Feasibility of personalised hip load modification using real-time biofeedback in hip osteoarthritis: A pilot study

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ABSTRACT

Objective: (i) Compare the feasibility of three load modification strategies to immediately increase hip contact force in people with hip osteoarthritis (OA) using real-time visual biofeedback during walking, and (ii) prospectively evaluate changes in pain and physical function following 6-weeks of walking using a prescribed personalised load modification strategy.

Design: Twenty participants with symptomatic mild-to-moderate hip OA walked on an instrumented treadmill while motion capture and electromyographic data were recorded (normal walk), then under three conditions: (i) neutral trunk lean; (ii) neutral pelvic obliquity; (iii) increased step length. The biomechanical parameter of interest and corresponding target value were displayed in real-time. Hip contact forces were subsequently computed using a calibrated electromyography-informed neuromusculoskeletal model. A decision tree was used to prescribe a personalised load modification strategy to each participant for integration into walking over 6-weeks.

Results: Only the step length modification significantly increased peak hip contact force compared to normal walking when performed by all participants (11.34 [95% CI 4.54, 18.13]%, P < 0.01). After participants were prescribed a personalised load modification strategy, both neutral pelvis (n = 5, 11.88[95%CI -0.49, 24.24]% ) and step length (n = 10, 12.79[95% CI 0.49, 25.09]%) subgroups increased peak hip contact force >10%. After 6-weeks, 77% and 46% of participants reported a clinically important improvement in hip pain during walking and physical function, respectively.

Conclusion: Most participants with hip OA could immediately increase hip contact force through personalised movement retraining by a magnitude estimated to promote cartilage health and reported an improvement in symptoms after 6-weeks. Findings provide preliminary support for a personalised load modification-based intervention for hip OA.

1. Introduction

Hip osteoarthritis (OA) is a chronic musculoskeletal disease predicted to affect one in four people during their lifetime [1]. Conservative non-drug interventions are recommended for clinical management of hip OA [2,3], though many patients report only small-to-modest improvements in pain, function, and quality of life [2,4]. These poor outcomes may exist because treatment targets are not well defined, not personalised, and are largely extrapolated from knee OA literature [4]. Further, current treatment approaches rarely lend themselves to self-management, which is central to hip OA clinical practice guidelines [2] and highly valued by patients [5]. Indeed, abnormal hip loading plays a fundamental role in OA worsening [6] and is potentially modifiable with movement retraining [7]. Personalised movement retraining designed to target a known mechanism of disease remains an entirely unexplored therapeutic strategy for people with hip OA.

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Contrary to knee OA, under-rather than over-loading has been implicated in the pathogenesis of hip OA. Compared to healthy controls, people with symptomatic and radiographic mild-to-moderate [8] and end-stage [9,10] hip OA walk with lower magnitude hip contact forces. These observations contrast with the higher knee loads extensively proven to drive knee OA progression [11] and may explain why management strategies based on evidence from knee OA literature, applied to hip OA, have been largely ineffective [4]. Hip contact forces interact with cartilage mechanobiology (i.e. tissue mechanics) to regulate cartilage structure [12]. Collagen networks in the extracellular matrix of cartilage undergo strains during habitual activities (e.g. walking) and require adequate stimulus (i.e. joint loading) to avoid degeneration associated with disuse [12]. Ex vivo data suggest increasing joint load by even 5% may stimulate cartilage health [13]. A management strategy designed to target hip contact force and adequately stimulate hip cartilage during walking may have therapeutic benefits for people with hip OA.

