

Research article

Sensory substitution for orthopaedic gait rehabilitation: A systematic review and meta-analysis for clinical practice guideline development

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ABSTRACT

Introduction: Sensory Substitution is a biofeedback intervention whereby at least sensory system is utilised to supplement environmental information which is traditionally gathered by another sense.

Objective: To present an evidence-based overview of the feasibility and effectiveness of wearable Sensory Substitution devices on gait outcomes in orthopaedic patient populations.

Methods: This Systematic Review and Meta-Analysis was reported according to the PRISMA 2020 statement. PubMed, the Cochrane Library, Web of science and PEDro were searched for relevant published literature. Inclusion criteria limited the search strictly to patients diagnosed with an orthopaedic condition and who were randomly grouped to a Sensory Substitution intervention or conventional therapy/training or an equivalent placebo intervention.

Results: Nine Randomised Controlled Trials and three Crossover Trials investigating the effectiveness of Sensory Substitution supplemented gait training were identified and included participants with a variety of orthopaedic conditions. Meta-Analyses revealed positive findings of feasibility as well as statistical and clinical effect of the interventions in improving measures of gait speed, weight-bearing control, measures of functionality and subjective self-reporting. Meta-Analyses also revealed the interventions effects were not significant in the management of pain and retention of gait speed. Negatively reinforced Sensory Substitution biofeedback was statistically and clinically effective, whilst positively reinforced biofeedback was not.

Conclusion: For orthopaedic patient populations to improve gait speed, weight-bearing control, functionality, pain and self-report measures, the authors recommend a Sensory Substitution supplemented gait training programme with negative biofeedback on performance. The intervention should be undertaken for 20 min per day, 3 days per week for 5 weeks. The intervention should coincide with structured analgesia administration to facilitate effective pain management. Limitations of the data included some low sample sizes and large age-ranges. No financial support was provided for this study.

1. Introduction

Globally, approximately 1.7 billion people were affected by musculoskeletal conditions in 2019 [1]. This data characterised musculoskeletal conditions broadly as conditions affecting joints, muscles, the spine and multiple body areas or systems, such as regional and widespread pain disorders and inflammatory diseases. Albeit the prevalence of musculoskeletal conditions fluctuates by age, people at every age were affected [1]. Musculoskeletal conditions were found to be the biggest global contributor to years lived with disability (YLDs), accountable for approximately 149 million YLDs, or 17% of all YLDs [1]. Projections

estimate global increases in the incidence and prevalence of musculoskeletal conditions, with low and middle-income countries estimated to see a large and rapid increase in the foreseeable future [2]. In 2017, the World Health Organisation (WHO) launched the 'Rehabilitation 2030—a call for action' initiative [3]. The initiative was launched to highlight and focus on the unfulfilled need for rehabilitation worldwide, and underline the importance of supporting healthcare systems to provide rehabilitation [3]. The initiative identified musculoskeletal conditions as a key sector of unmet rehabilitative need in global healthcare systems [3]. Orthopaedics is the branch of medicine concerned with treating musculoskeletal conditions. Gait is the pattern of limb movements made

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during locomotion or walking. Orthopaedic conditions are often perceived as most disabling when they affect an individual's gait and transfer ability [4, 5].

Neuroplasticity is the Central Nervous System's (CNS) ability to structurally and functionally adapt and change in response to a new stimulus [6]. Sensory Substitution (SS) is a biofeedback intervention founded on the physiological basis of neuroplasticity [7]. SS is any intervention where at least one sensory system (e.g. auditory, visual etc.) is utilised to substitute environmental information that is usually gathered by another sense (e.g. proprioception biofeedback) [8]. Whilst representation and processing is topographic in the mammalian brain, the 'plastic' structure of the CNS enables neuronal information processing to take place elsewhere from the traditional area(s) [9, 10]. A key neuroplasticity theory which rationalises this is that complex sequences (i.e. learning and skills) are encoded in the cumulative electrical wave patterns between neuronal connections, rather than in specific neurons [11]. As SS provides authentic real-time sensory information, the cumulative wave patterns produced during a task are can be interpreted and re-learned in different areas of the CNS [11]. The CNS is reported to possess substantial plastic properties to allow cortical reorganisation [12, 13].

A recent Systematic Literature Review (SLR) and Meta-Analysis (MA) proved that SS interventions are feasible and effective supplementations to functional training in neurological populations [14]. To our knowledge, no SLR and MA has examined SS supplemented gait training exclusively in orthopaedic patient populations.

2. Research question

Are wearable Sensory Substitution devices feasible and effective on gait outcomes in orthopaedic patient populations?

2.1. Methods

This study was reported utilising the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 statement as a template [15]. Relevant published literature was accessed via a search of the databases PubMed, the Cochrane Library, Web of science and PEDro. The Population, Intervention, Comparison, Outcome (PICO) tool was utilised to format the search strategy. The PICO tool is commonly used for SLRs and MAs in evidence based practice and is endorsed by the Cochrane Collaboration [16]. The search strategy employed a combination of MeSH terms, keywords, Boolean operators (AND or OR) and truncation (*). The search strategy varied slightly by database, depending on the search parameters permitted per database (see Table 1).

Inclusion criteria were:

- *Participants*: any cohort diagnosed with an orthopaedic condition;
- *Intervention*: SS and gait;
- *Comparators*: traditional therapy or training and/or placebo SS;
- *Outcomes*: recognised and/or rationalised measures of gait performance
- *Design*: Randomised Controlled Trial (RCT) or Crossover Trial.

Exclusion criteria were:

- *Language*: non-English Language;
- *Intervention*: non-SS stimulation devices.

The Cochrane Risk of Bias Assessment tool was administered to included articles [17]. A Random Effects Analysis Model was used to calculate effect of SS interventions compared with controls. This analysis model was used due to the diverse interventions and comparisons being assessed. A Standardised Mean Difference (SMD) was calculated to assess intervention effect size. SMD was the statistical measure used as varying numerically scaled outcome measures were

administered in the included studies. A positive SMD value indicates an overall average improvement of the intervention compared to controls. SMD is a measure of clinical effect and can be classified as Small (SMD = 0.2), Medium (SMD = 0.5) and Large (SMD = 0.8) [18]. Statistically, a P-value of less than 0.05 indicates significant effect [16]. Cochrane's I^2 test was assessed to determine Heterogeneity between studies [16]. Levels of heterogeneity were: 0%–40%–not important; 30%–60%–moderate; 50%–100%–extensive [19]. All statistical analysis was performed using The Cochrane Collaboration Review Manager (RevMan) (Version 5.4) [17].

