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Haptic biofeedback induces changes in ankle push-off during walking

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ABSTRACT

Background: Ankle push-off drives forward progression during gait. Reduced peak ankle moment and peak ankle power may contribute to the increased metabolic cost of walking observed in certain clinical populations. Biofeedback is an effective gait training tool, however biofeedback targeting ankle moment has not been previously studied.

Research Question: Does haptic biofeedback directly targeting ankle moment enable able-bodied adults to modulate peak ankle moment during gait?

Methods: 20 able-bodied adults participated in the study. Participants completed a 90-second baseline walking trial, followed by two 2-minute trials with haptic biofeedback. Haptic biofeedback guided participants to either increase peak ankle moment (Feedback High), or decrease peak ankle moment (Feedback Low). Ten participants received haptic biofeedback alone; the other ten participants additionally received verbal suggestions of movement strategies they could adopt during the biofeedback trials. Two-way analysis of variance was used to determine the effect of walking condition and verbal instruction on key gait parameters.

Results: A main effect of walking condition on peak ankle moment and peak ankle power was observed (all $P < 0.001$). Peak ankle moment did not change from baseline during Feedback High, however peak ankle power was increased ($P < 0.001$). A decrease in peak ankle moment and peak ankle power was observed during Feedback Low (all $P < 0.001$). Verbal instruction had a significant interaction effect with walking condition in only a limited number of parameters (all $P < 0.05$).

Significance: This study demonstrates the effects of haptic biofeedback targeting peak ankle moment during gait. While this study demonstrates that able-bodied individuals have some capacity to modulate their gait pattern in response to direct biofeedback on ankle moment, further investigation is required to develop a biofeedback paradigm that can increase peak ankle moment.

1. Introduction

Ankle push-off describes the period of high-magnitude positive power generated by the ankle joint during the step-to-step transition in human walking [1], as a result of high-magnitude ankle moment and rapid plantarflexion. Ankle push-off initiates leg swing and redirects the centre of mass during step-to-step transition [1–3]. The ankle joint provides the majority of positive centre of mass work during push-off [4], via contraction of the plantarflexor muscles and elastic energy return from the Achilles tendon [5]. Huang et al. found that restricting ankle push-off in able-bodied adults increased net metabolic power during walking [6]. Individuals with post-stroke hemiparesis have lower peak ankle moment during gait compared to speed-matched, able-bodied controls, which may contribute to reduced gait speed, step-length asymmetry, and increased metabolic cost of walking [7–10]. Multiple gait rehabilitation interventions have been developed with the goal of increasing ankle push-off, including functional electrical stimulation [11] and powered robotic exoskeletons [12]. A quantitative biofeedback tool that targets ankle moment could potentially be useful for gait retraining in post-stroke individuals and other clinical populations that have impaired ankle push-off.

Biofeedback uses technology to provide real-time, quantitative information to an individual regarding a physiological parameter of interest [13]. Visual displays, auditory cues, or haptic interfaces may be used individually, or in combination to provide information to the individual about their movement. Biofeedback is an effective strategy for modifying gait patterns in both able-bodied and clinical populations [13,14]. Recent studies have demonstrated that biofeedback can modulate anterior ground reaction force and ankle power during gait, suggesting that biofeedback may be useful in improving ankle push-off

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[15,16].

The goal of this study was to determine whether a novel haptic biofeedback intervention directly targeting ankle moment is effective in modulating ankle moment in able-bodied individuals. We hypothesised that able-bodied individuals would be able to both increase and decrease peak ankle moment compared to normal walking in response to direct biofeedback on peak ankle moment. A secondary goal of this study was to determine the effect of verbal instruction on biofeedback training. We hypothesised that providing participants with suggestions of different movement strategies they may use during training would improve their response to biofeedback.

2. Methods

2.1. Participants

20 able-bodied participants (11 male, 9 female; age 26 ± 5 years) without musculoskeletal or neurologic impairment were recruited to take part in the study. Every participant provided written informed consent before beginning the study. The study was approved by the institutional human participants ethics committee.

2.2. Instrumentation

An eight-camera motion capture system (Vicon, Oxford, UK) was used to track the position of infrared-reflective markers placed on the feet, shanks, thighs, pelvis and torso of each participant. Ground reaction forces were recorded with an instrumented split-belt treadmill (Bertec Corporation, Columbus, OH), used for all walking trials. Marker data and force data were collected synchronously with Vicon Nexus software at 200 Hz and 1000 Hz, respectively (Oxford Metrics Inc, Oxford, UK).