Several biomechanical parameters are thought to be responsible for abnormal hip loading in hip OA [14]. People with mild-to-moderate hip OA descend stairs with greater frontal plane trunk lean [15] and people with severe hip OA walk with greater frontal plane trunk lean [16] than healthy controls. Trunk kinematics influence the position of the centre of mass relative to the hip joint centre [17] and thus have direct implications for hip loading. Further, musculoskeletal modelling simulations have shown that contralateral pelvic drop will directly affect loading at the hip during walking [10]. Spatiotemporal features of walking, including speed and step length, also contribute to loads sustained by the hip [10]. Lower walking speed [18], driven by a 10% shorter step length [19], is characteristic of people with hip OA across the spectrum of disease severity compared to healthy controls. Biomechanical parameters relating to trunk and pelvis position, and step length are mechanically linked to hip loading and are potentially modifiable with movement retraining [20,21].

Biofeedback is a critical adjunct to the learning of motor skills [22]. Visual biofeedback has been effective for altering surrogate measures of knee load in people with knee OA [7,20]. However, movement retraining using real-time biofeedback customised to each individual's walking biomechanics and designed to target the physiological load acting directly on the joint's tissue (i.e. hip contact force) [23] remains entirely unexplored in those with hip OA. Given the complex relationship between joint loading and symptoms [24], it is imperative to concurrently evaluate changes in symptoms when modifying joint load. This pilot study included individuals with symptomatic mild-to-moderate hip OA, who were prime candidates for targeted disease modifying interventions, and aimed to (i) compare the feasibility of three load modification strategies to immediately increase hip contact force when participants were provided with real-time visual biofeedback during walking, and (ii) prospectively evaluate changes in pain and physical function following 6-weeks of walking using a prescribed personalised load modification strategy.

2. Methods

This study used a within-participant design and reporting followed items of the CONSORT guidelines [25] applicable to non-randomised pilot and feasibility studies. Fig. 1 illustrates an overview of the study, assessment time points, and outcomes. Ethical approval was obtained from the institutional Human Research Ethics Committee (GU#2019/103) and participants provided their written informed consent prior to testing.

2.1. Participants

Twenty participants were recruited from the South East Queensland community via advertisements on social media between January 2020 and March 2021. Hip OA was classified according to the American College of Rheumatology clinical criteria for hip OA [26]. Participants were included if they: (i) were aged 50 years or older; (ii) reported hip pain on most days of the past month for >3 months; (iii) reported hip pain over the past week while walking of >2 on an 11-point numerical rating scale (NRS, 0 = ‘no pain’ and 10 = ‘worst pain possible’); (iv) could walk independently for at least 20 min 3-times a week; and (v) had a body mass index (BMI) < 34 kg/m². Exclusion criteria were: (i) previous hip replacement in the affected hip; (ii) any hip surgery in the past 6-months; (iii) current or past (<3 months) use of oral or intra-articular corticosteroid; (iv) hip pain symptoms associated with extra-articular or lumbar pathology; (v) any other joint or muscle pain, such as back, other hip, knees, ankles or feet, which was worse than hip pain on the (most) affected side; (vi) any neurological or cardiovascular condition affecting the ability to perform testing; and (vii) work restrictions or other commitments preventing engagement in study protocol over the 6-week intervention period.

Fig. 1. Study overview including assessment time points and outcomes.
2.2. Procedures

Volunteers were screened via an online survey followed by telephone screening to confirm eligibility (Supplementary Figure S1). Potentially eligible participants underwent a clinical examination [26] to confirm hip OA by a registered physiotherapist (AH) prior to data collection. For participants with bilateral hip pain, the most symptomatic hip was considered the study hip. Biomechanics data were collected at Griffith University (Time 1) by the same researchers (DD, BC, MLP). Baseline (Time 1) and 6-week follow-up (Time 2) participant-reported data were collected via paper-based questionnaires and telephone (Time 2 only). Participants recorded weekly data, including estimated total minutes walking using their prescribed load modification strategy and adverse events, in a paper-based logbook.