3. Results

3.1. Systematic review

3.1.1. Study selection

The literature search was undertaken between 23/08/21 and 24/09/21. Selection of articles was implemented by two authors (P.L., K.M.). Where disagreements arose, third author (P.B.) carefully reviewed if articles met inclusion/exclusion criteria and made the final decision on inclusion. The search yielded 374 articles across the databases. Screening of article titles for potentially appropriate studies was undertaken. Any duplicate articles found across the databases were excluded. The abstract of all potentially appropriate studies were carefully reviewed. 83 abstracts in total were reviewed. Case studies, SLRs, incomplete 'ClinicalTrials', studies investigating reliability and validity of SS devices, narrative studies and studies including non-orthopaedic participants or non-SS interventions were all removed. The full text of the 41 remaining articles were retrieved and reviewed to assess potential inclusion. 30 articles were excluded at this stage as they failed to meet inclusion criteria. Most articles excluded at this stage included inappropriate outcome measures. 11 studies were judged to satisfy inclusion criteria and were included for analysis and synthesis [20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30]. References of these articles were reviewed to identify any further relevant studies. Following the same process, 1 additional study was included [31]. This article retrieval process is demonstrated using the PRISMA 2020 flow diagram (see Figure 1) [32].

3.1.2. Study characteristics

Characteristics and main findings of the 12 included articles were extracted and summarized in Appendix 1.

3.1.3. Risk of bias

The Cochrane Risk of Bias (RoB) Assessment Tool was applied to included studies [17]. The RoB assessments demonstrated judgements about each RoB item presented as total percentages (Figure 2), and judgements about each risk of bias item per study (Figure 3) [17]. The most frequent High or Unclear RoB items identified were related to blinding, due to not being specified or being single blinded. A lack of intention to treat analysis and potential selection bias were also identified as High or Unclear RoB.

3.1.4. Sample

This study included, analysed and synthesised nine RCTs and three Crossover Trials. Patient populations investigated within these articles included hip arthroplasty (n = 5) [23, 24, 27, 29, 30], Anterior Cruciate Ligament Reconstruction (n = 3) [21, 22, 31], Chronic Ankle Instability (n = 1) [20], knee arthroplasty (n = 1) [25], knee osteoarthritis (n = 1) [26], and meniscectomy (n = 1) [28]. The mean age of participants was 56 years. Sample sizes ranged from 12 to 48 participants.

3.1.5. Intervention

Training volume was between 3 to 24 sessions over the course of between 1 to 12 weeks. In all twelve included articles, controls undertook identical training to the experimental group, although without receiving SS biofeedback. One study provided a home-based intervention [28], ten

Table 1. Search strategy used per databases to access published literature.

Database	Search string
PubMed	((“Sensory Aids” [Mesh] OR Biofeedback OR Perception OR ‘Sensory substitution’) AND (“Orthopedics” [Mesh] OR Orthop* OR ‘Orthop* Surgery’)) AND (“Gait” [Mesh] OR Gait OR Walking OR Ambulation OR Mobility)
Cochrane Library	(Biofeedback OR Perception OR ‘Sensory substitution’) AND (Ortho*) AND (Gait OR Walking OR Ambulation OR Mobility)
Web of Science	(Biofeedback OR Perception OR ‘Sensory substitution’) AND (Ortho*) AND (Gait OR Walking OR Ambulation OR Mobility)
PEDro	(Biofeedback Ortho* Gait)

were clinic based [20, 21, 22, 23, 24, 25, 26, 29, 30, 31], and one study was set between orthopaedic clinic and the patients’ homes [27].

All studies included a gait training program, although they differed in the exact procedures undertaken.

3.1.5.1. Treadmill walking. Six studies included instrumented treadmill walking [20, 21, 22, 26, 30, 31]. Four studies used the same model of dual-belt instrumented treadmill (Bertec™, Columbus, OH, USA) [20, 21, 22, 31], whilst one used a different model (Gaitway, h/p/cosmos, sports and medical gmbh, Nussdorf-Traunstein, Germany) [26]. The remaining did not explicitly reveal the model of treadmill utilized [30]. Different custom program algorithms were used to process either weight-bearing (WB) load force through plates in the treadmill, or sensors to detect real-time kinematic data.

3.1.5.2. Overground walking. Five studies consisted of SS supplemented overground walking [23, 24, 25, 27, 29]. Three studies used in-sole pressure sensors [24, 27, 29], including the SensiStep system (Evalan, BV, Amsterdam, Holland) [27], the Pedalert system (Kettering Surgical Appliances Ltd, Northampton, UK) [27] and the SmartStep Gait system (Andante Medical Devices, Ltd, Omer, Israel) [29]. One study utilised an Inertial Measurement Unit (IMU) system distributed across lower limbs,

