Mean and standard deviation for the parameters of interest for the different measurements.

Variable	Baseline	Retention after intervention	Retention after month
	Mean (SD)	Mean (SD)	Mean (SD)
Peak tibial acceleration (g)	5.5 (0.6)	9.0 (0.6) *	10.8 (1.0) *
Foot strike angle (°)	20.2 (0.8)	20.1 (1.2)	18.5 (1.3)
Ankle dorsiflexion IC (°)	7.6 (0.8)	6.4 (0.8)	−0.5 (1.2) *†
Knee flexion IC (°)	14.2 (1.3)	17.3 (2.5)	14.8 (1.8)
Knee flexion excursion (°)	30.4 (1.6)	29.1 (2.7)	32.0 (1.7)
Hip flexion IC (°)	39.0 (1.3)	43.0 (1.3)	39.5 (1.3)
Hip adduction excursion (°)	12.6 (1.5)	17.0 (2.4) *	14.4 (1.2) *†
Ankle eversion excursion (°)	8.6 (1.8)	10.7 (1.2)	8.0 (1.4)
Landing distance (m)	0.33 (0.01)	0.33 (0.01)	0.33 (0.01)
Cadence (steps/s)	1.30 (0.07)	1.38 (0.04) *	1.33 (0.05) *†
Heel velocity IC (m/s)	0.54 (0.06)	0.38 (0.04)*	0.38 (0.06) *
Peak hip adduction (°)	13.8 (1.0)	24.2 (3.0) *	18.1 (0.8)
Peak ankle eversion (°)	8.0 (1.6)	6.9 (0.4)	16.8 (1.0) *†

IC = Initial contact, SD = standard deviation, * = real difference between retention measurement and baseline measurement, † = real difference between retention measurement taken directly after the measurement and retention taken after a month, IC = initial contact.

2.5.2. Group analysis

A repeated measures analysis of variance (ANOVA) was performed to compare B, R1, and R2 to determine the acceleration and kinematic response. The assumption of sphericity was checked. If the assumption was violated and the Greenhouse-Geisser epsilon was ≥ 0.75, the Huynh-Feldt correction was used, if the assumption was violated and the Greenhouse-Geisser epsilon was < 0.75 the Greenhouse-Geisser correction was used. Paired t-tests were used as post hoc tests to identify where the specific differences occurred between the measurements, with the main interest being in the difference between B and R2. The level of significance was set at 0.05. Calculations were performed using SPSS, version 24 (SPSS; Inc, Chicago, IL). Effect sizes were calculated with the use of Hedges' g. Hedges' g above 0.2, 0.5 and 0.8 were considered to represent small, medium, and large differences, respectively.

3. Results

3.1. Tibial acceleration response

A significant effect (F (2,20) = 4.07, p = 0.03) of the intervention was found on mean PTA. For the group, a large effect size was found when comparing mean PTA at R2 to B (B = 7.84 g, R2 = 5.79 g, p = 0.042, g = 0.94). Nine of the 11 participants demonstrated a real reduction in mean PTA comparing R2 to B (Fig. 3).

3.2. Kinematic and spatiotemporal responses

No significant group effect was found for the intervention in any of the kinematic or spatiotemporal variables (Table 2). However, a large effect size (g = 0.89) was found for the decrease in heel velocity at initial contact when comparing R1 to B. A moderate effect size (g = 0.52) was found for an increase in ankle plantarflexion at initial contact when comparing R2 to B. Further, large standard deviations were found for most variables suggesting the presence of inter-individual differences in responses.

Several adaptations were seen across participants (Table 3). Three participants (2, 5, and 7) changed from a rear/midfoot contact to a midfoot/forefoot contact when comparing R2 to B (Appendix 3). The other participants found different shock-absorbing solutions comparing R2 to B. These included increased knee flexion excursion (participants 1, 3, and 9); increased knee flexion at initial contact (participants 8 and 11); increased hip adduction excursion (participant 10); and/or

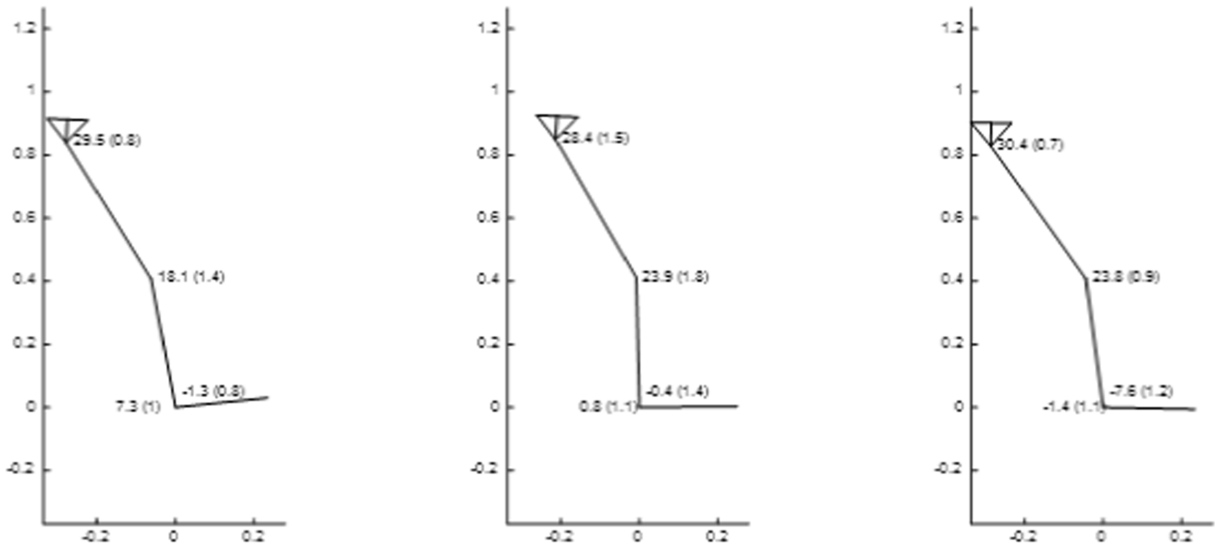

Fig. A5. Stick figures displaying the foot contact, ankle, knee and hip angle. From left to right: baseline measurement, retention test direct after the feedback intervention, and retention test after a month.

Table A5
Mean and standard deviation for the parameters of interest for the different measurements.

Variable	Baseline	Retention after intervention	Retention after month
	Mean (SD)	Mean (SD)	Mean (SD)
Peak tibial acceleration (g)	8.9 (0.7)	9.4 (0.8)	5.4 (0.7) *†
Foot strike angle (°)	7.3 (1.0)	0.8 (1.1) *	−1.4 (1.1) *
Ankle dorsiflexion IC (°)	−1.3 (0.8)	−0.4 (1.4)	−7.6 (1.2) *†
Knee flexion IC (°)	18.1 (1.4)	23.9 (1.8) *	23.8 (0.9) *
Knee flexion excursion (°)	19.4 (1.9)	12.5 (2.0) *	16.0 (1.2) *†
Hip flexion IC (°)	29.5 (0.8)	28.4 (1.5)	30.4 (0.7)
Hip adduction excursion (°)	2.5 (0.7)	6.1 (1.2) *	6.0 (1.1) *
Ankle eversion excursion (°)	9.0 (1.1)	1.7 (1.6) *	5.6 (0.9) *†
Landing distance (m)	0.19 (0.01)	0.17 (0.02) *	0.16 (0.01) †*
Cadence (steps/s)	1.40 (0.03)	1.41 (0.03)	1.40 (0.03)
Heel velocity IC (m/s)	0.44 (0.05)	0.27 (0.04) *	0.44 (0.06) †
Peak hip adduction (°)	13.3 (0.9)	18.8 (1.4)	20.9 (0.9) *
Peak ankle eversion (°)	0.8 (0.6)	0.8 (0.6)	0.7 (0.4)

IC = Initial contact, SD = standard deviation, * = real difference between retention measurement and baseline measurement, † = real difference between retention measurement taken directly after the measurement and retention taken after a month, IC = initial contact.

increased ankle eversion excursion (participant 1, 8, 9, and 10). For some variables, despite seeing little change in the group average, real individual changes were observed. For example, for the whole group, knee flexion angle at IC increased by a mean of 1.4° between baseline and one-month retention measurements. However, different responses were evident for individual participants with, for example, real decreases of – 5° (participant 9) and – 6.1° (participant 10) and real increases of between 3.8° and 10.1° (participant 2, 5, 7, 8, 11). Therefore, even though real differences were found within some participants, these were both positive and negative and cancelled each other out when adopting a group analysis approach. Similar findings were also found in the other key variables.