Biofeedback on peak ankle moment was provided to the participant via a haptic biofeedback bracelet (Fig. 1A), consisting of four vibrating disc motors and an Arduino Micro microcontroller [17]. A custom LabVIEW routine was developed to calculate ankle moment based on marker and force data and send control signals to the haptic biofeedback bracelet via Bluetooth. Peak ankle moment was estimated as the maximum value of the cross-product of the sagittal-plane component of the position vector from the ankle joint centre to the centre of pressure and the sagittal-plane component of the ground reaction force vector. The position of the ankle joint centre was defined as the midpoint of the line segment joining the markers placed on the medial and lateral malleoli. This method of estimating peak ankle moment was validated against inverse dynamics with an average error of less than 5% (see supplementary Fig. 1 for more information).

2.3. Experimental procedure

Body mass was measured with a digital scale, and height was measured with an analogue stadiometer. A static trial was captured for each participant while standing in anatomical neutral. This static trial, along with a dynamic range-of-motion trial, were used for real-time marker labelling in Vicon Nexus. Each participant's comfortable walking speed was determined by increasing the treadmill speed from 0.8 m/s until the participant indicated that the treadmill speed matched their comfortable walking speed. Each participant then walked at their comfortable walking speed for 90 s (Baseline). All subsequent walking trials were conducted at this speed. Marker and force data were collected from the final 10 gait cycles, and each participant's baseline peak ankle moment was calculated from these data.

Each participant was fitted with the haptic biofeedback bracelet on the shank of their dominant leg, determined by the Waterloo Footedness Questionnaire [18]. Two biofeedback conditions were tested. In the Feedback High condition, the target of haptic biofeedback was to increase peak ankle moment by 10% compared to Baseline. In the Feedback Low condition, the target of haptic biofeedback was to decrease peak ankle moment by 20% compared to Baseline. The lower-magnitude 10% target threshold was chosen for the Feedback High condition because in pilot testing it was found that increasing ankle moment was more challenging than decreasing ankle moment in response to biofeedback.

During the biofeedback conditions, the participants' peak ankle moment was estimated for each gait cycle and compared to the target. If the peak ankle moment was at least 10% greater than baseline in the Feedback High condition, or at least 20% less than baseline in the Feedback Low condition, the haptic biofeedback bracelet provided a single-pulse vibration, indicating a success. Each biofeedback trial consisted of 30 s of normal walking followed by two minutes of walking with haptic biofeedback. Marker data and force data from the final 10 gait cycles of each biofeedback trial were collected. The order of biofeedback condition was randomised by coin toss. Between biofeedback trials, participants walked without biofeedback for a 10-minute washout period with the goal of eliminating any learning effects of the first biofeedback trial [19]. The experimental protocol is summarised in Fig. 1B.

10 participants were given minimal verbal instruction before the biofeedback trial. They were instructed to "push more with your toes" during the Feedback High condition, and "push less with your toes" during the Feedback Low condition [20]. They were instructed that the

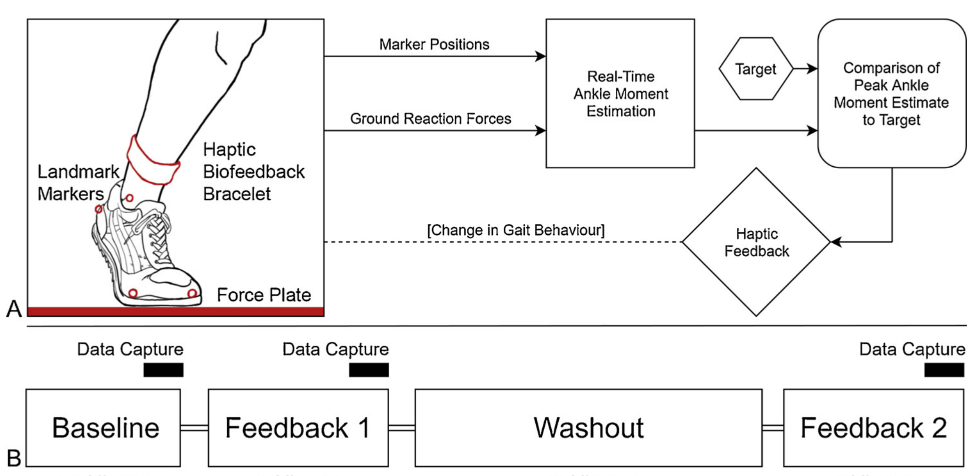

Fig. 1. Haptic biofeedback was given based on a real-time estimate of ankle plantarflexion moment. The control system is summarised in **A** above (Adapted from Chen et al., 2017). The feedback was administered in two walking trials that aimed to increase or decrease peak ankle moment, as in **B**.