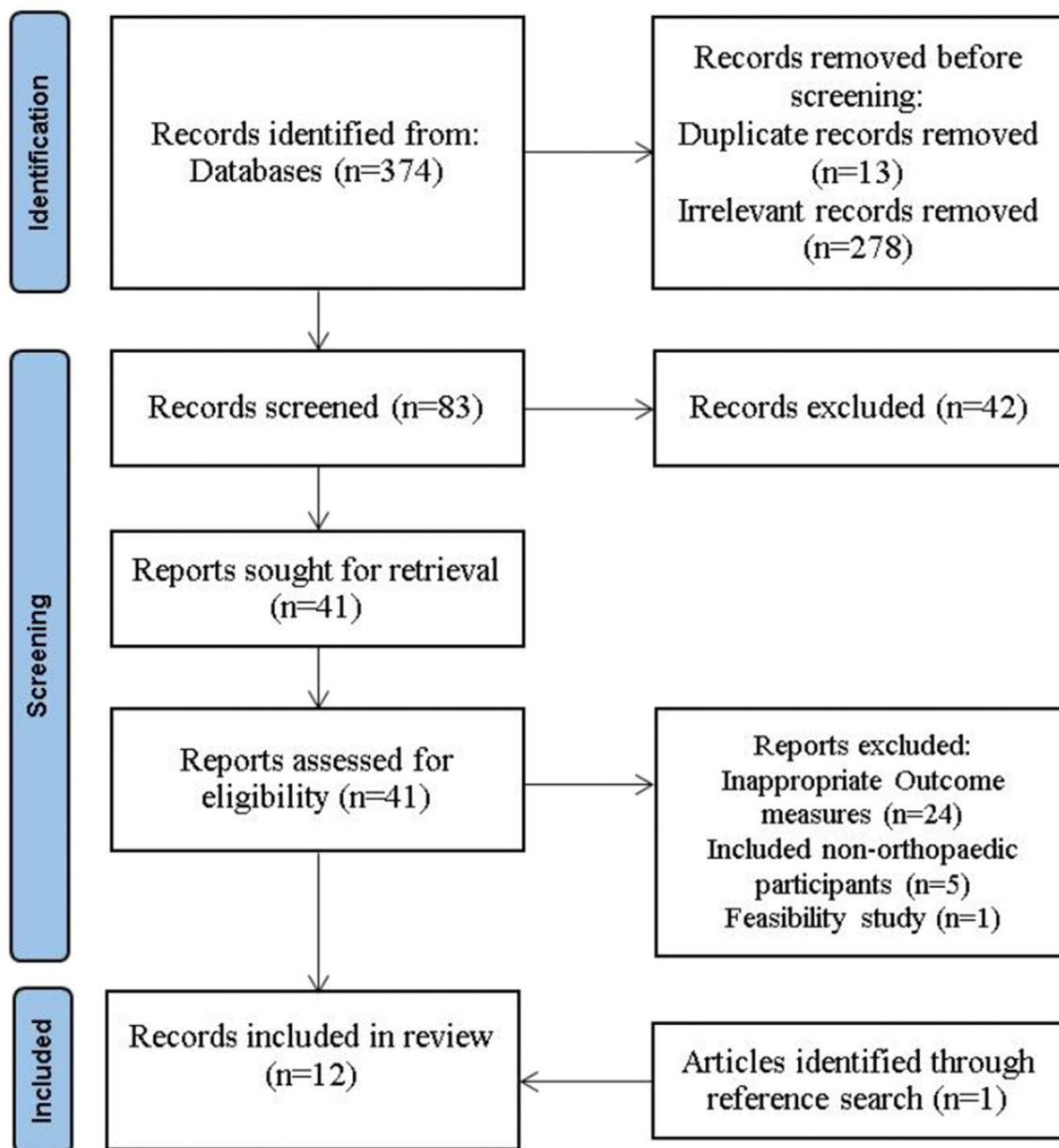


Figure 1. PRISMA 2020 flow diagram of article extraction process.

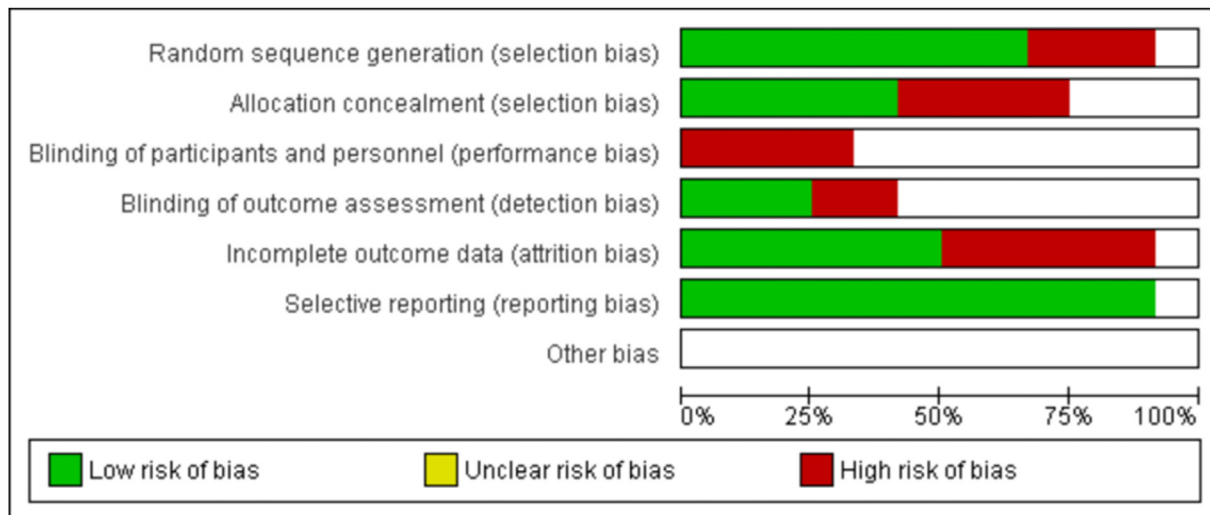


Figure 2. Risk of Bias graph: percentage review of authors' judgements about Risk of Bias items for included studies.

using the MVN Awinda (XSens Technologies B.V., Enschede, Holland) [23]. The final study used a Nintendo Wii Balance Board (Nintendo of America, Inc, Redmond, WA, USA) [25]. Different custom program algorithms were used to process WB and real-time kinematic data.

3.1.5.3. Home-exercise program. One study consisted of a home exercise program, which included gait training toward the latter stages of the structured program [28]. Muscle contraction was measured via an Electromyographic (EMG) unit, a Myomed 932 (Enraf-Nonius, Holland).

3.1.6. SS provided during intervention

Either visual or auditory SS was provided, with the information being substituted broadly associated with the type of gait training intervention undertaken.

3.1.6.1. Treadmill walking. Real-time interactive biofeedback was provided by substituting WB or kinematic information with visual information. Data collected either by instrumented treadmills or wearable sensors, were processed using a MATLAB algorithm (MathWorks, USA) [20, 21, 22, 31], Visual 3D software (C-Motion Inc, USA) [26] or a customised hardware-software interface [30]. Processed visualised data regarding real-time WB load force [21, 22, 30, 31] or kinematic data [20, 26] were projected onto a screen in front of each treadmill to provide visual SS feedback on performance.

3.1.6.2. Overground walking. Both visual and auditory real-time interactive biofeedback was provided by substituting WB and kinematic information for overground walking interventions. Data collected by insole pressure sensors was processed using either a MATLAB algorithm [24, 27] or built-in processing software [29]. Processed data was projected to provide visual (onto a mobile tablet) [24], auditory (beep) [27] or a combination of visual (computer screen) and auditory biofeedback [29]. Data collected from IMUs was processed by the software MVN Studio (BIOMECH (Version 4.1, XSens Technologies B.V., Enschede, Holland) to provide auditory (xylophone stroke) biofeedback [23]. Data processing software was built-in to the Nintendo Wii Balance Board to provide visual (screen) biofeedback on gait and balance performance parameters [25]. Processed visual and auditory SS information was provided to supplement real-time information on WB load force [24, 27, 29], kinematic data [23] or a combination of both [25].

3.1.6.3. Home exercise. Real-time interactive muscle contraction information was measured via an EMG unit [28]. This unit had built-in

processing capacity and analysed muscular contraction data, converting into both visual and auditory biofeedback.

3.2. Meta-analysis

All authors (P.L., K.M., and P.B.) contributed to statistical MA.