Further, different strategies between both retention measurements were found for most individuals (R1 and R2, Table 3, Appendix 3). For example, comparing R1 to B, participant 3 showed a real increase in ankle eversion excursion while comparing R2 to B measurement the participant showed a real increase in knee flexion excursion instead. Participant 3′s PTA was lower in both R1 and R2 compared to B.

4. Discussion

The aim of the current study was to investigate the individual responses to a biofeedback intervention aimed at reducing PTA. The first objective was to investigate the individual effects of a six-session multisensory feedback intervention on mean PTA. The second objective was to establish the kinematic strategies participants used to reduce PTA. These objectives will be discussed separately followed by the limitations and strengths of the study.

4.1. Response to a biofeedback intervention

As a group, there was a significant decrease of 26 % in mean PTA comparing R2 to B. Of the 11 participants, one participant was unable to respond to the feedback and showed an increase in mean PTA in all sessions compared to the baseline measurement. Another showed no response at R2, but did show reductions in mean PTA at R1. The results for this participant suggest even though the feedback was faded to facilitate improved learning to avoid dependency on the feedback (Winstein, 1991), the participant remained dependent. It is possible the current feedback schedule was insufficient for this participant and future

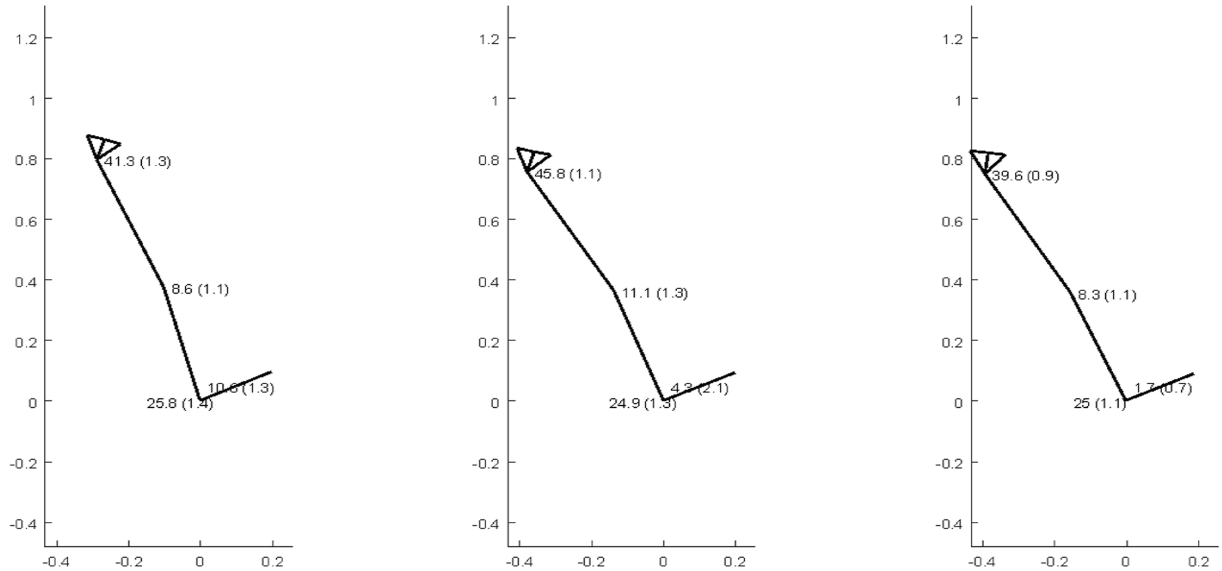

Fig. A6. Stick figures displaying the foot contact, ankle, knee and hip angle. From left to right: baseline measurement, retention test direct after the feedback intervention, and retention test after a month.

Table A6
Mean and standard deviation for the parameters of interest for the different measurements.

Variable	Baseline	Retention after intervention	Retention after month
	Mean (SD)	Mean (SD)	Mean (SD)
Peak tibial acceleration (g)	6.9 (0.6)	5.1 (0.5) *	7.3 (0.7) †
Foot strike angle (°)	25.8 (1.4)	24.9 (1.3)	25.0 (1.1)
Ankle dorsiflexion IC (°)	10.6 (1.3)	4.3 (2.1) *	1.7 (0.7) *
Knee flexion IC (°)	8.6 (1.1)	11.1 (1.3) *	8.3 (1.1) †
Knee flexion excursion (°)	31.9 (1.2)	29.8 (1.1)	28.5 (1.4) *
Hip flexion IC (°)	41.3 (1.3)	45.8 (1.1)	39.6 (0.9) †
Hip adduction excursion (°)	1.8 (0.9)	5.8 (1.6) *	0.2 (0.3) *†
Ankle eversion excursion (°)	14.1 (1.7)	14.9 (4.3)	13.6 (1.2)
Landing distance (m)	0.26 (0.01)	0.27 (0.01) *	0.27 (0.01) *
Cadence (steps/s)	1.45 (0.02)	1.66 (0.08) *	1.71 (0.11) *†
Heel velocity IC (m/s)	0.39 (0.05)	0.23 (0.04) *	0.05 (0.04) *†
Peak hip adduction (°)	20.1 (1.0)	20.7 (1.0)	16.2 (1.1)
Peak ankle eversion (°)	5.2 (1.2)	1.3 (0.6)	5.8 (0.8)

IC = Initial contact, SD = standard deviation, * = real difference between retention measurement and baseline measurement, † = real difference between retention measurement taken directly after the measurement and retention taken after a month, IC = initial contact.

research should focus on individualisation of fading of the feedback, number of sessions, and/or duration of the sessions. However, for nine out of the 11 participants, the feedback schedule was effective, and they reduced mean PTA after one month. These findings provide evidence that gait retraining using biofeedback is effective at reducing mean PTA and this reduction can be maintained, supporting previous work (Bowser et al., 2018; Clansey et al., 2014; Crowell and Davis, 2011; Sheerin et al., 2020).

4.2. Running strategies used in response to a biofeedback intervention

For the group, no significant effect of the intervention was found on any of the kinematic or spatiotemporal variables associated with shock attenuation. In contrast, Clansey et al. (2014) reported a significant change in foot strike pattern for an experimental group as a response to a biofeedback intervention aimed at reducing PTA. In the current research, 11 participants completed the study rather than the minimum of twelve participants suggested by the power calculation, it is, therefore, possible the current study was underpowered and a type II error occurred. However, individual responses indicate only three out of the 11 participants changed their foot contact pattern. This was accompanied by decreases in landing distance and knee flexion excursion and increases in plantarflexion and knee flexion at initial contact, and hip adduction excursion as found in previous studies (Almeida et al., 2015; Goss and Gross, 2012). It is possible that Clansey et al. (2014) might have falsely supported the null-hypothesis of no difference in knee flexion at initial contact due to aggregation masking individual performance strategies across a group of participants (Bates et al., 2004). In this study, as well as a change in foot contact pattern, different shock-absorbing solutions were found for reducing PTA matching those found in previous research (Almeida et al., 2015; Gerritsen et al., 1995; Milner et al., 2007; Novacheck, 1998). It is likely that these differing individual kinematic solutions to the problem of reducing tibial acceleration have led to the absence of a statistically significant overall change in group kinematics. The results of this study demonstrate the importance of a single-participant analysis by finding different individual gait strategies, but no group-based differences in kinematic strategies.