biofeedback only targeted push-off from the dominant leg, and that a vibration from the bracelet represented a success. The remaining 10 participants were given more detailed verbal instruction for the biofeedback trial, which was repeated during the trial as needed. In addition to the instruction of pushing more or less with their toes, they were provided suggestions of different movement strategies to modulate their ankle moment. These included 1) taking longer steps during Feedback High, and shorter steps during Feedback Low, because step length is correlated with ankle moment [21]; 2) Pushing off more with the calf muscles during Feedback High, and less with the calf muscles during Feedback Low, as well as changing the position of the foot during push-off, because muscle force and moment arm directly change joint moment [22], and 3) Relying on the hip and knee musculature less during late stance in Feedback High, and more during late stance in Feedback Low, because this would change the demands on the ankle to maintain a constant support moment (sum of extensor moments of the lower limb), which is constant at a constant gait speed [22].

2.4. Data processing and statistical analysis

A 10-Hz low-pass Butterworth filter was applied to ground reaction forces and joint kinematics. A subject-specific musculoskeletal model was created from the positions of lower-limb anatomical landmarks recorded from the static trial using the MAP Client [23]. The OpenSim (SimTK, Stanford, USA) inverse kinematics and inverse dynamics tools were used to compute joint angles and moments. Internal extensor moments are reported as positive [22]. Peak lower-limb joint angles, moments, and powers were determined as shown in Fig. 2. Peak anterior and vertical ground reaction forces were calculated. Ankle velocity and moment at the time of peak ankle power were calculated to interrogate the mechanism by which individuals modulate ankle power.

For all reported parameters, a two-way ANOVA was performed with the following factors: walking condition (Baseline, Feedback High, Feedback Low), and verbal instruction (limited instruction, detailed instruction). If the ANOVA showed significant main effect, post-hoc Bonferroni-corrected t-tests were performed. Significance level was set at $\alpha = 0.05$.

3. Results

The effect of biofeedback on key gait parameters is described below. Fig. 3 presents data from a representative participant to illustrate the effects of biofeedback on ankle parameters. Full results are presented in Table 1.

3.1. Ankle kinetics

There was a main effect of walking condition on peak ankle moment ($F = 22.38$, $P < 0.001$) and peak ankle power ($F = 50.63$, $P < 0.001$). Peak ankle moment was lower during Feedback Low compared to Baseline ($P < 0.001$), but peak ankle moment was not different from Baseline during Feedback High ($P = 0.08$). Peak ankle power was higher during Feedback High compared to Baseline, and lower during Feedback Low compared to Baseline (all $P < 0.001$). The