2.2.1. Biomechanics assessment

A full body marker set, consisting of 41 retro-reflective markers (Supplementary Figure S2) were fitted to each participant [23]. Surface electromyography (EMG) signals were synchronously recorded using a 16-channel wireless EMG system (2000 Hz; Cometa, Italy) from 12 lower-limb muscles of the study limb: gluteus maximus, gluteus medius, semitendinosus, biceps femoris, medial gastrocnemius, lateral gastrocnemius, soleus, vastus medialis, vastus lateralis, rectus femoris, tensor fascia latae, and tibialis anterior using standardised electrode placement [27]. Participants wore their regular walking shoes and were fitted with a safety harness that included shoulder, leg, and chest straps (ERGO Full Body Fall Arrest Harness, Spanset, Switzerland). The safety harness was secured such that participants could walk without impediment or discomfort (Fig. 2; Supplementary Figure S2).

Participants walked on an instrumented split-belt treadmill (Bertec Corporation, USA), sampling at 1000 Hz, for 5-min at a self-selected speed (normal walk - control condition), then for 5-min under each of the following experimental conditions: (i) neutral trunk lean (medial/lateral); (ii) neutral pelvic obliquity (rise/drop); and (iii) increased step length. Participants maintained the same walking speed for each condition. The biomechanical parameter of interest and a corresponding personalised target value were displayed in front of the treadmill in real-time (Fig. 2). The personalised targets were calculated using the normal walk condition and were set to decrease trunk lean towards the affected side, decrease pelvic drop on the contralateral side, and increase step length by 5% (an amount estimated to increase hip contact force by the desired 5%) [13]. Participants were provided instructions and a demonstration prior to walking under each condition. Specifically, participants were instructed to “keep your body upright and avoid moving the upper body from side to side” (neutral trunk), to “keep both sides of your hips level during walking/do not drop your hip” (neutral pelvis), and to “take longer steps” (increased step length). Motion data were captured using a 10-camera motion capture system (200 Hz; Vicon MX, UK) operating with Vicon Nexus (version 2.9.1); the biomechanical parameter of interest was computed and then continuously streamed to the visual display using the drawnow function in MATLAB R2018a (MathWorks, USA). Following each walking condition, participants were asked to rate their hip, knee, foot/ankle, and back pain, perceived difficulty, and confidence on a numeric rating scale (NRS) with terminal descriptors ‘no pain’, ‘not hard at all’, ‘not confident at all’ (score 0) and ‘worst pain possible’, ‘extremely hard’, ‘completely confident’ (score 10), respectively, and their perceived exertion using the 20-point Borg scale [28].

2.2.2. Personalised load modification

A decision tree (Fig. 3) based on pain, confidence, and competence during each of the walking conditions was used to prescribe a personalised load modification strategy to each participant, from the pool of available movements strategies, for integration into their walking routine over 6-weeks. Immediately following 5-min of walking using each load modification strategy, participants were asked to rate their hip pain and confidence on a NRS. Competence was assessed visually by the researcher and used in combination with an objective measure (computed as the percentage of strides where the participant successfully achieved the personalised target). Prior to leaving the laboratory, participants walked for an additional 5-min using their prescribed personalised load modification strategy with assistance from visual biofeedback. Participants were expected to walk a minimum of 20 min 3-times per week (per study inclusion criteria) using their prescribed personalised load modification strategy. Participants wore pedometers (Alvita Ultimate, Omron, Japan) during the 7-days before their baseline (laboratory) and 6-week follow-up (phone) assessments. Number of steps per day were tracked to confirm walking targets were met during these periods.

2.2.3. Participant-reported outcomes

2.2.3.1. Pain (Time 1, Time 2). Participants were asked to rate their hip pain intensity over the last week and during walking in both their (most) painful hip and their contralateral hip on NRS with terminal descriptors.

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Fig. 2. The biomechanical parameter of interest and a corresponding personalised target value (derived from the normal walk/control condition) were displayed in front of the treadmill. The target value was updated in real-time to provide immediate visual biofeedback to participants.
Joint angles, moments, and musculotendon kinematics were scaled to preserve dimensionless muscle and tendon operating curves. Optimal freedom was linearly scaled to match individual anthropometry based on 'L.E. Diamond et al. Osteoarthritis and Cartilage Open 4 (2022) 100230.

