The use of biofeedback for gait retraining: A mapping review

VAN GELDER, Linda, BARNES, Andrew <http://orcid.org/0000-0001-8262-5132>, WHEAT, Jonathan <http://orcid.org/0000-0002-1107-6452> and HELLER, Ben <http://orcid.org/0000-0003-0805-8170>

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Title:

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Authors:

Linda M. A. van Gelder [a], Andrew Barnes[b], Jonathan S. Wheat[b], Ben W. Heller[a]

Affiliations:

[a] Sheffield Hallam University, Faculty of Health and Wellbeing, Centre for Sports Engineering Research, 11 Broomgrove Road, Sheffield S10 2LX , United Kingdom

[b] Sheffield Hallam University, Faculty of Health and Wellbeing, Academy of Sport and Physical Activity, Collegiate Hall, Sheffield, S10 2BP, United Kingdom

Corresponding author:

Linda van Gelder
l.v.gelder@shu.ac.uk
The Centre for Sports Engineering Research (CSER)
Faculty of Health and Wellbeing
Sheffield Hallam University
11 Broomgrove Road
S10 2LX Sheffield, United Kingdom

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Abstract:

Background: Biofeedback seems to be a promising tool to improve gait outcomes for both healthy individuals and patient groups. However, due to differences in study designs and outcome measurements, it remains uncertain how different forms of feedback affect gait outcomes. Therefore, the aim of this study is to review primary biomechanical literature which has used biofeedback to alter gait-related outcomes in human participants.

Methods: Medline, Cinahl, Cochrane, SPORTDiscus and Pubmed were searched from inception to December 2017 using various keywords and the following MeSHterms: biofeedback, feedback, gait, walking and running. From the included studies, sixteen different study characteristics were extracted.

Findings: In this mapping review 173 studies were included. The most common feedback mode used was visual feedback (42%, n=73) and the majority fed-back kinematic parameters (36%, n=62). The design of the studies were poor: only 8% (n=13) of the studies had both a control group and a retention test; 69% (n=120) of the studies had neither. A retention test after 6 months was performed in 3% (n=5) of the studies, feedback was faded in 9% (n=15) and feedback was given in the field rather than the laboratory in 4% (n=8) of the studies.

Interpretation: Further work on biofeedback and gait should focus on the direct comparison between different modes of feedback or feedback parameters, along with better designed and field based studies.

Keywords:

Gait; movement retraining; biofeedback; real-time feedback

1. Introduction

Patient groups with lower-limb musculoskeletal and neurological conditions experience gait limitations (Baram, 2013; James, 1992; Richards et al., 2016; Tate and Milner, 2010), such as reduced walking speed and distance (Baram, 2013; James, 1992; Richards et al., 2016; Tate and Milner, 2010). These limitations can have a major impact on patients' lives, as their daily living activities and social interactions are often affected (Baram and Miller, 2006). Other examples of gait limitations include insufficient foot clearance for patients with multiple sclerosis (Bregman et al., 2010) and stroke patients (Balaban and Tok, 2014), leading to increased risk of trips and falls, a reduced push-off power for patients with multiple sclerosis (Bregman et al., 2010) and diabetes (Mueller et al., 1994) and increased knee flexion or excessive knee extension during walking for stroke patients (Balaban and Tok, 2014) and individuals with cerebral palsy (Rodda and Graham, 2001). Healthy individuals might also display gait patterns that predispose them to chronic overuse injuries. Tibial stress injuries (Agresta and Brown, 2015) and patellofemoral pain (Cheung and Davis, 2011) are both common running injuries for which altered landing mechanics have been identified as key risk factors (Noehren et al., 2012). Such overuse injuries can cause significant disruption to training, a reduction in physical fitness as well as personal frustration (Clansey et al., 2014).

Treatment options to reduce the risk of overuse injuries in athletes and improve gait limitations in patients, range from the use of orthotic devices to surgical procedures on nerves or muscles (National Institute for Health and Care Excellence, 2016a, 2016b, 2013; Yeung and Yeung, 2001). Gait retraining, a non-invasive technique which focusses on the rehabilitation of gait by either muscle strengthening, treadmill training, neurodevelopmental techniques or intensive mobility exercises (Eng and Fang Tang, 2007), is an additional treatment option. Understanding how gait retraining may be used to benefit different patient groups or reduce the risk of overuse injuries is an important step in developing non-invasive treatment plans or prevention strategies to help improve individual outcomes.