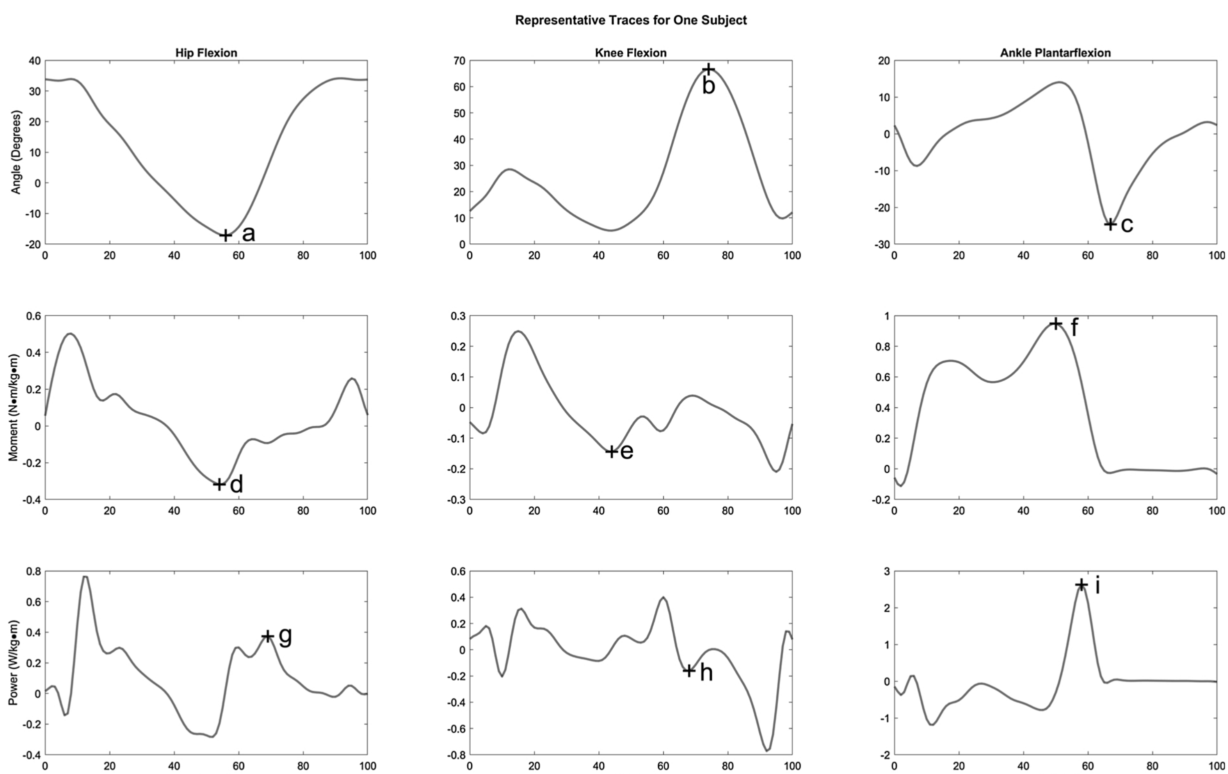

Fig. 2. Average results of kinematic and kinetic analysis of 10 gait cycles for one subject without gait feedback. Peak values of interest were selected as indicated.
a: Peak Hip Extension Angle
b: Peak Knee Flexion Angle
c: Peak Ankle Plantarflexion Angle
d: Peak Hip Extension Moment
e: Peak Knee Flexion Moment (mid-stride)
f: Peak Ankle Plantarflexion Moment
g: H3 Hip Power Peak (late-stride positive)
h: K3 Knee Power Peak (late-stride absorption)
i: Peak Ankle Plantarflexion Power (end-stance positive).