3.2.1. Gait Speed

Seven articles assessed intervention effects on Gait Speed [21, 23, 24, 25, 26, 28, 29]. 99 participants were included in experimental groups and 106 across controls. Outcome measures included Gait Speed, cadence, velocity, stride interval time, the Long Distance Corridor Walk (LDCW) test, and the Timed up and Go (TUG) test. There was a moderate-to-high level of heterogeneity between studies ($I^2 = 64\%$; $P = 0.01$) [19]. Due to the length of the test and evaluation measured in seconds, the LDCW presented as an outlier in this MA, with heterogeneity found to be within a non-important range ($I^2 = 4\%$) when this study was excluded from the MA [19]. MA revealed significant and Medium clinical overall effects of the intervention on Gait Speed compared to controls ($P = 0.02$; $SMD = 0.57$; 95% CI: 0.09, 1.06) (Figure 4) [17, 18].

3.2.2. Gait speed retention

Four articles included follow-up assessment to access retention of Gait Speed effects after 6 weeks, 12 weeks, 26 weeks and 12 months respectively [24, 25, 26, 28]. 59 patients were included in experimental groups and 69 across controls. Outcome measures accessed were Gait Speed, velocity, cadence and the LDCW. There was no measurable level of heterogeneity ($I^2 = 0\%$; $P = 0.84$) [19]. MA findings showed Gait Speed retention effects of the intervention were not significant and clinically Small compared with controls ($P = 0.11$; $SMD = 0.29$; 95% CI: -0.06 , 0.64) (Figure 5) [17, 18].

3.2.3. Weight-bearing control

Eight articles evaluated training effects on WB control [20, 22, 24, 25, 27, 29, 30, 31]. 161 participants were included in experimental groups and 153 across controls. Outcome measures included WB control, WB during gait, peak loading, mean peak load (MPL) maintained at set WB, peak vertical ground reaction force (vGRF), and serum cartilage oligomeric matrix protein concentration (sComp) (biomarker of cartilage breakdown). Heterogeneity was high between studies ($I^2 = 85\%$; $P < 0.0001$) [19]. As eight diverse measures of WB control were analysed for this MA, high heterogeneity was anticipated. Numerical values varied largely due to measures coming from large percentage change values to

	Random sequence generation (selection bias)	Allocation concealment (selection bias)	Blinding of participants and personnel (performance bias)	Blinding of outcome assessment (detection bias)	Incomplete outcome data (attrition bias)	Selective reporting (reporting bias)	Other bias
Akkaya 2011	+	+		+	+	+	
Armitano-Lago 2020	-	-			+	+	
Christiansen 2015	+	+		+	-	+	
Hershko 2008	+	-	-	-		+	
Hurkmans 2012	+	+	-		-	+	
Koldenhoven 2021	+	+	-	+	-	+	
Luc-Harkey 2018	-	-			+	+	
Luc-Harkey 2020	-	-			+		
Raaben 2018	+		-	-	+	+	
Reh 2019					+	+	
Segal 2015	+	+			-	+	
White 2005	+				-	+	

Figure 3. Risk of Bias summary: review of authors' judgements about each Risk of Bias item for each included study.

changes in WB ratio where values are presented in respect to a baseline value of 1.00. MA revealed WB control effects of the intervention were significant and clinically very Large compared to controls ($P = 0.002$; $SMD = 1.05$; 95% CI: 0.39, 1.70) (Figure 6) [17, 18].

3.2.4. Functionality

Six articles assessed training effects on functionality [20, 21, 23, 24, 28, 30]. 106 participants were included in experimental groups and 93 across controls. Outcome measures included gait pattern consistency, affected side step length, walking aid use, the Lysholm Knee Scale, the Late Life Function and Disability Instrument (LLFDI) - Basic Lower Limb Function score, the Harris hip score and the Star Excursion Balance Test (SEBT). Heterogeneity was high between studies ($I^2 = 89%$; $P < 0.0001$) [19]. The large difference between experimental and control groups for the LLFDI - Basic Lower Limb Function score was found to be an outlier in this MA. When removed, heterogeneity was found to be within a non-important to moderate range ($I^2 = 42%$) [19]. MA revealed

functionality effects of the intervention were significant and clinically very Large compared to controls ($P = 0.03$; $SMD = 1.07$; 95% CI: 0.09, 2.05) (Figure 7) [17, 18].

3.2.5. Pain

Four studies evaluated training effects on pain [24, 26, 28, 29]. 71 participants were included in experimental groups and 64 across controls. Outcome measures included the Visual Analogue Scale (VAS) and the Knee injury and Osteoarthritis Outcome Score (KOOS)—Pain section. Heterogeneity was high between studies ($I^2 = 87%$; $P < 0.0001$) [19]. Three of the four studies in this MA evaluated the VAS. When the study evaluating the KOOS—pain section, is excluded from analysis, the solely VAS analysis displays no measurable level of heterogeneity between studies ($I^2 = 0%$) [19]. The VAS and KOOS use differing numerically valued scales. MA revealed pain effects of the intervention were not significant and clinically Medium compared to controls ($P = 0.18$; $SMD = 0.71$; 95% CI: -0.32, 1.74) (Figure 8) [17, 18].

3.2.6. Self-report measures

Four studies evaluated training effects on self-report measures [20, 26, 30, 31]. 80 participants were included in experimental groups and 75 across controls. Outcome measures included perceived difficulty, the Rate of Perceived Exertion (RPE) scale, the KOOS—symptom section and the Global Rating of Change (GROC). There was a moderate level of heterogeneity detected ($I^2 = 44%$; $P = 0.15$) [19]. MA revealed self-report measure effects of the intervention were significant and clinically Large compared to controls ($P = 0.003$; $SMD = 0.86$; 95% CI: 0.39, 1.32) (Figure 9) [17, 18].

3.2.7. Negative biofeedback

Seven studies evaluated training effects of interventions administering negative biofeedback [21, 22, 24, 26, 27, 30, 31]. Negatively reinforced biofeedback is a type of feedback that is administered to indicate to the participant they are not achieving the desired target. 131 participants were included in experimental groups and 136 across controls. Heterogeneity was high between studies ($I^2 = 88%$; $P < 0.0001$) [19]. High heterogeneity was anticipated for this MA. Numerical valued scales varied largely, and extracted measures evaluated in percentages (e.g. 49.3%) were compared with changes measuring WB ratio, where values were presented in respect to a baseline value of 1.00 (e.g. 1.01). MA revealed negative biofeedback SS supplemented gait training had a statistically significant and very Large clinical effect compared to controls ($P = 0.002$; $SMD = 1.30$; 95% CI: 0.47, 2.13) (Figure 10) [17, 18].