Biofeedback makes use of electronic equipment to provide the user with additional biological information, beyond that which is naturally available to them (Agresta and Brown, 2015; James, 1992; Tate and Milner, 2010). Advances in technology have made biofeedback systems more affordable and more accessible to researchers; as a result there has been an increase in the literature in this area over recent years. Research suggests biofeedback to be a promising tool used to complement gait retraining (Stanton et al., 2011; Tate and Milner, 2010) and improve outcomes among several patient groups (Baram, 2013; James, 1992; Richards et al., 2016). For instance, stroke patients decreased the number of knee hyperextensions and increased gait speed when they received feedback on their joint kinematics (Stanton et al., 2011). Biofeedback has also been found to be effective at altering gait patterns in healthy subjects (Agresta and Brown, 2015; Richards et al., 2016) and reducing injury risk factors in runners (Agresta and Brown, 2015). Agresta and Brown (2015) found in their systematic review that runners demonstrated reduced kinetic risk factors associated with tibial stress fracture when receiving feedback on their peak tibial accelerations over the course of a run. Despite this, other studies included in the review of Tate and Milner (2010) have failed to find the use of biofeedback in gait retraining to be an effective tool in improving gait outcomes. These conflicting results might be due to differences in study designs and the populations examined (Stanton et al., 2011; Tate and Milner, 2010).

It is suggested that presenting the feedback in the field results in a more representative experimental design (Brunswik, 1956; Araújo et al., 2007). A more representative experimental design provides a better representation of the behavioural setting, which could lead to more beneficial and representative results (Araújo et al., 2007). With respect to the mode of feedback, researchers have suggested that multisensory feedback is superior to separate modes (visual, auditory, sensory) of feedback, not only due to encoding the most information but also due to the reduction of cognitive load associated with the separate systems due to distribution of information processing (Sigrist et al., 2013). With respect to the feedback parameter, feedback on knowledge of results might be more beneficial then feedback on knowledge of performance (Winstein, 1991). Further, studies have suggested that gradually removing feedback over time -fading the feedback- reduces the chances of participants becoming dependent on the feedback, facilitating improved learning (Agresta and Brown, 2015; Richards et al., 2016). Moreover, long term follow-up retention tests after gait retraining are important to assess learning (Agresta and Brown, 2015; Tate and Milner, 2010). Studies in the literature differ in the choice of feedback parameters and mode of feedback given, as well as the length of any retention period, which makes it difficult to draw firm conclusions about the effectiveness of, and optimal strategies for, gait retraining interventions. Advances in technology have made biofeedback systems more affordable and more accessible to researchers; as a result, there has been a surge in the literature in this area over recent years. Therefore, a mapping review of the biofeedback for gait retraining literature is required to get a broader understanding of the studies, characterise what has been done, and to identify what areas need future research.

The aim of this study was to review primary biomechanical literature which has used biofeedback to alter gait-related outcomes in human participants. Areas of interest included the mode of feedback, which parameters were fed-back, the intervention design and the length of any retention period. We intend that this rigorous approach to evaluating the trends in the area will help to inform future research in these key areas, to help provide clarity for the use of biofeedback for gait retraining applications.

2. Methods

2.1 Research design

This study used a mapping review approach; mapping reviews give an overview of the existing published research and can be used to obtain a better insight into the literature within a particular area (Booth et al., 2016). The results can be used to identify gaps in the literature and inform more specific future reviews and/or primary research studies. A mapping review searches the literature in a systematic way, but does not exclude articles based on quality. In the current mapping review the focus was on the methods used rather than the outcome.

2.2 Data sources and search strategy

The following databases were systematically searched from inception to December 2017: Medline (via EBSCOhost Research Databases), Cinahl (via EBSCOhost Research Databases), Cochrane, SPORTDiscus (via EBSCOhost Research Databases) and Pubmed. Searches used the following combination of MeSH terms: (biofeedback (psychology) OR feedback (sensory)) AND (gait OR walking OR running). The same terms were searched separately in: Title, Abstract and Subject/Keywords. An exception was the term feedback which was not searched in the different fields as the term is too broad and led to an unmanageable volume of results. Instead, a selection of terms was combined to make the search more specific to the area of interest: augmented feedback, real-time feedback, sensory feedback, proprioceptive feedback, vibrotactile feedback, tactile feedback, visual feedback, virtual feedback, auditory feedback and audio feedback. There were exceptions for the databases: Cinahl and SPORTDiscus, which did not have a separate MeSH term for feedback (sensory), for these databases the other MeSH terms were searched together with the separate search terms. Since there was no separate field for Keywords/Subject in Pubmed, all fields were searched in this database. Furthermore reference lists were checked from all relevant reviews that were found and additional articles were identified.