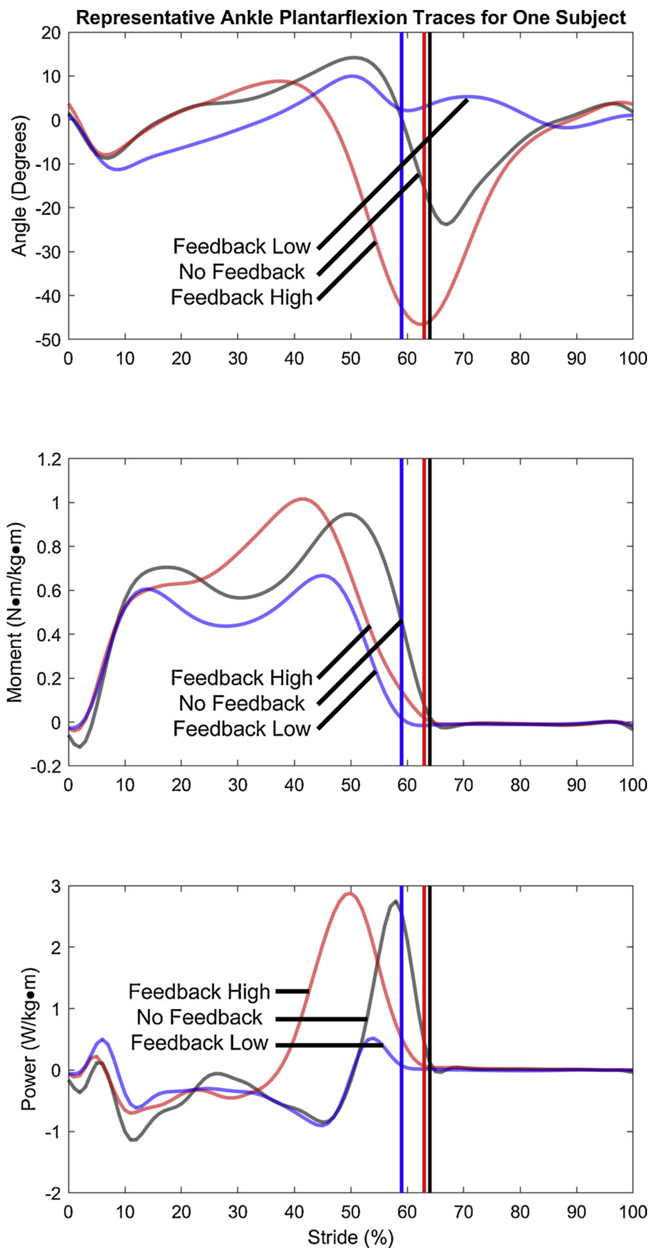

Fig. 3. Average results of kinematic and kinetic analysis of 10 gait cycles for the ankle joint of one subject in no feedback (grey), feedback low (blue), and feedback high (red) conditions (also labelled in-figure). This subject's results illustrate the effects of low and high feedback on plantarflexion angle, plantarflexion moment, and ankle power. Vertical lines in matching colour indicate mean toe-off point for each modality. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

effect of biofeedback on ankle kinetics is illustrated in Fig. 4.

3.2. Mechanism of ankle power modulation

There was a main effect of walking condition on ankle moment ($F = 40.87$, $P < 0.001$) and ankle velocity ($F = 45.47$, $P < 0.001$) at the time of peak ankle power (Table 2). Post-hoc tests reveal that ankle moment at the time of peak ankle power was increased during Feedback High ($P < 0.001$), and decreased during Feedback Low ($P < 0.001$), whereas ankle velocity at the time of peak ankle power was only different during Feedback Low ($P < 0.001$).

3.3. Hip kinetics

There was a main effect of walking condition on hip power ($F = 5.50$, $P = 0.02$). The peak positive hip power during late stance and early swing (H3 hip power) was lower during the Feedback High condition compared to Baseline ($P < 0.001$). There was an interaction effect between verbal instruction and walking condition on peak hip flexion moment ($F = 4.26$, $P = 0.04$). A main effect of walking condition on hip flexion moment was only found in the group that received detailed verbal instruction ($F = 7.21$, $P = 0.02$).

3.4. Knee kinetics

There was a main effect of walking condition on peak knee flexion moment ($F = 30.81$, $P < 0.001$). Knee flexion moment was greater in magnitude during Feedback High compared to Baseline ($P = 0.003$), and smaller in magnitude during Feedback Low compared to Baseline ($P = 0.001$). There was an interaction effect between verbal instruction and walking condition on peak knee absorption power during mid-stance and late stance (K3 knee power) ($F = 9.96$, $P = 0.001$). There was a main effect of walking condition only in the group that received detailed verbal instruction ($F = 11.02$, $P = 0.007$).

3.5. Ground reaction forces

There was an interaction effect between verbal instruction and walking condition on peak anterior ground reaction force (AGRF) ($F = 4.109$, $P = 0.025$). Increased peak AGRF during Feedback High was observed both for the group that received limited verbal instruction ($P < 0.024$) and detailed verbal instruction ($P < 0.002$). Decreased peak AGRF during Feedback Low was observed both for the group that received limited verbal instruction ($P < 0.002$) and detailed verbal instruction ($P < 0.002$). No difference in the magnitude of change from Baseline during Feedback High or Feedback Low ($P > 0.40$) was observed between groups. There was a main effect of walking condition on vertical ground reaction force (VGRF) ($F = 6.26$, $P = 0.012$). VGRF was decreased during Feedback Low ($P < 0.001$). No change in VGRF was observed during Feedback High compared to Baseline.

3.6. Kinematics

There was a main effect of walking condition on peak ankle plantarflexion angle ($F = 82.98$, $P < 0.001$), peak hip extension angle ($F = 36.38$, $P < 0.001$), and peak knee flexion angle ($F = 27.64$, $P < 0.001$). Ankle plantarflexion angle was larger in magnitude during Feedback High compared to Baseline, and smaller in magnitude during Feedback Low (all $P < 0.001$). Hip extension and knee flexion angles were smaller in magnitude during Feedback Low compared to Baseline (all $P < 0.001$), but did not differ from Baseline during Feedback High.