3.2.8. Positive biofeedback

Three studies evaluated training effects of interventions administering positive biofeedback [20, 23, 28]. Positively reinforced biofeedback is a type of feedback that is administered to indicate to the participant that they are achieving the desired target. 38 participants were included in experimental groups and 39 across controls. There was no measurable level of heterogeneity between studies ($I^2 = 0%$; $P = 0.53$) [19]. MA revealed positive biofeedback SS supplemented gait training was statistically not significant and had a clinically Small effect compared to controls ($P = 0.21$; $SMD = 0.29$; 95% CI: -0.16, 0.74) (Figure 11) [17, 18].

4. Discussion

403 participants in total were recruited. 351 of these participants adhered to complete study protocols in full. Therefore, there was approximately a 90% adherence rate for the interventions. 52 participants dropped out at varying stages, with rationale for doing so a lack of time to commit to the trial, relocating, issues with transportation, medical reasons (e.g. illness, surgery, etc.), family emergencies, deaths and withdrawal without given explicit explanation. Overall, dropout rates were similar between the intervention and control groups. Only 1

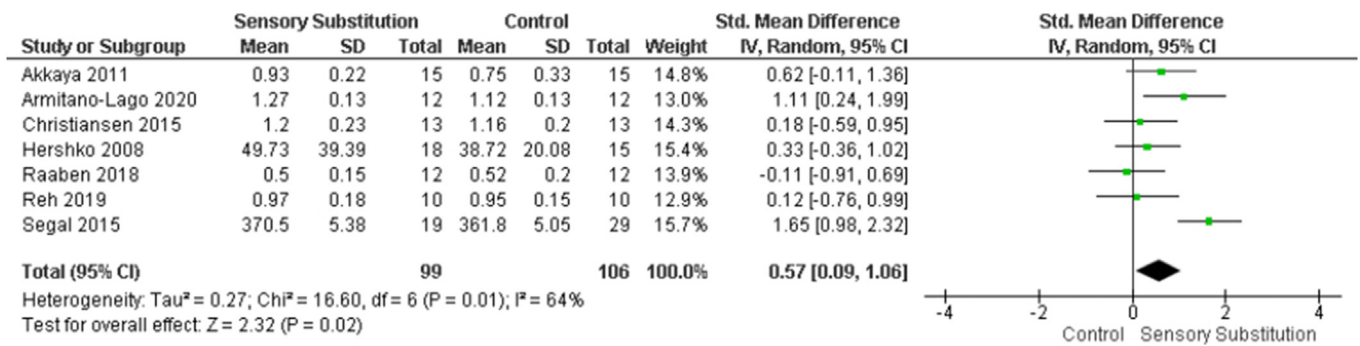


Figure 4. Training effects on gait speed.

participant (0.25%) of the total recruited population withdrew due to issues experienced with the SS intervention device, although the exact problem faced was not reported. An absence of reported difficulties with the intervention itself further propose that SS interventions are a feasible supplementation to gait training for orthopaedic patient populations.

Data gathering instrumentation varied across the included studies. Instrumented treadmills for detecting weight-bearing force were most consistently used [20, 21, 22, 26, 30, 31]. Other data gathering instrumentation included in-sole pressure sensors [24, 27, 29], IMUs spread across the trunk and lower limbs [23], EMG sensors placed on the lower

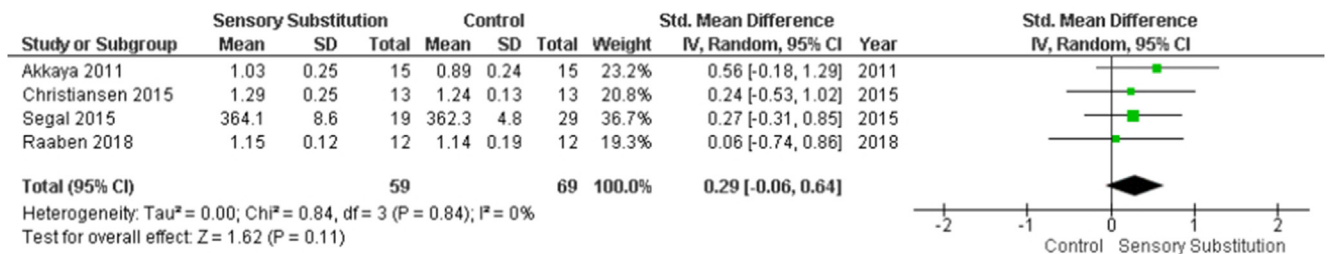


Figure 5. Training effects on gait speed retention.

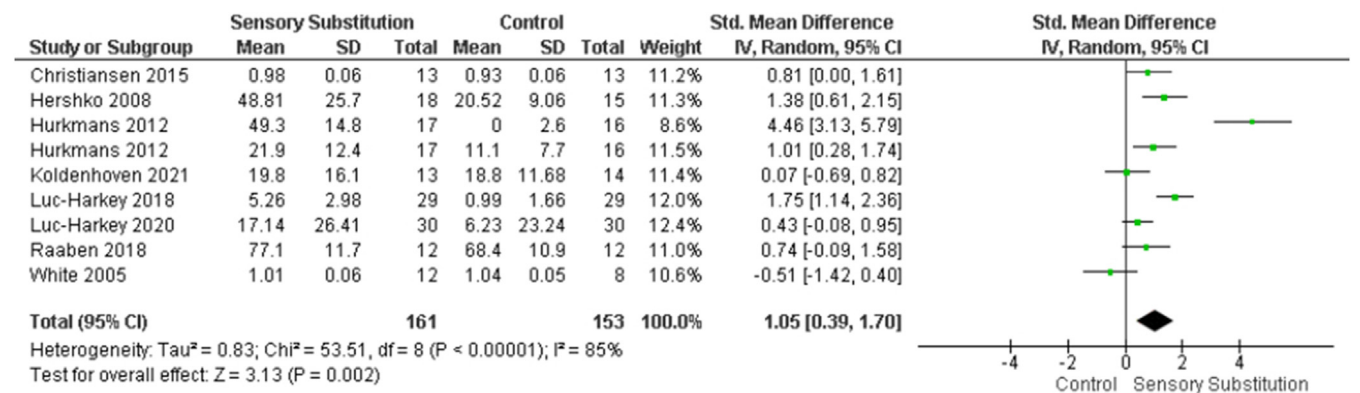


Figure 6. Training effects on WB control.