Participants adopted different movement patterns between R1 and R2, without associated changes in mean PTA. This finding might be explained by the inherent degeneracy in the human neuromuscular system, a concept that is of key importance in the ecological dynamics

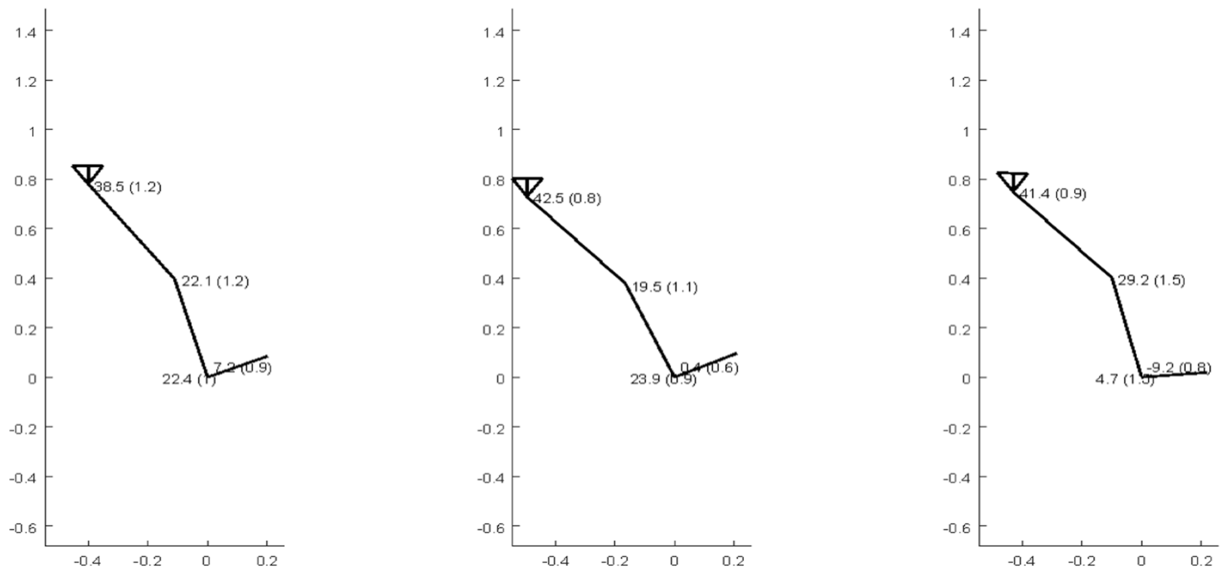

Fig. A7. Stick figures displaying the foot contact, ankle, knee and hip angle. From left to right: baseline measurement, retention test direct after the feedback intervention, and retention test after a month.

Table A7
Mean and standard deviation for the parameters of interest for the different measurements.

Variable	Baseline	Retention after intervention	Retention after month
	Mean (SD)	Mean (SD)	Mean (SD)
Peak tibial acceleration (g)	6.9 (0.6)	6.5 (1.0)	4.8 (0.9) *†
Foot strike angle (°)	22.4 (1.0)	23.9 (0.9)	4.7 (1.5) *†
Ankle dorsiflexion IC (°)	7.2 (0.9)	0.4 (0.6) *	−9.2 (0.8) *†
Knee flexion IC (°)	22.1 (1.2)	19.5 (1.1)	29.2 (1.5) *†
Knee flexion excursion (°)	23.6 (1.5)	24.9 (1.1)	16.7 (1.5) *†
Hip flexion IC (°)	38.5 (1.2)	42.5 (0.8)	41.4 (0.9)
Hip adduction excursion (°)	4.8 (1.0)	8.1 (0.8) *	7.6 (0.9) *
Ankle eversion excursion (°)	12.0 (1.8)	9.5 (1.5)	14.1 (1.4) †
Landing distance (m)	0.30 (0.01)	0.30 (0.01)	0.22 (0.01) *†
Cadence (steps/s)	1.49 (0.02)	1.44 (0.01) *	1.45 (0.01) *
Heel velocity IC (m/s)	0.30 (0.06)	0.31 (0.05)	0.50 (0.06) *†
Peak hip adduction (°)	22.1 (1.6)	21.9 (1.1)	24.0 (1.2)
Peak ankle eversion (°)	2.8 (1.2)	10.4 (1.1)	0.8 (0.7) †

IC = Initial contact, SD = standard deviation, * = real difference between retention measurement and baseline measurement, † = real difference between retention measurement taken directly after the measurement and retention taken after a month, IC = initial contact.

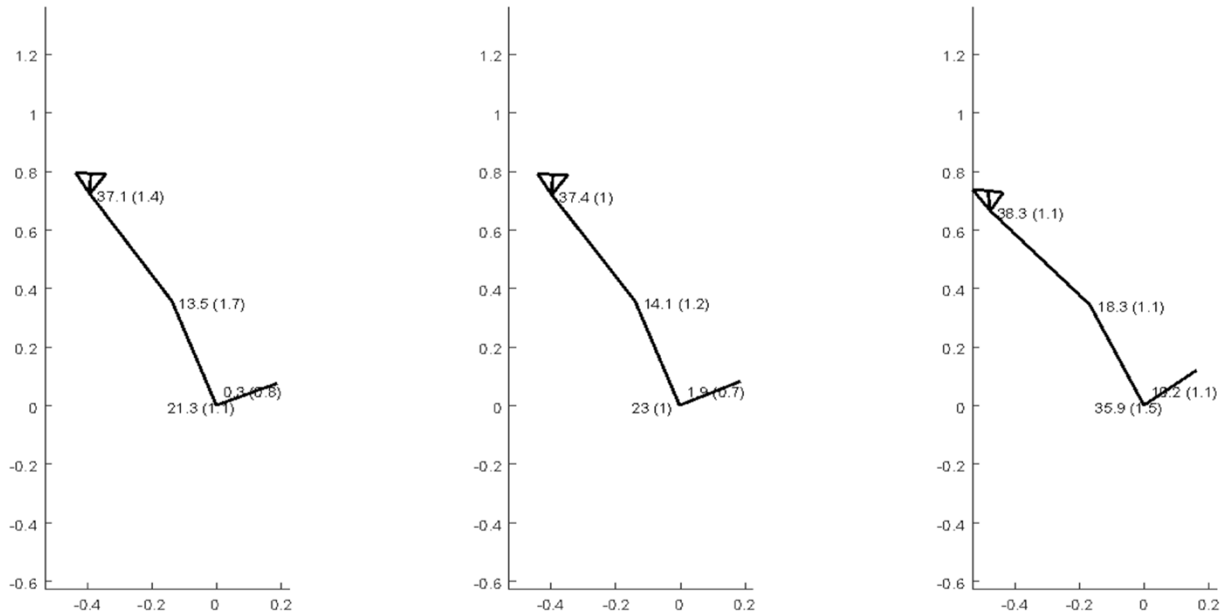

Fig. A8. Stick figures displaying the foot contact, ankle, knee and hip angle. From left to right: baseline measurement, retention test direct after the feedback intervention, and retention test after a month.