4. Discussion

The goal of this study was to determine whether a novel haptic biofeedback intervention directly targeting ankle moment is effective in modulating ankle moment in able-bodied individuals. We hypothesised that able-bodied individuals would be able to both increase and decrease peak ankle moment compared to normal walking in response to direct biofeedback on peak ankle moment. Participants walked with lower peak ankle moment during Feedback Low (mean 18% decrease, SD 16%), partially supporting the hypothesis that direct biofeedback would modulate peak ankle moment in able-bodied individuals. The change in ankle moment during Feedback High compared to Baseline was not significant (mean 6.1% increase, SD 11%).

A secondary goal of this study was to determine the effect of verbal instruction on biofeedback training. We hypothesised that providing participants with suggestions of different movement strategies they

Table 1
Key gait parameters measured during Baseline and Feedback conditions. Values are reported as Mean (Standard Deviation). FBHigh, Feedback High; FBLow, Feedback Low; LV, group that received limited verbal instruction; DV, group that received detailed verbal instruction.

Response Variable	Condition						Change (% Baseline)			
	Baseline		FBHigh		FBLow		FBHigh – Baseline		FBLow – Baseline	
Joint Moment (N·m/kg·m)										
Ankle Plantarflexion Moment	0.904	(0.099)	0.955	(0.116)	0.750	(0.189)*	6.1	(11.3)	−17.6	(16.4)
Hip Flexion Moment (LV)	−0.294	(0.047)	−0.318	(0.201)	−0.280	(0.089)	7.7	(60.8)	−5.2	(27.7)
Hip Flexion Moment (DV)	−0.309	(0.083)	−0.220	(0.117)	−0.357	(0.079)	−28.8	(25.1)	19.9	(26.9)
Knee Flexion Moment	−0.204	(0.082)	−0.283	(0.112)*	−0.114	(0.081)*	46.5	(62.2)	−43.1	(40.2)
Joint Power (W/kg·m)										
Positive Ankle Power	1.92	(0.55)	2.69	(0.83)*	0.895	(0.631)*	46.2	(47.5)	−54.2	(31.6)
Hi Hip Power	0.489	(0.123)	0.337	(0.170)*	0.489	(0.282)	−31.9	(23.9)	0.4	(45.8)
K3 Knee Power (LV)	−0.301	(0.108)	−0.443	(0.161)	−0.381	(0.200)	67.5	(105)	32.6	(85.6)
K3 Knee Power (DV)	−0.282	(0.095)	−0.151	(0.056)*	−0.549	(0.350)*	−43.6	(25.2)	104	(111)
Joint Angle (deg)							Change (Absolute)			
Ankle Plantarflexion Angle	−25.0	(6.7)	−38.9	(8.9)*	−11.7	(7.9)*	−13.8	(6.7)	13.3	(10.6)
Hip Extension Angle	−10.7	(6.2)	−12.2	(6.7)	−3.3	(7.1)*	−1.5	(3.5)	7.3	(4.8)
Knee Flexion Angle	65.8	(2.9)	63.2	(10.0)	45.1	(16.1)*	−2.6	(9.5)	−20.6	(15.3)

* $P < 0.05$.