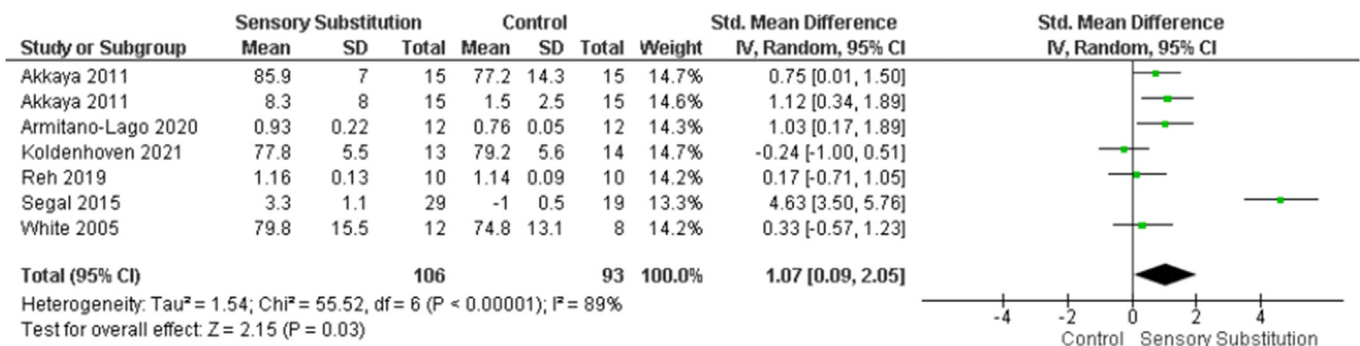


Figure 7. Training effects on functionality.

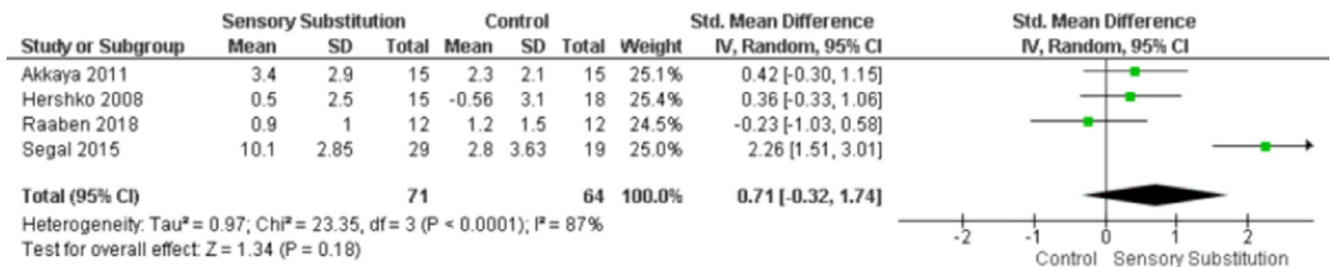


Figure 8. Training effects on pain.

limbs [28] and a WB detecting balance board [25]. This variation in instrumentation and placement limited the usefulness of comparing for MA; with more studies examining each variation needed in order to perform a more definitive sub-analysis and comparison between specific SS intervention.

Recently published clinical practice guidelines synthesised current evidence and produced ‘Key Guidelines for adults with chronic health conditions’ including orthopaedic conditions [33]. The guidelines recommend adults undertake 150–300 min per week of moderate-intensity aerobic physical activity (PA) [33]. Only one included study met this weekly guideline with PA time reported during the intervention together with reported warm-up and assessment time [29]. Of all the included studies, intervention time ranged from 1 to 12

weeks, with duration of each session between 15–45 min. Albeit most interventions reportedly did not achieve weekly recommended PA guidelines, MA revealed significant effects of the interventions on measures of gait speed, WB control, functionality, and self-report outcomes.

When undertaking motor system training with feedback, the influence of using either positive or negative feedback is a key consideration. Whilst positive feedback (i.e. feedback provided when achieving desired target) facilitates motivation, negative feedback (i.e. feedback provided when not achieving desired target) is crucial to encourage learning [34]. Sub-analysis from this review supports the correlation theory between negative feedback and motor learning. Seven studies provided negative biofeedback [21, 22, 24, 26, 27, 30, 31], whilst three provided positive [20, 23, 28] and two studies did not specify the exact mechanism of how

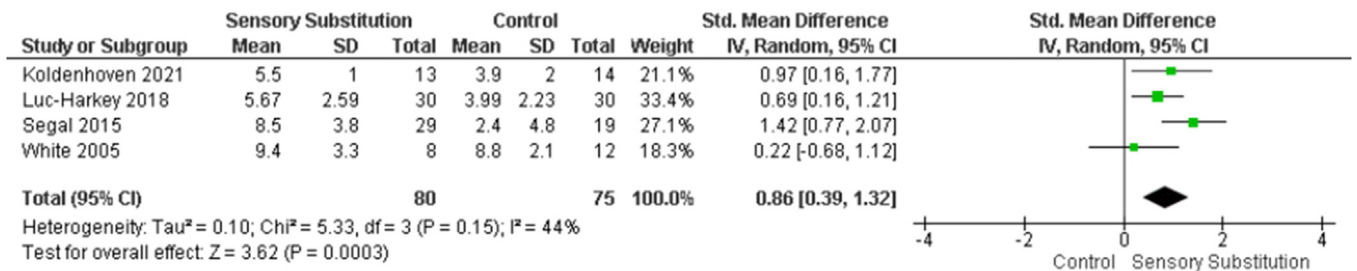


Figure 9. Training effects on self-report measures.

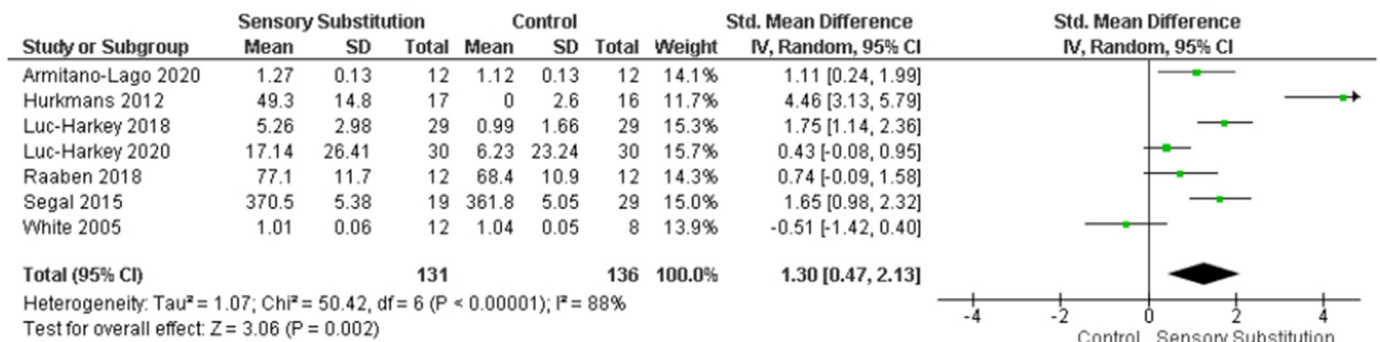


Figure 10. Training effects on negative biofeedback.