Table A8
Mean and standard deviation for the parameters of interest for the different measurements.

Variable	Baseline	Retention after intervention	Retention after month
	Mean (SD)	Mean (SD)	Mean (SD)
Peak tibial acceleration (g)	4.3 (1.0)	2.8 (0.9) *	3.0 (0.5) *
Foot strike angle (°)	21.3 (1.1)	23.0 (1.0)	35.9 (1.5) *†
Ankle dorsiflexion IC (°)	0.3 (0.8)	1.9 (0.7)	10.2 (1.1) *†
Knee flexion IC (°)	13.5 (1.7)	14.1 (1.2)	18.3 (1.1) *†
Knee flexion excursion (°)	30.9 (1.6)	32.9 (1.4)	30.7 (1.4)
Hip flexion IC (°)	37.1 (1.4)	37.4 (1.0)	38.3 (1.1)
Hip adduction excursion (°)	9.3 (1.1)	7.5 (0.7) *	5.8 (1.3) *†
Ankle eversion excursion (°)	14.0 (1.0)	16.8 (1.5)	31.6 (3.9) *†
Landing distance (m)	0.26 (0.01)	0.30 (0.01) *	0.32 (0.01) *†
Cadence (steps/s)	1.40 (0.03)	1.44 (0.02) *	1.47 (0.02) *†
Heel velocity IC (m/s)	0.25 (0.03)	0.17 (0.03) *	0.11 (0.04) *†
Peak hip adduction (°)	13.9 (1.1)	22.8 (0.7) *	15.4 (0.9) †
Peak ankle eversion (°)	6.5 (0.8)	13.2 (0.8)	7.0 (1.9)

IC = Initial contact, SD = standard deviation, * = real difference between retention measurement and baseline measurement, † = real difference between retention measurement taken directly after the measurement and retention taken after a month, IC = initial contact.

approach to motor learning and skill acquisition (Seifert et al., 2014). Degeneracy is "… the ability of elements that are structurally different to perform the same function or yield the same output" (Edelman and Gally, 2001). In terms of learning, this concept suggests participants were able to vary the way they performed the movement (running movement patterns) between-sessions, whilst maintaining a similar outcome (lower tibial acceleration). Participants may have attuned to important perceptuomotor system specifying information, learning the relationship between flexibly different movement patterns and tibial acceleration, rather than learning a particular movement pattern to achieve the task. However, further work is required to test this speculation, investigating the effects of biofeedback on learning to reduce tibial acceleration within an ecological dynamics theoretical framework.

4.3. Limitations and strengths

The current study was laboratory-based and both the training and the measurements were conducted on a treadmill. Participants were selected based on a high PTA measured during a five-kilometre time-trial in the field; however, the baseline value of PTA in the first session on the treadmill was lower than previous studies (Bowser et al., 2018; Clansey et al., 2014; Crowell and Davis, 2011). Lower baseline values of mean PTA might have led to a reduced capacity for change. It could be that the measurements made in the laboratory were not representative of acceleration in the field (Sheerin et al., 2019; Zhang et al., 2019). This is a potential limitation of the current study and future research should focus on the difference between measurements taken in the field and the laboratory.

Ideally, to improve the representative design of experiments (Araújo et al., 2007) feedback should be presented in the field rather than in laboratories. With the development of new feedback systems using inertial measurement units (Baumgartner et al., 2019; Karatsidis et al., 2018) and wireless pressure sensors (Yasuda et al., 2019), delivery of feedback in the field becomes more applicable; for example Van den Berghe et al. (2022) used music-based feedback for track running and showed a significant reduction in PTA in their intervention group. It remains uncertain whether similar results will be found when multisensory feedback is given compared to a single mode of feedback.

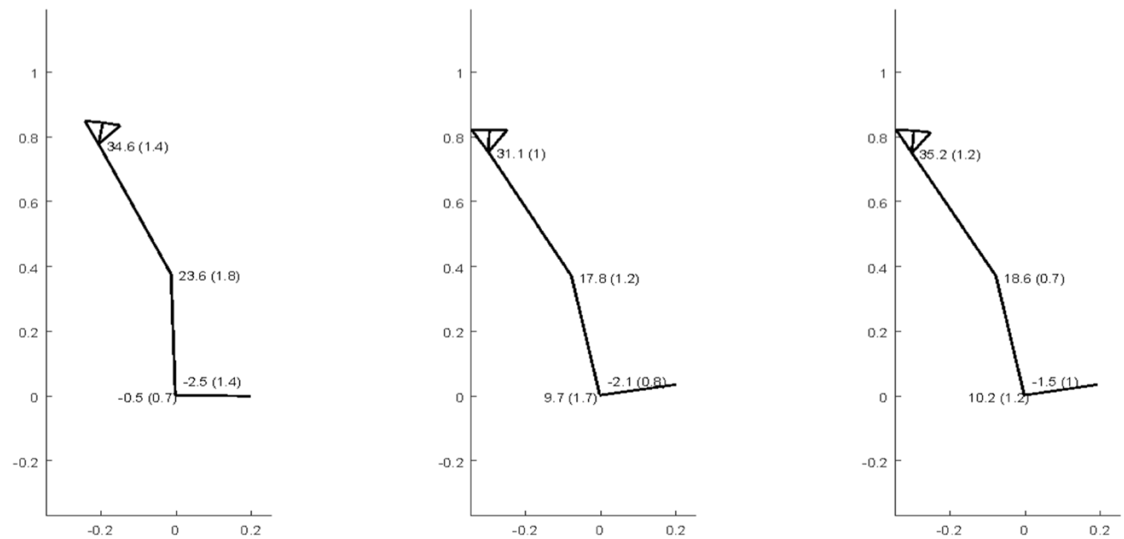

Fig. A9. Stick figures displaying the foot contact, ankle, knee and hip angle. From left to right: baseline measurement, retention test direct after the feedback intervention, and retention test after a month.

Table A9
Mean and standard deviation for the parameters of interestz for the different measurements.

Variable	Baseline	Retention after intervention	Retention after month
	Mean (SD)	Mean (SD)	Mean (SD)
Peak tibial acceleration (g)	10.2 (1.5)	9.7 (0.9)	7.5 (0.8) *†
Foot strike angle (°)	−0.5 (0.7)	9.7 (1.7) *	10.2 (1.2) *
Ankle dorsiflexion IC (°)	−2.5 (1.4)	−2.1 (0.8)	−1.5 (1.0)
Knee flexion IC (°)	23.6 (1.8)	17.8 (1.2) *	18.6 (0.7) *
Knee flexion excursion (°)	21.4 (1.9)	25.5 (1.5) *	24.8 (1.3) *
Hip flexion IC (°)	34.6 (1.4)	31.1 (1.0)	35.2 (1.2)
Hip adduction excursion (°)	4.5 (1.4)	3.4 (0.9)	3.1 (1.3) *
Ankle eversion excursion (°)	2.8 (1.2)	8.3 (1.7) *	7.4 (1.1) *
Landing distance (m)	0.17 (0.01)	0.23 (0.01) *	0.21 (0.01) *†
Cadence (steps/s)	1.39 (0.04)	1.41 (0.02)	1.41 (0.02) *
Heel velocity IC (m/s)	0.40 (0.09)	0.34 (0.05) *	0.29 (0.05) *†
Peak hip adduction (°)	34.4 (1.4)	29.8 (1.0)	26.8 (0.5) *
Peak ankle eversion (°)	9.2 (1.3)	1.9 (0.8)	3.8 (0.8)

IC = Initial contact, SD = standard deviation, * = real difference between retention measurement and baseline measurement, † = real difference between retention measurement taken directly after the measurement and retention taken after a month, IC = initial contact.