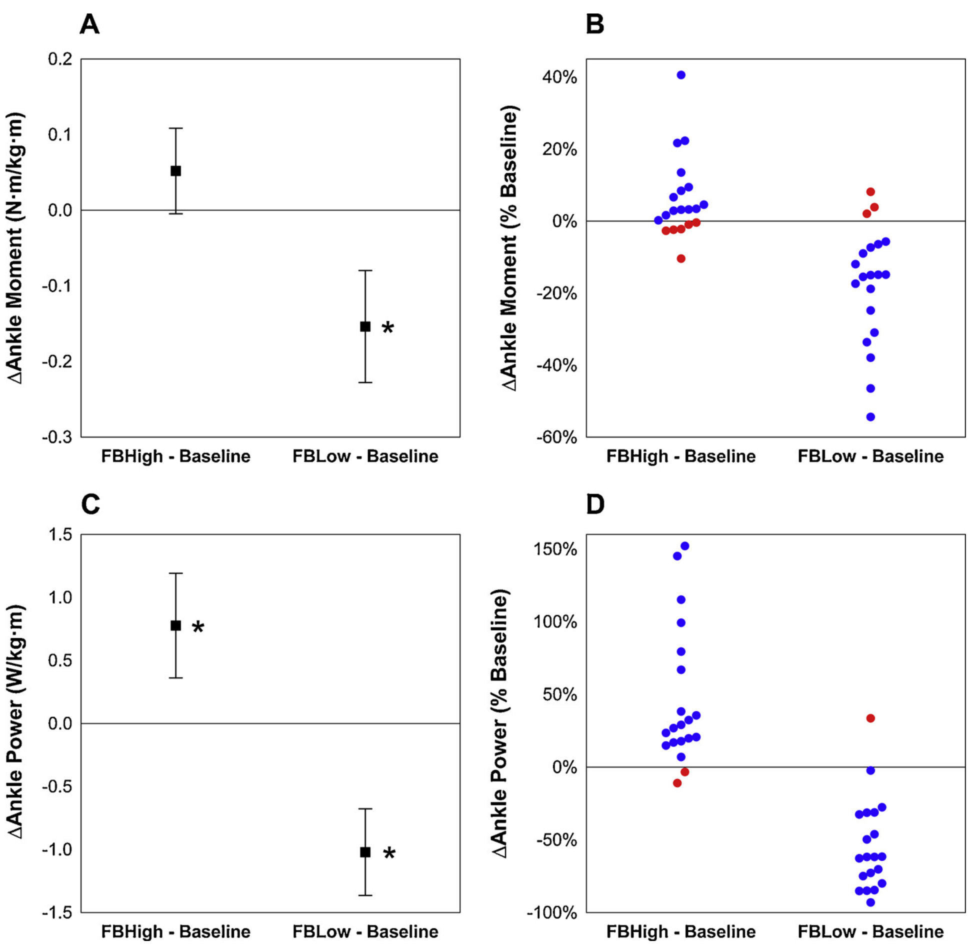

Fig. 4. Biofeedback-induced changes in peak ankle moment (A, B) and peak ankle power (C, D) compared to Baseline. Plots A and C show mean values across participants; error bars represent 95% confidence interval; asterisk indicates significant change. Plots B and D show changes expressed as a percentage of baseline for each participant, coloured according to direction of feedback (blue indicates intended change, red indicates a non-intended change). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Table 2
Positive ankle power, ankle moment, and ankle velocity at the time of peak ankle power. Values are reported as Mean (Standard Deviation). FBHigh, Feedback High; FBLow, Feedback Low.

Response Variable	Condition						Change (% Baseline)			
	Baseline		FBHigh		FBLow		FBHigh – Baseline		FBLow – Baseline	
Positive Ankle Power (W/kg·m)	1.92	(0.55)	2.69	(0.83)*	0.895	(0.631)*	46.2	(47.5)	−54.2	(31.6)
Ankle Moment (N·m/kg·m)	0.494	(0.076)	0.627	(0.101)*	0.376	(0.136)*	28.2	(20.8)	−24.7	(22.9)
Ankle Velocity (deg/s)	−222	(41)	−247	(46)	−142	(50)*	14.3	(28.5)	−35.7	(19.9)

* $P < 0.05$.

may use during training would improve their response to biofeedback. Detailed verbal instruction only influenced a limited number of gait parameters: peak hip flexion moment, K3 knee power and AGRF. The group that received detailed verbal instruction were encouraged to try using their hip and knee differently during biofeedback, which may have influenced the strategies participants adopted during biofeedback without influencing ankle moment, the primary outcome variable. Although this study does not demonstrate added benefit of detailed verbal instruction, the authors recognise that it may help individuals better understand the movement task.

There are possible methodological and biomechanical reasons that a significant change in ankle moment was not observed during Feedback High. A smaller target threshold was used in Feedback High compared to Feedback Low. The 2-minute biofeedback exposure may be insufficient to modify the gait pattern in a way that increases peak ankle moment. Ankle moment is largely determined by the forward progression of the centre of pressure [6,24], which may have contributed to the lower magnitude response during Feedback High compared to Feedback Low. During Feedback Low, participants changed the forward progression of the centre of pressure by changing the entire lower limb position, as evidenced by reduced peak hip extension and knee flexion. By comparison, there was no difference in hip extension or knee flexion in Feedback High. Additionally, the ability to increase peak ankle moment during walking may be limited by the force production of the gastrocnemius and soleus. Computational modelling predicts that the muscle forces in the gastrocnemius and soleus do not increase at speeds above comfortable walking pace, which may indicate an upper limit to plantarflexor force generation at a comfortable walking speed [25]. Further investigation is warranted to elucidate biomechanical strategies to increase peak ankle moment during gait.