2.3 Study selection

The primary researcher (LvG) selected articles based on the relevance of the title and abstract using the following inclusion criteria: (1) feedback was given on biological information beyond what was naturally available to the participants; (2) feedback was given on one or more gait related parameters (corresponding to the categories of 'Feedback parameter' in Table 1); (3) at least one of the tasks performed in the research was gait (4) the study aimed to modify one or more gait related parameters as opposed to, for example, testing the validity of a system; (5) feedback was given in real-time; (6) measurements were performed using technology as opposed to verbal feedback; (7) treatment did not involve a combination of biofeedback and another treatment; (8) the article was written in English and (9) the article gave sufficient information on all the items listed in Table 1. The full texts of all articles that were deemed potentially relevant were then checked by the primary researcher using the same inclusion criteria.

2.4 Data extraction of included articles

The primary researcher extracted the information of interest (Table 1) from all articles that met the inclusion criteria. When an article reported a study that covered more than one category, each category was considered separately. This could occur when more than one participant group was tested, for example healthy participants and participants who experienced a stroke, when more than one feedback mode was tested, for example one group got auditory feedback and one group got visual feedback or when different parameters were fed-back, for example one group got feedback on knee angle while another group got feedback on knee moment. A second researcher (AB) reviewed a random sample of 10% of the articles at the start of the process to check the reliability of data extraction. Any disagreements between the researches were discussed and a consensus was sought with a third researcher (BH). This informed the final data extraction form which was used for all articles.

2.5 Study design categorisation

The final set of articles were assigned to four categories based on their research design: (A) the study had an experimental and a control group of at least ten participants per group and a retention test; (B) the study had an experimental and a control group of at least ten participants per group, but no retention test; (C) the study had no control group or a control group with less than ten persons per group and a retention test and (D) the study had no control group or a control group with less than ten persons per group and no retention test. A control group was defined as a group who received no intervention or an alternative (non-biofeedback) intervention at the same time as the experimental group received biofeedback. Ten participants per group was used as a cut off since this was recommended by Whitehead et al. (2016) for trials with a large effect size (0.8) with 90% power and two-sided 5% significance. A retention test was defined as a test after one day or longer during which participants had to walk or run without biofeedback.

Topics	Categories
Authors	
Journal	
Year of publication	
Number of participants	
Participant group	Healthy, runners, stroke/hemiplegia, Parkinson's, incomplete spinal cord injuries, cerebral palsy, multiple sclerosis, amputees, diabetics, knee injuries, other (included: ibromyalgia syndrome; uncompensated unilateral vestibular loss; bilateral peripheral vestibular loss/areflexia; different neurological gait disorders; out patients referred to a geriatric falls and balance clinic; inpatient rehabilitation program; asymptomatic participants; orthopaedic surgery; chronic ankle instability; hip arthroplasty with trochanteric osteotomy; idiopathic bilateral peripheral neuropath and Charcot-marie-tooth-disease; toe walking and Parkinson or stroke; spina bifida; lower extremity disabilities)
Mode of feedback	Visual, auditory, sensory, visual-auditory, visual-sensory, auditory-sensory, multisensory which is a combination of visual, auditory and sensory feedback
Feedback parameter	**Spatiotemporal** (included: stride width and symmetry, step length, stride length and symmetry, stance time, swing time, temporal symmetry in stance), **kinematic** (included: ankle, knee, hip, pelvis and trunk joint angles, foot contact angle, shank angle, foot progression angle, toe-out in stance phase, knee distance, minimum toe clearance, peak tibial acceleration, anterior-posterior and medial-lateral position of the subject's trunk, trunk sway and angular velocity), **kinetic** (included: ground reaction force, average loading rate, torque, pressure of the heel, pressure of the foot, centre of pressure, centre of mass, weight bearing, knee medial tibiofemoral contact force, peak vertical force on the cane during gait and human-machine interaction forces), **muscle activation, physiological** (included: heart rate, ventilation, VO2 and lower extremity temperature), **combination**
Feedback system	Force sensors fixed on participants, force plates fixed in place, optical motion capture system, motion capture system and force plates fixed in place, inertial measurement unit, electromyography systems, other (included: video camera, green screen; two sensors who have to be close to each other; electrogoniometer; position transducer; ultrasound; electrode to measure brain waves; biofeedback unit stabilizer, P pressure of muscles; Lokomat system (exoskeleton); Cycle-ergometer; heart rate monitor; thermal feedback system; motion capture and accelerometers; force plates and inertial sensors; EMG, 3D kinematics and instrumented treadmill, infrared, SPLnFFT Noise Meter)
Feedback in the laboratory or in the field	Laboratory, field, combination
Number of sessions	1, 2-5, 6-10, 11-20, >20, continuously wearing the device
Frequency of training	1 session, daily, twice a day, once a week, 2 times a week, 2-3 a week, 3 times a week, 4 times a week, 5 times a week, continuously wearing the device, unknown
Fading of the feedback	Yes, no
Retention test and if so, after what time	None, < 1 week, ≥ 1 week, ≥4 weeks, ≥ 3 months, ≥ 6 months
Test with or without feedback	With, without
Feedback on gait or another task	Feedback on gait, feedback on gait and another task
Outcome	Beneficial, no difference between an experimental and a control group or between a pre- and post- test, negative, no inferential statistics