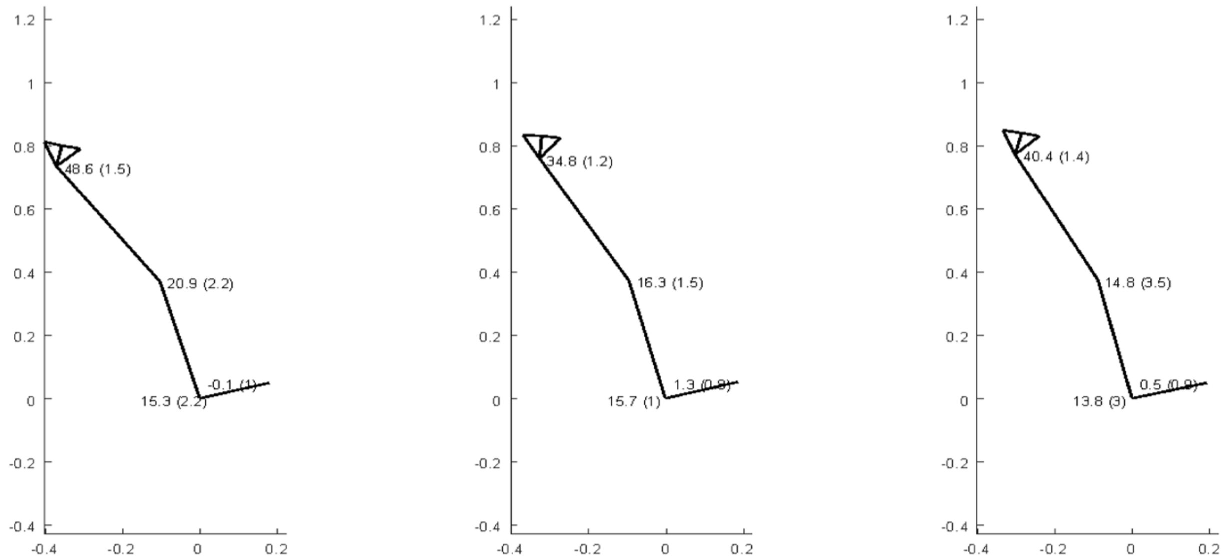

Fig. A10. Stick figures displaying the foot contact, ankle, knee and hip angle. From left to right: baseline measurement, retention test direct after the feedback intervention, and retention test after a month.

Table A10
Mean and standard deviation for the parameters of interest for the different measurements.

Variable	Baseline	Retention after intervention	Retention after month
	Mean (SD)	Mean (SD)	Mean (SD)
Peak tibial acceleration (g)	10.3 (2.2)	5.3 (1.0) *	6.3 (1.7) *
Foot strike angle (°)	15.3 (2.2)	15.7 (1.0)	13.8 (3.0)
Ankle dorsiflexion IC (°)	−0.1 (1.0)	1.3 (0.8)	0.5 (0.9)
Knee flexion IC (°)	20.9 (2.2)	16.3 (1.5)	14.8 (3.5) *
Knee flexion excursion (°)	27.4 (2.8)	25.4 (1.7)	26.5 (4.3)
Hip flexion IC (°)	48.6 (1.5)	34.8 (1.2) *	40.4 (1.4) *
Hip adduction excursion (°)	3.5 (1.2)	7.9 (0.9) *	5.3 (1.1) *†
Ankle eversion excursion (°)	11.3 (1.9)	16.0 (1.4) *	17.8 (1.9) *
Landing distance (m)	0.27 (0.02)	0.28 (0.01) *	0.27 (0.02)
Cadence (steps/s)	1.35 (0.04)	1.41 (0.02) *	1.40 (0.02) *
Heel velocity IC (m/s)	0.41 (0.06)	0.33 (0.04) *	0.34 (0.08) *
Peak hip adduction (°)	18.8 (1.4)	12.8 (0.8)	15.3 (0.8)
Peak ankle eversion (°)	10.7 (0.9)	20.8 (0.7) *	13.9 (0.9)

IC = Initial contact, SD = standard deviation, * = real difference between retention measurement and baseline measurement, † = real difference between retention measurement taken directly after the measurement and retention taken after a month, IC = initial contact.

Multisensory feedback has been found to improve participants' gait most when compared to single modes of biofeedback (Sigrist et al., 2013; van Gelder et al., 2018). While auditory and sensory feedback are feasible in the field, visual feedback would be harder to accomplish. Therefore, future research should test the validity and repeatability of inertial measurement unit based data capture systems and different feedback modes in field-based settings. Based on the results of this future research, feedback could then be presented in field-based interventions.

While the gait retraining was successful in reducing participants' PTA, the link between PTA and running injury is uncertain. Evidence from Chan et al. (2018) found occurrence of injuries to be 62 per cent lower during a 12-month follow-up period following gait retraining with feedback given on vertical ground reaction force impact peak. They further noted a shift in the types of injuries participants incurred, with the participants in the feedback group incurring relatively more Achilles tendinitis and calf strain injuries compared to the control group. The most common injuries in the control group were plantar fasciitis and patellofemoral pain. These findings highlight an important issue not considered by previous researchers in that by providing feedback on a single variable, it may be possible to reduce the risk of one type of injury, but movement pattern changes may increase the risk of other injury types. Future research should, therefore, investigate the occurrence of injuries after a feedback intervention aimed at reducing PTA in a large-scale, randomised, controlled study with long-term follow-up.

This study showed the importance of a single-subject analysis in this area of research by finding different individual gait strategies to reduce PTA, but not finding a change in kinematic and spatiotemporal parameters as an effect of the intervention for the group. These results suggest

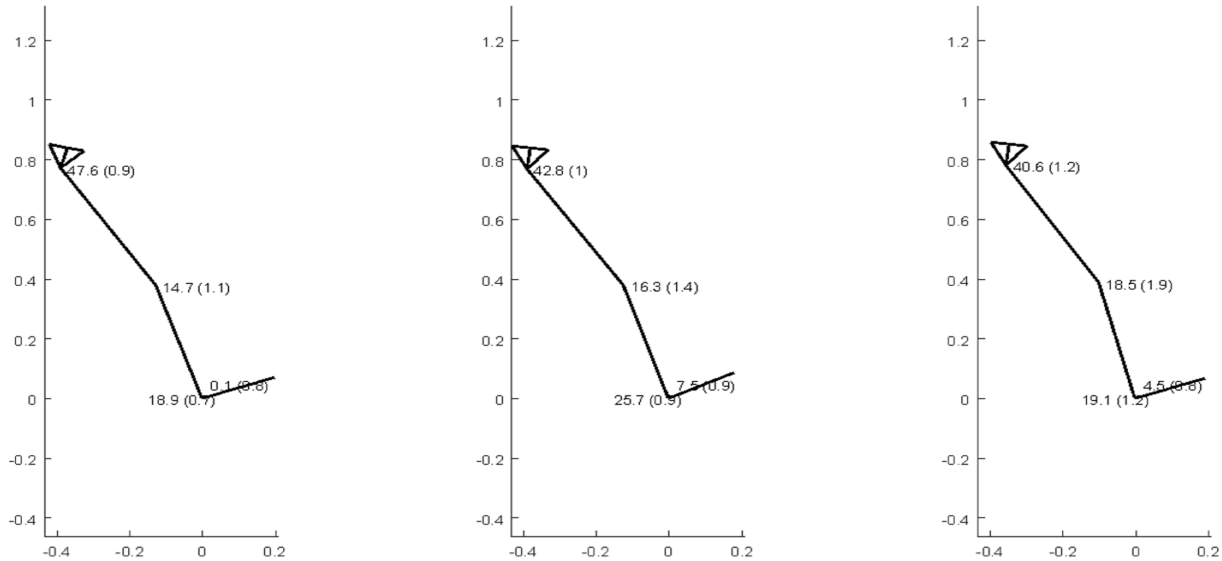

Fig. A11. Stick figures displaying the foot contact, ankle, knee and hip angle. From left to right: baseline measurement, retention test direct after the feedback intervention, and retention test after a month.