Full-wave rectified reaction forces were low-pass filtered with a 4th order, dual-pass, zero-lag Butterworth filter with a nominal cut-off frequency of 6 Hz. Electromyograms from each muscle were band-pass filtered (30–300 Hz), full-wave rectified, and low-pass filtered with 4th order, dual-pass, zero-lag Butterworth filter (6 Hz). The EMG were subsequently amplitude-normalized to the maximum processed value recorded across all walking trials. A generic full-body model with 23 joints was calibrated to each participant using data from one randomly selected trial from each walking condition for each participant.

2.2.3.3. Acceptability of intervention (Time 2). Participants were asked about how confident they were walking with their personalised load modification strategy in regular daily life over the 6-week follow up period using an 11-point NRS ranging from ‘not confident at all’ (score 0) to ‘completely confident’ (score 10).

2.3. Data processing

Body marker motion and ground reaction forces from 7 trials for each walking condition (28 in total) were processed using MOToNMS software (version 2.2) [34] in MATLAB R2019b (MathWorks, USA) for subsequent use in OpenSim (version 3.3) [35]. Body marker motion and ground reaction forces were low-pass filtered with a 4th order, dual-pass, zero-lag Butterworth filter with a nominal cut-off frequency of 6 Hz. Electromyograms from each muscle were band-pass filtered (30–300 Hz), full-wave rectified, and low-pass filtered with 4th order, dual-pass, zero-lag Butterworth filter (6 Hz). The EMG were subsequently amplitude-normalized to the maximum processed value recorded across all walking trials. A generic full-body model with 23 joints was calibrated to each participant using data from one randomly selected trial from each walking condition for each participant.

2.4. Statistical analysis

Peak hip contact force was compared between walking conditions for all participants using a repeated measures analysis of variance and post-hoc pairwise comparisons were made using paired sample t-tests (P < 0.05). Peak hip contact force change (load modification condition minus normal walk) with 95% confidence intervals (CI) was calculated for participant subgroups based on their prescribed personalised load modification strategy. The number of participants (%) who reached the minimum clinically importance change in self-reported pain and physical function at 6-week follow-up was calculated for the entire cohort and for participant subgroups. Statistical analyses were performed using Statistical Package for the Social Sciences (SPSS, version 27, IBM Corporations).
3. Results

Of the 145 individuals who completed the online expression of interest, 118 (81%) were excluded at telephone screening, 7 (5%) were excluded at physical screening, and 20 (14%) were enrolled in the study (Supplementary Figure S1). Five (28%) participants did not return all 6-week follow-up (Time 2) questionnaires or pedometer assessments. On average, participants walked 6460 ± 2644 steps/day and 7067 ± 1987 steps/day (mean difference −637 [95%CI -694, 1968] steps/day) during the 7-days before their baseline and 6-week follow-up assessments, respectively. Participant characteristics are reported in Table 1.

Table 1
Participant characteristics at baseline (mean ± standard deviation unless otherwise stated).

| Characteristic                  | n = 18 | Mean ± SD |
|--------------------------------|--------|-----------|
| Age (years)                    |        | 60.8 ± 6.3|
| Sex, female n (%)              |        | 13 (72%)  |
| Height (m)                     |        | 1.65 ± 0.10|
| Body mass (kg)                 |        | 82.7 ± 15.2|
| Body mass index (kg/m²)        |        | 30.0 ± 4.1|
| Bilateral symptoms, n (%)      |        | 3 (17%)   |
| Duration of symptoms, n (%)    |        |           |
| <1 year                        |        | 1 (6%)    |
| 1-2 years                      |        | 4 (22%)   |
| 2-5 years                      |        | 10 (56%)  |
| >5 years                       |        | 2 (11%)   |

Participants walked on the treadmill with an average speed of 0.93 ± 0.2 m/s. Peak hip contact force increased significantly when all participants walked using the step length modification compared to normal walking (mean difference 11.34 [95%CI 4.54, 18.13] %, P < 0.01), though not when using the other modifications (neutral trunk: mean difference 1.27 [95%CI -3.26, 5.82] %; neutral pelvis: mean difference −0.13 [95%CI -5.53, 5.28] %; Fig. 4). Changes in peak hip contact force were driven by changes in the biomechanical parameter specific to each walking condition (trunk lean – Supplementary Figure S4; pelvic obliquity – Supplementary Figure S4; step length – Supplementary Figure S5).