Table 1. The fields that were extracted and in the second column the categories that were found for each field.

3. Results

3.1 Search results

1316 articles were identified in Medline, 392 in Cinahl, 333 in Cochrane, 303 in SPORTDiscus and 1769 in Pubmed (Fig 1). After removing duplicates a total of 2165 articles were checked for relevance based on the title and abstract and 1674 articles were excluded. The full text of the remaining 491 articles was checked against the inclusion criteria and 143 articles were identified as relevant to the review. Five additional articles from the reference lists of the reviews identified were also included. Details of all articles included in this review (n=148) can be found in the supplementary material. These articles included a total of 173 studies, since some articles reported more than one study.

3.2 Overview of study characteristics

3.2.1 Year of publication

There has been an increase in published studies over recent years (Fig 2), with most studies published in 2016 (n=26) and 2017 (n=20). When considering older studies from 1977 until 1994, participants only received auditory feedback or a combination of auditory and visual feedback. Sensory feedback was first reported in 1994 and multimodal feedback was not reported until 2010. The use of motion capture systems in combination with biofeedback for gait was first reported in 2010.

3.2.2 Participant groups

A total of 2479 participants, across the 173 studies, were included - with a mean of 15.5 (range: 1-240) participants per study. Groups included healthy participants, runners (healthy or injured) and participants with various gait disorders, numbers and percentages are depicted above the groups in the figure (Table 1, Fig 3).

3.2.3 Feedback mode

A range of feedback modes and combinations of modes were used within the included studies (Table 1, Fig 4). The most common mode of feedback used was visual.

3.2.4 Feedback parameter

A range of feedback parameters were used in the included studies (Table 1, Fig 5). Kinematic parameters were most frequently fed-back.

3.2.5 Feedback system

A variety of feedback systems (Table 1) were used to provide biofeedback to participants. Force sensors fixed to the participants feet or shoes were most frequently used (28%, n=49), followed by optical motion capture systems (15%, n=26), inertial measurement units (15%, n=25), motion capture in combination with force platforms (11%, n=19), force platforms alone (9%, n=16) and electromyography systems (9%, n=15). Other approaches were adopted in 13% (n=23) of the included studies.

3.2.6 Laboratory or field based studies

Ninety six percent (n=165) of the included studies were performed in a laboratory, 2% (n=4) in the field and the remaining 2% (n=4) used feedback given in both field and laboratory settings.

3.2.7 Training strategy and retention

More than half of all studies (53%, n=92) reported only one gait retraining session in which the participants received biofeedback. Three percent (n=5) of the studies reported 2-5 sessions, 20% (n=34) 6-10 session, 16% (n=27) 11-20 sessions while only 6% (n=11) gave the participants more than 20 sessions of feedback. In two percent (n=4) of cases participants were constantly wearing the device for the duration of the intervention. .