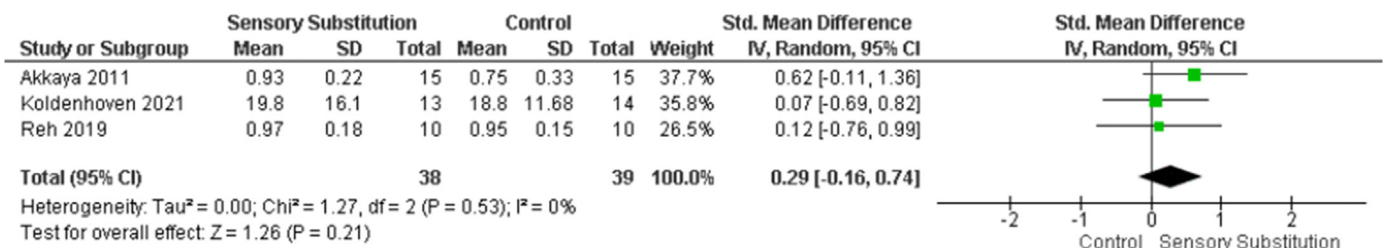


Figure 11. Training effects on positive biofeedback.

biofeedback was administered [25, 29]. This MA revealed negative biofeedback SS supplemented gait training had a significant ($P = 0.002$) and very Large clinical effect ($SMD = 1.30$) compared to controls, whilst positive biofeedback was found to have a non-significant ($P = 0.21$) and clinically Small effect ($SMD = 0.29$) [17, 18]. Whilst future research to provide a more volume dense data set on positive biofeedback is recommended, the findings of this MA clearly lead the authors to suggest the prioritisation of negative biofeedback SS supplemented gait training when designing future interventions and trials in order to maximise gait outcome effects.

Considering the finding in regard to prioritisation of negative biofeedback for SS supplemented gait training, it is possible to extrapolate an estimated effective training dosage from intervention duration [21, 22, 24, 26, 27, 30, 31]. From pooled data of negative biofeedback, average total duration of interventions was 300 min over a total of 5 weeks. Given orthopaedic patients commonly suffer symptoms of morbidity, particularly if surgical intervention is indicated, it is rational for the recommended 300 min total duration be evenly distributed over the course of the 5 weeks. Therefore, the authors recommend negative biofeedback SS supplemented gait training is conducted for 20 min per day, 3 days per week for 5 weeks in order to ensure adequate training dosage to facilitate effects of the intervention. Intervention time should coincide with regular PA in order to meet weekly guidelines for adults with chronic health conditions [33].

4.1. Effects on gait speed

According to a recent retrospective study, gait speed is a simple and useful prognostic indicator of functional recovery in patients who have undergone joint replacement [35]. Furthermore, a longitudinal cohort study identified that orthopaedic patients' who are discharged from hospital with slow gait speeds are more likely to develop limited functional mobility and a high risk of further adverse health events [36]. This evidence highlights the importance of interventions to increase gait speed in orthopaedic populations. Therefore, according to the findings of this MA, the authors suggest that SS supplemented gait training with negative biofeedback can be an effective addition to healthcare planning for orthopaedic populations. Moreover, it would provide an avenue for continued therapy for patients with slow gait who seek discharge from hospital.

Regarding long-term effect, MA findings showed retention of Gait Speed effects following the interventions were not significant and clinically Small compared with controls (Figure 5). The lack of long term effect amongst included data may potentially be associated with a lack of meeting PA guidelines, as no study which assessed retention effects achieved weekly PA guidelines [33]. Also, during the period between each follow-up assessment, participants no longer undertook interventions. These findings suggest that in order to retain effects of the intervention, constant training or maintenance dose training is required. Therefore there is a warranted consideration for alternative delivery of SS supplemented gait interventions to accommodate a maintenance dose of training to sustain effects. Potentially, these interventions could be delivered as part of remote rehabilitation to allow patients the opportunity to undertake the intervention more frequently to conveniently meet weekly PA guidelines alongside the SS supplemented gait intervention. Nevertheless, more evidence with additional follow-up assessments is required in order to provide a definitive conclusion regarding long term effect of SS supplemented gait interventions.

4.2. Effects on weight bearing control

A very important consideration is this outcome included interventions and measures that assessed both the ability to take more weight on the affected side, as well maintain WB within a set range (e.g. 5–20% Body Weight). Results indicate SS supplemented gait training interventions are effective for both outcomes.

Encouraging WB through an affected limb is important. WB is a vital factor for bone healing following orthopaedic surgery. Evidence suggests that increased metabolism is induced by increased WB which facilitates the healing response [37, 38]. Despite the metabolic advantage, research promotes caution and consideration with the speed of increasing WB. Following orthopaedic surgery, surgeons and/or therapists often prescribe partial WB of the affected side to patients. Common prescriptions range between 20–75% of Body Weight WB depending on the severity of surgery and progression through rehabilitation [39]. The authors emphasise that failure to comply with WB instruction could risk further injury or jeopardize the success of the surgery [39]. A recent publication found that amongst healthcare professionals in the United Kingdom, interpretation of partial WB varied greatly [40]. The authors suggested this varied interpretation presents a challenge through the potential inconsistency of rehabilitation, and suggested there is an unmet need for tools to provide objective interpretation of partial WB [40]. Furthermore, a recent publication accentuated the extent of the problem, concluding “most patients are not able to follow loading limitation, even a few days after surgery and even if the patients were trained by a physiotherapist” [41]. Following a thorough search of literature, there appears to be no readily available commercial device to objectively measure partial WB, and most patients are instructed to subjectively determine WB output through the affected lower limb. This highlights a gap in healthcare systems which SS supplemented gait training interventions can fulfil and which have been shown to be very effective in doing so ($P = 0.002$; $SMD = 1.05$) [17, 18].

4.3. Effects on functionality

Gait pattern consistency is an important therapeutic consideration as research suggests that gait disturbances have a major influence on quality of life, morbidity, and mortality [42]. A recent prospective study found that of all gait pattern measures, step length is independently associated with functional loss and falls in older adults, even after stratifying for numerous known risk factors [43]. A previous SLR and MA produced comprehensive evidence-based assessment of risk factors associated with falls in older adults, including those with orthopaedic conditions [44]. Findings suggest that the use of walking aids (versus non-use) is associated with a 2 to 3-fold increase in risk of falling [44]. After orthopaedic surgery, intervention to reduce falls risk is important. A retrospective analysis of 212,617 orthopaedic patients has highlighted that falls can occur even in patients with a low predicted risk of fall [45]. Therefore, effective interventions for variables associated with falls are warranted in healthcare planning for these patient populations.