Following application of the decision tree, load modification subgroups included: neutral trunk n = 3; neutral pelvis n = 5; increased step length n = 10. Thirteen (72%) participants increased peak hip contact force >5% when walking using their prescribed personalised load modification strategy (Fig. 5). These participants included 5 (100%) in the neutral pelvis subgroup and 8 (80%) in the step length subgroup. No participants in the trunk lean subgroup achieved a 5% increase in peak hip contact force, and on average, neutralised peak trunk lean by only ~1 (mean difference 0.97 [95%CI -0.71, 2.65] degrees) compared to their normal walk condition (Supplementary Figure S4). On average, the neutral pelvis (11.88 [95%CI -0.49, 24.24] %) and step length (mean difference 12.79 [95%CI 0.49, 25.09] %) subgroups increased peak hip contact force by >10% (Fig. 5).

Participant-reported outcomes are summarised in Table 2. All but three participants (77%) reported a clinically important improvement in hip pain during walking (>1.8 NRS units) following the 6-week intervention (neutral trunk n = 2 (67%); neutral pelvis n = 4 (80%); increased

![Fig. 4. Ensemble average (±1 standard error, n = 18) hip contact force across the stance phase of normal walking (red - dashed) and three load modifying conditions (neutral trunk lean (khaki), neutral pelvic obliquity (blue), increased step length (green)) (top left) with assistance from real-time visual biofeedback. Neutral trunk lean (top right), neutral pelvic obliquity (bottom left), and increased step length (bottom right) are also shown individually with normal walking. BW: bodyweight.](image-url)
Table 2
Participant-reported outcomes.

| Outcome                                      | Time 1 mean (SD) | Time 2 mean (SD) | Mean difference (95% CI) |
|----------------------------------------------|------------------|------------------|-------------------------|
| Overall hip pain during previous week        | 4.9 ± 1.9        | 2.9 ± 2.3        | −1.7 (−2.5, −0.9)       |
| Hip pain during walking during previous week | 4.4 ± 2.2        | 2.3 ± 2.1        | −2.1 (−2.8, −0.9)       |
| Overall hip pain during previous week (contralateral hip) | 0.9 ± 1.6 | 0.7 ± 1.3 | −0.2 (−1.4, 0.7) |
| Hip pain during walking during previous week (contralateral hip) | 1.1 ± 1.9 | 0.6 ± 1.2 | −0.6 (−1.8, 0.6) |
| WOMAC physical function (0–68)              | 22.0 ± 10.1      | 14.7 ± 8.1       | −7.6 ± 2.0              |
| Confidence walking using prescribed load modification over 6-week intervention period, (0–10 NRS) | – | 7.6 ± 3.1 | – |

NRS: numeric rating scale (higher score indicates worse pain); NRS change indicates greater confidence; WOMAC: Western Ontario and McMaster Universities Osteoarthritis Index (higher score indicates worse function); calculated as Time 2 (6-week follow-up) minus Time 1; SD: standard deviation; CI: confidence interval.

4. Discussion

This study compared the feasibility of three load modification strategies to immediately increase hip contact force when participants were provided with real-time visual biofeedback during walking, and prospectively evaluated changes in pain and physical function following 6-weeks of walking using a prescribed personalised load modification strategy. The primary findings were that, on average, only the step length load modification significantly increased peak hip contact force compared to normal walking when performed by all participants. However, after participants were prescribed a personalised load modification strategy, both the neutral pelvis and step length load modification subgroups increased peak hip contact force by >10% compared to normal walking, an amount more than double the 5% estimated to promote cartilage health [13]. Regardless of the personalised load modification strategy prescribed based on decision tree results, most participants reported an improvement in hip pain during walking after 6-weeks of walking using their prescribed strategy. These findings provide preliminary support for a personalised load modification-based intervention in people with hip OA.