When studies included several sessions, most studies included 3 training sessions per week (n=24, 14%), 11% (n=19) included two sessions a week and 6% (n=11) of the studies reported up to 5 sessions a week. Three percent (n=5) of the studies included one training session a week, 3% (n=5) included four sessions a week, 2% (n=3) of the studies had daily training sessions, 1% of the studies included 2-3 training sessions a week (n=2) and 1% of the studies included training sessions twice a day (n=2). In 2% (n=4) of the studies participants wore the devices continuously in the field. Four percent (n=6) of the studies did not report the frequency of the feedback sessions.

Only 9% (n=15) of the studies faded the feedback over the course of the gait retraining intervention. In nine of these studies the task duration increased over time and the duration of the feedback decreased. The other six articles did not increase task duration, but did progressively decrease the feedback. Decreasing the feedback was done by giving alternating blocks of feedback and blocks of no feedback. In 10% (n=18) of the studies feedback was given on gait in combination with another task, such as a postural balance task.

Forty four percent (n=76) of the studies had no retention test, so the re-test was completed while participants were still receiving biofeedback. Thirty-two percent (n=55) had a retention test within a week of the intervention finishing, 8% (n=15) completed a retention test after more than a week and within 4 weeks, 10% (n=17) after 4 weeks and within 3 months, 3%

(n=5) after 3 months and within 6 months, while only 3% (n=5) completed a retention test 6 months or more after the intervention finished.

3.3 Outcomes

Sixty eight percent (n=118) of the studies reported beneficial outcomes related to one or more gait parameters, 20% (n=34) reported no difference between the experimental and control groups and/or pre- and post- test outcomes and 12% (n=21) did not report inferential statistics. Negative effects of biofeedback on gait parameters were not reported in any studies.

3.4 Study design categories

Based on the study design categories outlined in the methods, only 8% (n=13) of all studies were in category A, 8% (n=14) in category B, 15% (n=26) in category C with the remaining studies (69%, n=120) categorized as group D. Since all studies in category A had an experimental and a control group of at least ten participants and a retention test, these studies were considered in further detail.

Research in category A used a range of participant groups (Table 2) with the majority of studies using visual feedback (n=5, S25, S328, S50, S105, S122) followed by a combination of visual and auditory (n=4, S24, S33, S96-1, S96-2), auditory (n=3, S61, S77, S101) feedback and one article using multisensory feedback (S94).

Most of these studies (S24, S33, S38, S94, S96-1, S96-2, S101, S122) provided feedback on kinematic parameters. Seven of the studies in this category (S24, S61, S77, S96-1, S96-2, S101, S122) reported 18 feedback sessions or more while 2 studies (S38, S105) used only a single feedback session. Two studies (S24, S25) faded the feedback given and only one study (S61) gave feedback in the field. Only 4 (S25, S33, S96-2, S101) of the 13 (31%) studies reported beneficial effects of gait retraining on their selected outcome variable. In 6 (S50, S38, S61, S94, S96-1, S122) of the studies a significant difference was reported between the baseline and retention tests, but no significant difference was reported between the experimental and the control groups. The remaining studies (S24, S105, S77) reported no difference between baseline and retention tests or between groups.

Author	**Year**	**Participant group**	**Number of parti-cipants**	**Mode of feedback**	**Feedback parameter**	**Feedback system**	**Training time**	**Fa-ding**	**Retention**	**Study outcomes**	**Feedback on gait**	**Lab or field**
Carpinella S24	2017	Parkinsons disease	Exp: 17 Con: 20	Visual and auditory	Combination of kinematic variables	Six inertial sensors	20 sessions, 45 minutes each, 3 times a week	Yes	1 month post training	No difference: No pre-post differences for walking speed. Significant differences were found for balance measurements.	Yes	Lab
Chan S25	2017	Novice runners	Exp: 166 con: 154	Visual	Vertical ground-reaction force signal	Instrumented treadmill	8 sessions, 4 times a week for 2 weeks	Yes	12 months post training	Beneficial: Both significant differences between baseline and retention test and between the experimental and control group.	Yes	Lab
Clansey S33	2014	Recreational rearfoot striking male runners	Exp: 12 Con: 10	Visual and auditory	Peak tibial axial accelerations	A tri-axial accelerometer	6 sessions, 2 times a week for 3 weeks	No	1 month post training	Beneficial: Both significant differences between baseline and retention test and between the experimental and control group.	Yes	Lab
Creaby S38	2016	Healthy male runners	Exp: 11 Con: 11	Visual	Peak tibial axial accelerations	A tri-axial accelerometer	1 session, 10 min	No	1 week post training	No difference: No between-group differences	Yes	Lab
Drużbicki S50	2016	Stroke	Exp: 25 Con: 25	Visual	Step length	Instrumented treadmill	10 sessions, 5 times a week for 2 weeks	No	6 months post training	No difference: No between-group differences	Yes	Lab
Ginis S61	2016	Patients with Parkinson's disease	Exp: 22 Con: 18	Auditory	Cadence, stride length, symmetry and gait speed	CuPiD smartphone application, inertial measurement units	18 sessions, 3 times a week for six weeks	No	4 weeks post training	No difference: No between-group differences	Yes	Field