Table A11
Mean and standard deviation for the parameters of interest for the different measurements.

Variable	Baseline	Retention after intervention	Retention after month
	Mean (SD)	Mean (SD)	Mean (SD)
Peak tibial acceleration (g)	8.9 (0.8)	5.9 (0.7) *	5.2 (0.6) *
Foot strike angle (°)	18.9 (0.7)	25.7 (0.9) *	19.1 (1.2) †
Ankle dorsiflexion IC (°)	0.1 (0.8)	7.5 (0.9) *	4.5 (0.8)
Knee flexion IC (°)	14.7 (1.1)	16.3 (1.4)	18.5 (1.9) *
Knee flexion excursion (°)	26.3 (1.4)	25.0 (1.5)	23.7 (1.7)
Hip flexion IC (°)	47.6 (0.9)	42.8 (1.0)	40.6 (1.2) *
Hip adduction excursion (°)	5.7 (0.9)	5.3 (0.4)	4.6 (0.9)
Ankle eversion excursion (°)	7.3 (1.6)	7.0 (2.4)	9.1 (1.9)
Landing distance (m)	0.30 (0.01)	0.33 (0.01) *	0.31 (0.01) †
Cadence (steps/s)	1.43 (0.02)	1.45 (0.01)	1.49 (0.01) *†
Heel velocity IC (m/s)	0.34 (0.05)	0.23 (0.04) *	0.25 (0.04) *
Peak hip adduction (°)	21.7 (0.9)	13.6 (0.5) *	13.9 (1.2) *
Peak ankle eversion (°)	3.4 (0.8)	8.3 (0.9)	16.1 (1.0) *†

IC = Initial contact, SD = standard deviation, * = real difference between retention measurement and baseline measurement, † = real difference between retention measurement taken directly after the measurement and retention taken after a month, IC = initial contact.

that group analyses might mask individual results and future research on biofeedback in gait-retraining should include single-subject analysis. By not providing an instruction to the participant on how to change their gait it would have given participants the opportunity to adapt and explore movement solutions that were specific to their particular organismic constraints, which is a strength of the current study (Bates, 1996; Newell, 1986). The results indicate future research and gait retraining should investigate individual learning responses and focus on the different strategies participants use between sessions. Future research should focus on not only individual differences between sessions but also within sessions to get a further understanding of the learning process within participants.

5. Conclusion

A significant decrease of 26 % in mean PTA was found for a group of runners one month after a six-session biofeedback intervention study. Shock-absorbing solutions differed both within and between participants, suggesting participants did not learn a specific solution to reduce PTA but rather learned the concept of reducing PTA. These results suggest that future research and gait retraining should investigate individual learning responses and focus on the different strategies participants use between and within sessions. To aid gait retraining, trying to find further reductions in mean PTA, participants should not focus on learning one running strategy, but they should explore several strategies which will make them more adaptable to the changes in constraints that are seen when running in the field.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix 1:. Pre-screening questionnaire intervention study

Sheffield Hallam University | Centre for Sports Engineering Research

Pre-Parkrun Questionnaire

Exploring different strategies participants use to reduce tibial acceleration

Name: ________________________________ Age: _______________

Please answer the following questions by putting a circle round the appropriate response or filling in the blank.

1. How many times do you run during a typical week? ….. times a week

2. How many kilometres or miles do you run during a typical week: ....km/mi

3. Do you currently have any form of muscle or joint injury? Yes / No
   If you answered Yes, please give details ……..…………………………….
   ………………………………………………………………………………
   ………………………………………………………………………………
   ………………………………………………………………………………
   ………………………………………………………………………………

4. Do you have any previous running-related injuries? For example: stress fractures, inflamed tendons, ACL injuries, etc. Please state the type of injury, how long ago it occurred and duration. Yes / No
   If you answered Yes, please give details ……………………………………
   ………………………………………………………………………………
   ………………………………………………………………………………
   ………………………………………………………………………………
   ………………………………………………………………………………
   ………………………………………………………………………………

5. Are you allergic to tape or cohesive bandage? Yes / No

6. As far as you are aware, is there anything that might prevent you from successfully completing the tests that have been outlined to you? Yes/No
   If you answered Yes, please give details ……………………………………
   ………………………………………………………………………………
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Appendix 2:. Reliability and minimal detectable difference

The intraclass correlation coefficient and 95% confidence intervals, mean absolute and relative difference, paired-samples *t*-test, limits of agreement, Pearson's correlation between the absolute difference and the mean of the two methods, and either the ratio value or the minimal detectable difference based on 8 participants running two sessions 1 week apart.

Variable	Ses 1 Mean (SD)	Ses 2 Mean (SD)	ICC (95% interval)	Mean diff abs (%)	*t*-test (p)	Limits of Agr	corr r (p)	MD/Rat
Pk tibial acc (g)	5.81 (2.18)	5.63 (1.90)	0.92 (0.65–0.98)	0.18 (3%)	0.58	0.18 ± 1.71	0.48 (0.22)	21%
Foot contact ang (°)	13.33 (12.09)	13.07 (11.74)	0.98 (0.88–0.99)	0.3 (1%)	0.80	0.26 ± 5.49	0.07 (0.87)	3.9
Ank dorsflex IC (°)	4.17 (9.27)	3.78 (10.89)	0.92 (0.65–0.98)	0.4 (10%)	0.81	0.38 ± 8.39	0.22 (0.60)	5.9
Knee flexion IC (°)	21.05 (4.25)	20.08 (2.38)	0.54 (-0.19–0.89)	1.0 (5%)	0.44	0.98 ± 6.55	0.90 (0.00)	23%
Knee flexion ex (°)	25.27 (3.44)	25.47 (4.22)	0.90 (0.59–0.98)	0.2 (1%)	0.75	−0.20 ± 3.50	0.56 (0.15)	10%
Hip flexion IC (°)	38.40 (7.77)	36.37 (6.03)	0.80 (0.33–0.95)	2.0 (6%)	0.22	2.04 ± 8.38	−0.11 (0.80)	5.9
Hip adduction ex (°)	4.24 (2.87)	3.63 (3.30)	0.94 (0.71–0.99)	0.6 (17%)	0.11	0.61 ± 1.87	0.30 (0.47)	1.3
Ank eversion ex (°)	12.83 (3.76)	12.87 (4.14)	0.96 (0.83–0.99)	0.1 (0%)	0.96	−0.04 ± 4.51	−0.43 (0.28)	3.2
Landing distance (m)	0.24 (0.05)	0.25 (0.05)	0.98 (0.51–0.99)	0.01 (4%)	**0.01**	−0.01 ± 0.01	0.29 (0.49)	0.01
Cadence (steps/s)	1.46 (0.05)	1.46 (0.07)	0.94 (0.73–0.99)	0.00 (0%)	0.65	−0.00 ± 0.04	−0.07 (0.86)	0.02
Heel veloc IC (m/s)	0.47 (0.29)	0.48 (0.27)	0.99 (0.97–0.99)	0.01 (2%)	0.41	−0.01 ± 0.06	−0.08 (0.85)	0.05
Pk hip adduction (°)	14.54 (7.04)	14.51 (5.26)	0.76 (0.16–0.95)	0.0 (0.2%)	0.99	0.03 ± 8.81	0.43 (0.29)	6.2
Pk ank eversion (°)	11.64 (3.94)	12.94 (3.93)	−0.03 (-0.77–0.67)	1.3 (10%)	0.54	−1.30 ± 11.03	−0.18 (0.67)	7.8

Ses = session, SD = standard deiavtion, ICC = intraclass correlation coefficient, diff = difference, abs = absolute, p = p-value, Agr = agreement, corr = Pearson's correlation, r = Pearson's r, MD/rat = minimal detactable difference / ratio, Pk = peak, acc = acceleration, W = within, ang = angle, Ank = ankle, dorsflex = dorsiflexion, IC = initial contact, ex = excursion, veloc = velocity, **Bold** = significant, p < 0.05.