Biofeedback on peak ankle moment induced changes in peak ankle power in both Feedback High (mean 46% increase, SD 48%) and Feedback Low (mean 54% decrease, SD 32%), suggesting that individuals may have a greater capacity to modulate peak ankle power compared to peak ankle moment. During Feedback High, ankle moment at the time of peak ankle power was higher than Baseline (mean 28% increase, SD 21%) with no change in ankle velocity. During Feedback Low, both ankle moment (25% decrease, SD 23%) and ankle velocity (36% decrease, SD 20%) were lower than Baseline. The mechanism of increasing ankle power is likely due to higher ankle moment values during the period of highest ankle plantarflexion velocity preceding toe-off. This subtle temporal shift enabled an increase in peak power even though the peak moment and peak ankle velocity remain unchanged. Conversely, when reducing ankle power, we noted reductions in both ankle moment and angular velocity. This observation was supported by the consequent increase in hip flexion power at push-off, to compensate for the loss in ankle power.

Fickey and colleagues (2018) showed that biofeedback targeting ankle power could successfully increase or decrease peak ankle power in healthy individuals (mean 13% increase and 28% decrease, respectively) [16]. The study described by Fickey and colleagues differs from the study described here in several key ways: visual biofeedback targeting ankle power was provided in contrast to haptic biofeedback targeting ankle moment, and participants were instructed to change their gait bilaterally in contrast to targeting the dominant leg. While the changes in peak ankle power observed in this study are larger in magnitude than those observed by Fickey and colleagues, this may result from these methodological differences. Further research directly comparing the biomechanical changes induced by biofeedback on ankle moment and ankle power is warranted.

Biofeedback led to increased AGRF during Feedback High and decreased AGRF during Feedback Low. Biofeedback targeting AGRF has been previously investigated as a method of increasing push-off during gait [15,26,27]. Biofeedback targeting ankle push-off may offer benefit over AGRF biofeedback by specifically targeting ankle deficits in clinical populations without capturing compensatory contributions from the hip and knee.

The ankle and hip provide the majority of positive power during walking in able-bodied individuals [28], and play complementary roles during step-to-swing transition [22]. Experimental studies have demonstrated an inverse relationship between positive power generation at the hip and ankle [29]. In this study, we observed increased positive ankle power and decreased positive H3 hip power during the Feedback High condition compared to Baseline, in agreement with this relationship. Interestingly, there was no effect of biofeedback on H3 hip power during the Feedback Low condition, despite the decrease in ankle power compared to Baseline.

5. Limitations

All participants were young and able-bodied, so further investigation is warranted to determine the effect of direct ankle moment biofeedback in clinical populations such as people post-stroke. Another limitation is the short duration of biofeedback exposure (2 min for each condition). Longer training may be required to induce significant changes in gait pattern despite the capacity of healthy individuals to adapt quickly to novel gait tasks [22,30]. Both conditions were tested in the same day, so it is unknown whether the first biofeedback exposure affected participants' response to the second biofeedback condition. A 10-minute washout period and randomised trial order were implemented to minimize this possible effect. Evaluating retention of modified gait patterns following biofeedback training was outside of the scope of this study, however future studies should evaluate retention and learning in response to direct ankle moment biofeedback. The method used in this study for estimating ankle moment for biofeedback relies on an instrumented treadmill and motion capture cameras, limiting the capacity for clinical translation until emerging technologies enable the measurement of gait kinetics outside of the laboratory.

6. Conclusion

Direct biofeedback on peak ankle moment only caused a change in peak ankle moment during Feedback Low, however changes in peak ankle power were observed in both conditions. Detailed verbal instruction may have affected the movement strategies adopted by participants, but did not cause change in ankle moment beyond biofeedback alone. Further investigation is ongoing to elicit biomechanical mechanisms to increase ankle moment and develop a biofeedback paradigm capable of increasing ankle moment.

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Declaration of Competing Interest

The authors have no Acknowledgements

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.gaitpost.2019.07.252.

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