On average, increasing step length was the only load modification to significantly increase peak hip contact force compared to normal walking when performed by all participants. After participants were prescribed a personalised load modification strategy based on decision tree results, both the neutral pelvis and step length load modification subgroups increased peak hip contact force by >10% compared to normal walking. Increasing step length requires greater muscle activation and elicits higher force [42] in hip extensor muscles (e.g. gluteus maximus) during stance, which may have contributed to the higher hip contact forces observed during this walking condition. Reducing contralateral pelvic drop during walking has a direct effect on the moment arm of the centre of mass relative to the hip joint centre [40], making the observed consequences for hip contact force unsurprising. Participants in the trunk load modification subgroup only neutralised peak trunk lean by ~1°, which may explain why no participant achieved a 5% increase in
peak hip contact force. The efficacy of the neutral trunk modification relied on participants using an excessive trunk lean strategy during their normal walking, though participant walking strategy was not factored into the decision tree used for subgrouping. Further, trunk and pelvis motion are often interconnected, particularly in populations with hip pathology [43], and may be difficult to target in isolation. Nevertheless, our results highlight that the hip’s load response to each modification was unique across participants and emphasise the need for personalised interventions for management of hip OA [2].

Most participants with hip OA could immediately modulate their hip contact force during walking with assistance from real-time visual biofeedback of a target biomechanical parameter. Although mechanical loading is considered a modifiable mechanism of disease [6], internal loads acting directly on the hip have never before been targeted or assessed in conservative management programs for people with hip OA. Instead, gait modification interventions have largely focused on surrogates of joint load [7] and been primarily limited to people with knee OA [21,44]. Lower hip contact forces are characteristics of people with hip OA across the spectrum of disease severity compared to healthy controls [8–10] and increasing these internal loads to stimulate cartilage remodelling could have therapeutic benefit [45]. After participants were prescribed a personalised load modification strategy, most could immediately increase hip contact force up to 12% by neutralising frontal plane pelvic obliquity or increasing step length during walking. Although ex vivo and animal studies suggest a 1–4% increase in compressive force could be enough to stimulate aggrecan and protein synthesis in cartilage [13], robust in vivo studies in humans are lacking. It remains unclear what magnitude increase in hip contact force, if any, will restore anabolic activities without inducing catabolic cartilage degeneration [12] commonly observed in overloaded knees of people with knee OA [11]. Future research is essential to establish the relationship between cartilage strains during walking and cartilage health in people with hip OA.

After 6-weeks of walking using a prescribed personalised load modification strategy, 77% of participants reached or exceeded the minimum clinically important change for hip pain during walking. Almost half of these participants (46%) also achieved a clinically important change in physical function. Interestingly, the percentage of participants who reached a clinically important improvement in hip pain during walking was comparable between subgroups (neutral trunk = 67%; neutral pelvis = 75%; increased step length = 80%). Given that biomechanical data were not acquired at 6-week follow-up, it is impossible to confirm whether observed improvements in symptoms corresponded with increases in hip contact force. The complex relationship between joint loading and symptoms is widely recognised [24] and future well-powered studies should aim to elucidate the extent to which hip contact force must be increased to be associated with a clinically meaningful improvement in symptoms. Many participants (71%) reported they were confident (≥ 7/10) walking using their prescribed personalised load modification strategy during the 6-week follow-up period. This study used laboratory-based visual biofeedback to assist with motor learning [22], though at least in some people with hip OA, wearable technology equipped with haptic biofeedback may be required to reinforce motor learning during walking in the real world [46].