Appendix 3:. Individual learning response to a biofeedback intervention

Participant 1

Comparing the retention measurement taken directly after the intervention to the baseline measurement the shock-absorbing mechanism existed of increases in ankle plantarflexion at initial contact and cadence, and a decrease in heel velocity at initial contact (Fig. A1, Table A1). An increase in ankle plantarflexion at initial contact was also found comparing the retention measurement taken after a month to the baseline measurement, but on the contrary, increases in knee flexion excursion and ankle eversion excursion were shown.

Participant 2 From the baseline measurement to the retention measurement taken directly after the intervention a real increase in foot strike angle was found (Fig. A2, Table A2). This was accompanied by an increase in knee extension at initial contact and knee flexion excursion, and a decrease in heel velocity at initial contact. Comparing the measurement taken during the one-month retention measurement to the baseline measurement the participant went from a rearfoot to a midfoot contact pattern. This was accompanied by a real increase in knee flexion at initial contact, and a real decrease in landing distance, knee flexion excursion, and heel velocity at initial contact.

Participant 3

Focusing on the kinematic and spatiotemporal data, the participant used different strategies to decrease tibial acceleration when comparing both retention measurements to the baseline measurement (Fig. A3, Table A3). A real decrease in heel velocity at initial contact was found for both retention measurements to the baseline measurement. However, comparing the retention measurement taken after a month to the baseline measurement a real difference was shown in knee flexion excursion. Comparing the retention measurement taken directly after the feedback intervention to the baseline measurement a real increase was shown in ankle eversion excursion, both being different shock-absorbing strategies.

Participant 4

Participant 4 found a similar strategy to increase tibial acceleration at both measurements taken during the retention tests, compared to the baseline measurement. Compared to the baseline measurement, for both measurements taken during the retention tests, a real decrease was found for heel velocity at initial contact and a real increase in cadence and hip adduction excursion (Fig. A4, Table A4). These differences are differences you would expect for a participant who would be able to reduce mean peak tibial acceleration, this participant, however, increased mean peak tibial acceleration over the sessions. However, though some parameters changed, others did not, an increased cadence and increased plantarflexion, which was found comparing the measurement taken during the retention test after a month to the baseline measurement, in combination with a change in foot strike angle might decrease tibial acceleration, however, no real difference in foot strike angle was found. This suggests that whether a change in parameters is beneficial could depend on the combination of parameters and is not depending on individual parameters.

Participant 5

Comparing both retention measurements to the baseline measurement, the participant found a real change in their foot strike pattern, changing from contact more towards the heel to contact more towards the front of the foot. However, they stayed within the midfoot contact range (Fig. A5, Table A5). This was accompanied by a real increase in knee flexion at initial contact, and hip adduction excursion, and a real decrease in landing distance, and knee flexion excursion. Comparing the retention measurement taken after a month to the baseline measurement a real increase in plantarflexion at initial contact was found, which was not found comparing the retention measurement taken directly after the feedback intervention to the baseline measurement.

Participant 6

Comparing the baseline measurement to the retention measurement taken directly after the feedback intervention a real increase in flexion in the knee at initial contact, hip adduction excursion, and cadence, and a real decrease in heel velocity at initial contact were found (Fig. A6, Table A6). The increases in knee flexion at initial contact and hip adduction excursion were no longer present comparing the one-month follow-up retention measurement to the baseline measurement.

Participant 7

Comparing the retention measurement taken after one month to the baseline measurement the participant changed from a rearfoot contact to a midfoot contact (Fig. A7, Table A7). This was accompanied by a real decrease in landing distance and knee flexion excursion, and a real increase in plantarflexion and knee flexion at initial contact and hip adduction excursion. Of these parameters, only increases in plantarflexion and hip adduction excursion were found comparing the retention measurement taken directly after the feedback intervention to the baseline measurement.

Participant 8

For both retention measurements, an increase was found in cadence and a decrease in heel velocity at initial contact which could be related to a decrease in mean peak tibial acceleration (Fig. A8, Table A8). Further, from the baseline measurement to the retention measurement taken after a month real increases in knee flexion at initial contact and ankle eversion excursion were found.

Participant 9

Similar changes in the running pattern were found when comparing the retention measurements to the baseline measurement (Fig. A9, Table A9). These changes included a landing with a more extended leg (real increase in knee extension at initial contact and landing distance) but followed by more flexion in the knee (real increase in knee flexion excursion), a real increase in ankle eversion excursion and a real decrease in heel velocity at initial contact. The difference between the retention measurements included a decrease in landing distance and heel velocity at initial contact comparing the one-month retention measurement to the retention measurement taken directly after the feedback intervention.

Participant 10

For both retention measurements, a real increase in ankle eversion excursion, hip adduction excursion, and cadence, and a real decrease in heel velocity at initial contact were found compared to the baseline measurement (Fig. A10, Table A10).

Participant 11

Comparing both retention measurements to the baseline measurement a real decrease was found in heel velocity at initial contact (Fig. A11, Table A11). Comparing the retention measurement taken directly after the feedback intervention to the baseline measurement a real increase in dorsiflexion and foot strike angle was found. Comparing the one-month retention to the baseline measurement, a real increase in cadence and knee flexion at initial contact was found.

References

Almeida, M.O., Davis, I.S., Lopes, A.D., 2015. Biomechanical differences of foot-strike patterns during running: a systematic review with meta-analysis. J. Orthop. Sport. Phys. Ther. 45, 738–755. https://doi.org/10.2519/jospt.2015.6019.

Altman, A.R., Davis, I.S., 2012. A kinematic method for footstrike pattern detection in barefoot and shod runners. Gait Posture 35, 298–300. https://doi.org/10.1016/j.gaitpost.2011.09.104.

Araújo, D., Davids, K., Passos, P., 2007. Ecological validity, representative design, and correspondence between experimental task constraints and behavioral setting: comment on Rogers, Kadar, and Costall (2005). Ecol. Psychol. 19, 69–78. https://doi.org/10.1080/10407410709336951.

Atkinson, G., Nevill, A.M., 1998. Statistical methods for assessing measurement error (Reliability) in variables relevant to sports medicine. Sport. Med. 26, 217–238. https://doi.org/10.2165/00007256-199826040-00002.

Bates, B.T., 1996. Single-subject methodology: an alternative approach. Med. Sci. Sport. Exerc. 28, 631–638. https://doi.org/10.1097/00005768-199605000-00016.

Bates, B.T., James, C.R., Dufek, J.S., 2004. Single-subject analysis, innovative analyses of. Human Movement. 3–28.

Baumgartner, J., Gusmer, R., Hollman, J., Finnoff, J.T., 2019. Increased stride-rate in runners following an independent retraining program: a randomized controlled trial. Scand. J. Med. Sci. Sports 29, 1789–1796. https://doi.org/10.1111/sms.13509.

Begon, M., Monnet, T., Lacouture, P., 2007. Effects of movement for estimating the hip joint centre. Gait Posture 25, 353–359. https://doi.org/10.1016/j.gaitpost.2006.04.010.