The Lysholm scale has been found to be a valid and reliable measurement of orthopaedic knee disability for ligament, meniscal and chondral injuries and patellar dislocation [46]. A SLR including seventy-one studies and 17,301 participants provides extensive evidence to support the construct validity and sensitivity to change of the Late Life Function and Disability Instrument among various clinical populations [47]. The Harris Hip Score has been reported to demonstrate excellent reliability for both physicians and physiotherapists assessing hip disability [48]. In terms of validity, the Harris Hip Score has demonstrated no major differences when tested against the standard 36-Item Short Form Survey (SF-36) [48]. Lastly, evidence suggests the SEBT demonstrates excellent reliability [49], but further research is needed to conclusively determine validity [50].

Considering the impact of the range of measures discussed, and the reliability and validity of the measures utilised for assessment, the proven effectiveness of SS supplemented gait training would be welcome and have quite a universal application to orthopaedic therapeutic healthcare.

4.4. Effects on pain

The VAS is a very common unidimensional measure of pain intensity, which has been widely administered to a diversity of adult population.

Test–retest reliability has been shown to be good among rheumatology patients [51]. In the absence of a gold-standard for pain measurement, criterion validity cannot be evaluated. Construct validity has been shown to be good in patients with a variety of rheumatic diseases [52]. The KOOS is a knee-specific assessment tool used to analyse patients' opinion about their knee and associated problems, containing a pain specific section. The KOOS psychometric properties have shown high reliability and validity, and are particularly responsive to change in subjects with knee degeneration or injury [53].

As data from this MA suggests pain is not significantly reduced following SS supplemented gait training compared to controls, the authors therefore suggest the consideration of analgesia administration during the intervention. The coinciding use of analgesia would support potential benefits of the intervention in terms of gait speed, WB control and functionality, whilst also facilitating effective pain management for orthopaedic patients'.

4.5. Effects on self-report measures

As discussed previously, the KOOS is a knee-specific assessment tool used to analyse patients' opinion about their knee and associated problems, with the section focused on symptom change analysed for this self-report measure outcome. The KOOS psychometric properties have shown high reliability and validity, and are particularly responsive to change in subjects with knee degeneration or injury [53]. The RPE scale is another subjective outcome measure, used to evaluate intensity during PA or exercise [54]. The RPE scale has been shown to have moderate validity in measuring exertion in patients with chronic low back pain (LBP). However, combined with measuring Heart Rate, the RPE scale was found to be a very efficient method for measuring exertion in chronic LBP patients [55]. The RPE scale has also been found to have excellent test-retest reliability [56]. The GroC is a frequently used outcome measure completed by participants to independently score self-perceived improvement following an intervention or activity. A recent SLR and MA analysed a total of 1533 patients with neck pain [57]. The authors concluded that pooled analysed data from very good-to-excellent quality studies identify GroC scores as having moderate validity [57]. Whilst evidence investigating reliability is limited, one study reported excellent test-retest reliability of the GroC in patients with LBP [58].

Considering the strong evidence-base of the measures utilised for assessment, the proven effectiveness of SS supplemented gait training on self-report measures would be welcome to orthopaedic therapeutic healthcare.

5. Limitations

There were limitations of this MA to consider. One limitation comes from potential RoB. The most frequent High or Unclear RoB items identified were related to blinding, due to not being specified. A lack of intention to treat analysis and potential selection bias were also identified as High or Unclear RoB. Clarity in original research is important as these items were identified as potential RoB largely due to a lack of information.

Another limitation to consider is that a lot of the included studies were characterized by low sample sizes. Also, studies included a large age-range with some participants of a quite advanced age (20–84 years of age). There is some evidence to suggest that younger adults have more capacity for neuroplasticity than older adults [59, 60]. One experimental study reports that motor cortex plasticity in terms of excitation and potentiation reduces with increasing age [61]. To our knowledge there is no evidence available which measures and compares capacity for neuroplasticity in young and old adults in terms of physical functional changes after a SS intervention. Further research with larger sample sizes investigating capacity for neuroplasticity in young and old adults after a

SS intervention is needed to clearly determine age-related capacity and develop age-dependent clinical practice guidelines.

Finally, heterogeneity levels varied greatly in this MA. Some analyses presented with little-to-no heterogeneity. Other analyses presented with high levels of heterogeneity, although could be rationalised. High levels of heterogeneity were detected in analyses where the scale of outcome measures varied greatly. For example, units of percentage or seconds were analysed with units of ratios where values are presented in respect to a baseline value of 1.00. Low levels of heterogeneity were found once these variations were accounted for. Also, some analyses presented a study which acted as an outlier. Once this study was removed from the analysis, the level of heterogeneity lowered considerably. Establishing core outcome measures which follow the same scale when assessing particular populations would be useful to limit external influence and truly measure the heterogeneity of results for an intervention in future research.

6. Conclusion

To the authors' awareness, no other research has investigated SS supplemented gait training solely in orthopaedic patient populations. The research provides evidence of feasibility and a global positive statistical and clinical effect of the intervention in improving measures of gait speed, WB control, various measures of functionality and subjective self-reporting compared to controls. Statistical analysis revealed non-significant effects of the intervention in the management of pain and also the retention of gait speed improvements following the intervention. Data indicates the largest clinical effect improvements of the intervention were seen in WB control, functionality and self-report measures.

In summary, there is a clear and comprehensive recommendation that can be extrapolated from the findings of this SLR and MA. For orthopaedic patient populations to improve gait speed, WB control, functionality, pain and self-report measures, the authors recommend a SS supplemented gait training programme with negative biofeedback on performance. The intervention should be undertaken for 20 min per day, 3 days per week for 5 weeks in order to ensure adequate training dosage. The authors also recommend the intervention coincide with structured analgesia administration to facilitate effective pain management alongside subjective and objective benefit.

Future research should include follow-up assessments in order to provide a definitive conclusion regarding long term effect of SS supplemented gait interventions. Nevertheless, findings from this study suggest that in order to retain effects of the intervention, constant training or maintenance dose training is required. Therefore there is a warranted consideration for alternative delivery of SS supplemented gait interventions to accommodate a maintenance dose of training. Potentially, these interventions could be delivered as part of remote rehabilitation to allow patients the opportunity to undertake the intervention more frequently and at their own convenience.

Finally, this research highlights a specific deficit in healthcare systems which SS supplemented gait training interventions can fulfil. There appears to be no readily available commercial device to objectively measure partial WB, causing patients to be instructed to subjectively determine their WB. As a result, the authors propose a device or system which provides negative biofeedback SS based on desired WB parameters during gait. This would be a welcomed addition to healthcare planning for orthopaedic populations in the future, and will fulfil a dilemma which currently exists in rehabilitation.

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