Given the absence of a control group in this study, we caution extrapolation of results beyond those presented. Previous research has shown the placebo effect can be powerful in people with OA, leading in some cases to reductions in pain of up to 75% [47]. Further, biomechanical data were not acquired at 6-week follow-up, and thus we cannot confirm whether observed improvements in symptoms corresponded with increases in hip contact force. Future randomised controlled trials are required to establish causative links between reductions in pain and increases in hip contact force. Incorporating measures of joint structure will be essential to confirm whether increases in hip contact force are favourable, and not detrimental, to cartilage health. Our results may be used to inform sample size calculations for intervention studies that aim to investigate hip load and symptom altering effects of personalised load modification in people with hip OA. We used an EMG-informed modelling approach to estimate hip contact force, which has demonstrated excellent agreement with experimental data of people with hip OA and measurements from instrumented hip implants [48]. We calculated hip contact force via a neuromusculoskeletal model with some degree of personalisation (inclusion of EMG measurements, linear scaling, calibration of muscle parameters). However, higher levels of model personalisation, including accounting for personalised bone geometry [49], may further improve hip contact force estimates. Including estimates of regional hip contact loading (e.g. force orientation and distribution), loading frequency, and cartilage strain may provide further insight into the effects of a personalised load modification-based intervention. Participants in our study walked on a treadmill which was required to implement our real-time biofeedback technology, therefore, participants walked at slightly slower speeds than previous reports of people with hip OA [14]. Further, walking conditions were not randomised between participants in this pilot study. We included participants who had symptoms consistent with hip OA [26], though radiographs were not acquired. Some participants had bilateral hip OA, and notably, 4/6 of these participants reported an improvement in contralateral hip pain after 6-weeks. Our small sample size did not allow for unilateral/bilateral subgrouping, though this may be worthwhile in future well-powered studies. We assessed only immediate effects of the load modification interventions (one laboratory retraining session and a 6-week home-based follow-up period). Future studies should aim to establish the training period required to optimise outcomes of hip load modification-based interventions in hip OA.

Many people with hip OA continue to report unsatisfactory symptom relief [50]. There is an escalating need to improve the efficacy of conservative management strategies [2], while maintaining a persistent focus on patients’ desire to self-manage their condition [5]. Our results provide preliminary support for a personalised load modification-based intervention for the self-management of hip OA. These findings should be confirmed in future studies using an adequately powered robust randomised controlled trial design.

**Author contributions**

LED, MH, RSH, CP, DJS conceived the idea and designed the study. DD, BC, MLP, AH contributed to data acquisition and analysis. DD, BC, MLP, LED contributed to data analysis and interpretation. LED wrote the first draft of the article. All authors revised the paper and provided scientific input. All authors approved the final version of the manuscript. LED, on behalf of all authors, takes responsibility for the integrity of the work, from inception to manuscript.

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**Authorship**

All authors have made substantial contributions to all of the following: (1) the conception and design of the study, or acquisition of data, or analysis and interpretation of data, (2) drafting the article or revising it critically for important intellectual content, (3) final approval of the version to be submitted. By signing below each author also verifies that he (she) confirms that neither this manuscript, nor one with substantially similar content, has been submitted, accepted or published.
elsewhere (except as an abstract). Each manuscript must be accompanied by a declaration of contributions relating to sections (1), (2) and (3) above. This declaration should also name one or more authors who take responsibility for the integrity of the work as a whole, from inception to finished article. These declarations will be included in the published manuscript.

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Studies involving humans or animals

Clinical trials or other experimentation on humans must be in accordance with the ethical standards of the responsible committee on human experimentation (institutional and national) and with the Helsinki Declaration of 1975, as revised in 2000. Randomized controlled trials should follow the Consolidated Standards of Reporting Trials (CONSORT) guidelines and be registered in a public trials registry.

Studies involving experiments with animals were in accordance with institution guidelines.

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Declaration of competing interest

The authors have no competing interests to declare.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ocarto.2021.100230.

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