Bowser, B.J., Fellin, R., Milner, C.E., Pohl, M.B., Davis, I.S., 2018. Reducing impact loading in runners: a one-year follow-up. Med. Sci. Sport. Exerc. 50, 2500–2506. https://doi.org/10.1249/MSS.0000000000001710.

Chan, Z.Y.S., Zhang, J.H., Au, I.P.H., An, W.W., Shum, G.L.K., Ng, G.Y.F., Cheung, R.T.H., 2018. 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. 46, 388–395. https://doi.org/10.1177/0363546517736277.

Clansey, A.C., Hanlon, M., Wallace, E.S., Nevill, A., Lake, M.J., 2014. Influence of Tibial shock feedback training on impact loading and running economy. Med. Sci. Sports Exerc. 46, 973–981. https://doi.org/10.1249/MSS.0000000000000182.

Crowell, H.P., Davis, I.S., 2011. Gait retraining to reduce lower extremity loading in runners. Clin. Biomech. 26, 78–83. https://doi.org/10.1016/j.clinbiomech.2010.09.003.

Edelman, G.M., Gally, J.A., 2001. Degeneracy and complexity in biological systems. Proc. Natl. Acad. Sci. 98, 13763–13768. https://doi.org/10.1073/pnas.231499798.

Faul, F., Erdfelder, E., Buchner, A., Lang, A.-G., 2013. G*Power Version 3.1.7 [computer software].

Gerritsen, K.G.M., van den Bogert, A.J., Nigg, B.M., 1995. Direct dynamics simulation of the impact phase in heel-toe running. J. Biomech. 28, 661–668. https://doi.org/10.1016/0021-9290(94)00127-P.

Goss, D.L., Gross, M.T., 2012. A review of mechanics and injury trends among various running styles. US. Army Med. Dep. J. Jul-Sep 62–71.

Grood, E.S., Suntay, W.J., 1983. A joint coordinate system for the clinical description of three-dimensional motions: application to the knee. J. Biomech. Eng. 105, 136–144. https://doi.org/10.1115/1.3138397.

Hennig, E.M., Lafortune, M.A., 1991. Relationships between ground reaction force and Tibial bone acceleration parameters. J. Appl. Biomech. 7, 303–309. https://doi.org/10.1123/ijsb.7.3.303.

Hennig, E.M., Milani, T.L., Lafortune, M.A., 1993. Use of ground reaction force parameters in predicting peak Tibial accelerations in running. J. Appl. Biomech. 9, 306–314. https://doi.org/10.1123/jab.9.4.306.

Johnson, C.D., Tenforde, A.S., Outerleys, J., Reilly, J., Davis, I.S., 2020. Impact-related ground reaction forces are more strongly associated with some running injuries than others. Am. J. Sports Med. 48, 3072–3080. https://doi.org/10.1177/0363546520950731.

Karatsidis, A., Richards, R.E., Konrath, J.M., van den Noort, J.C., Schepers, H.M., Bellusci, G., Harlaar, J., Veltink, P.H., 2018. Validation of wearable visual feedback for retraining foot progression angle using inertial sensors and an augmented reality headset. J. Neuroeng. Rehabil. 15, 78. https://doi.org/10.1186/s12984-018-0419-2.

Laughton, C.A., McClay Davis, I., Hamill, J., 2003. Effect of strike pattern and orthotic intervention on tibial shock during running. J. Appl. Biomech. 19, 153–168. https://doi.org/10.1123/jab.19.2.153.

Maiwald, C., Sterzing, T., Mayer, T.A., Milani, T.L., 2009. Detecting foot-to-ground contact from kinematic data in running. Footwear Sci. 1, 111–118. https://doi.org/10.1080/19424280903133938.

Milner, C.E., Hamill, J., Davis, I., 2007. Are knee mechanics during early stance related to tibial stress fracture in runners? Clin. Biomech. 22, 697–703. https://doi.org/10.1016/j.clinbiomech.2007.03.003.

Newell, K.M., 1986. Constraints on the Development of Coordination, in: Motor Development in Children: Aspects of Coordination and Control. Springer Netherlands, Dordrecht, pp. 341–360. Doi: 10.1007/978-94-009-4460-2_19.

Novacheck, 1998. The biomechanics of running. Gait Posture 7, 77–95. https://doi.org/10.1016/S0966-6362(97)00038-6.

Seifert, L., Wattebled, L., Herault, R., Poizat, G., Adé, D., Gal-Petitfaux, N., Davids, K., 2014. Neurobiological degeneracy and affordance perception support functional intra-individual variability of inter-limb coordination during ice climbing. PLoS One 9, e89865.

Sheerin, K.R., Reid, D., Besier, T.F., 2019. The measurement of tibial acceleration in runners: a review of the factors that can affect tibial acceleration during running and evidence-based guidelines for its use. Gait Posture 67, 12–24. https://doi.org/10.1016/j.gaitpost.2018.09.017.

Sheerin, K.R., Reid, D., Taylor, D., Besier, T.F., 2020. The effectiveness of real-time haptic feedback gait retraining for reducing resultant tibial acceleration with runners. Phys. Ther. Sport 43, 173–180. https://doi.org/10.1016/j.ptsp.2020.03.001.

Sigrist, R., Rauter, G., Riener, R., Wolf, P., 2013. Augmented visual, auditory, haptic, and multimodal feedback in motor learning: a review. Psychon. Bull. Rev. 20, 21–53. https://doi.org/10.3758/s13423-012-0333-8.

Stiffler-Joachim, M.R., Wille, C.M., Kliethermes, S.A., Johnston, W., Heiderscheit, B.C., 2019. Foot angle and loading rate during running demonstrate a nonlinear relationship. Med. Sci. Sports and Exercise. https://doi.org/10.1249/MSS.0000000000002023.

Van den Berghe, P., Derie, R., Bauwens, P., Gerlo, J., Segers, V., Leman, M., De Clercq, D., 2022. Reducing the peak tibial acceleration of running by music-based biofeedback: a quasi-randomized controlled trial. Scand. J. Med. Sci. Sport. 32, 698–709. https://doi.org/10.1111/sms.14123.

van Gelder, L.M.A., Barnes, A., Wheat, J.S., Heller, B.W., 2018. The use of biofeedback for gait retraining: a mapping review. Clin. Biomech. 59, 159–166. https://doi.org/10.1016/j.clinbiomech.2018.09.020.

Videbæk, S., Bueno, A.M., Nielsen, R.O., Rasmussen, S., 2015. Incidence of running-related injuries Per 1000 h of running in different types of runners: a systematic review and meta-analysis. Med Sport. https://doi.org/10.1007/s40279-015-0333-8.

Winstein, C.J., 1991. Knowledge of results and motor learning - implications for physical therapy. Phys. Ther. 71, 140–149. https://doi.org/10.1093/ptj/71.2.140.

Yasuda, K., Hayashi, Y., Tawara, A., Iwata, H., 2019. Using a Vibrotactile Biofeedback Device to Augment Foot Pressure During Walking in Healthy Older Adults: A Brief Report. Front. Psychol. 10, Article 1008. Doi: 10.3389/fpsyg.2019.01008.

Yong, J.R., Silder, A., Montgomery, K.L., Fredericson, M., Delp, S.L., 2018. Acute changes in foot strike pattern and cadence affect running parameters associated with tibial stress fractures. J. Biomech. 76, 2–7. https://doi.org/10.1016/j.jbiomech.2018.05.017.

Zhang, J.H., Chan, Z.-Y.-S., Au, I.-P.-H., An, W.W., Shull, P.B., Cheung, R.-T.-H., 2019. Transfer learning effects of biofeedback running retraining in untrained conditions. Med. Sci. Sport. Exerc. 51, 1904–1908. https://doi.org/10.1249/MSS.0000000000002007.