Table 2. Key data extracted from the studies in category A. References can be found in the supplement. Exp = experimental, Con = control.

Author	Year	Participant group	Number of participants	Mode of feedback	Feedback parameter	Feedback system	Training time	Fading	Retention	Study outcomes	Feedback on gait	Lab or field
Hurkmans S77	2012	Total hip arthroplasty with trochanteric osteotomy	Exp: 18 Con: 20	Auditory	Peak vertical force for each footstep	Insole pressure system, Pedalert system	Once per day during the entire hospital stay (6-8 weeks)	No	3 weeks post training	No difference: No between-group differences and no difference between the different retention tests	Yes	Lab
Lim S94	2016	Healthy older adults	Exp: 18 Con: 18	Multisensory	Trunk sway	SwayStarTMd gyroscopes	6 sessions, 3 times a week for 2 weeks	No	1 month post training	No difference: No between-group differences	Yes and balance tasks	Lab
Mandel S96	1990 (1)	Hemiparetic stroke patients	Exp: 13 Con: 11	Visual and auditory	Muscle activation of pretibial and calf muscle	Electromyography system	24 sessions, frequency unknown	No	3 months post training	No difference: No between-group differences	Yes and sitting, standing walking	Lab
Mandel S96	1990 (2)	Hemiparetic stroke patients	Exp: 13 Con: 11	Visual and auditory	Ankle position	Electrogoniometer	24 sessions, frequency unknown	No	3 months post training	Beneficial: Both significant differences between baseline and retention test and between the experimental and control group.	Yes and sitting, long sitting, standing and walking	Lab
Morris S101	1992	Patients with genu recurvatum following stroke	Exp: 13 Con: 13	Auditory	Peak amplitude of knee hyperextension	Electrogoniometer	20 session, 5 times a week for 4 weeks	No	4 weeks post training	Beneficial: Both significant differences between baseline and retention test and between the experimental and control group.	Yes	Lab
Oude Lansink S105	2017	Healthy participants	Exp: 13 Con: 11	Visual	Step width	Motion capture system	1 session, 1 min feedback	No	7-10 days post training	No difference, no effect of the treatment	Yes	Lab
Segal S122	2015	Patients with knee osteoarthritis	Exp: 19 Con: 19	Visual	Different kinematic trunk pelvic	Motion capture system	24 sessions, twice a week for 3 months	No	12 months post training	No difference: No between-group differences	Yes	Lab

Table 2 continued. Key data extracted from the studies in category A. References can be found in the supplement. Exp = experimental, Con = control.

4. Discussion

The aim of this study was to review primary biomechanical literature which has used biofeedback to alter gait-related outcomes in human participants. A total of 173 relevant studies were identified. Visual feedback was the most commonly used mode and feedback on kinematic parameters was most commonly used. The vast majority of studies were performed in a laboratory and reported only one feedback session, did not fade the feedback given and had no retention test. Sixty-nine percent of all studies suggested some beneficial effects of biofeedback on gait outcomes with no significant negative effects reported, however this percentage of beneficial results was lower in studies that both included a control group and a retention test (Category A articles).

Visual feedback was given most frequently in the studies included in this mapping review. In a systematic review on injured and healthy runners, different modes of feedback were found to be effective in reducing variables related to ground reaction forces, but no mode of feedback was identified as being superior (Agresta and Brown, 2015). This is important since some modes of feedback such as auditory and sensory may be more practicable for use in field-based biofeedback systems. It has previously been suggested that multisensory is superior to separate modes of feedback, not only due to presenting the most information but also due to the reduction of cognitive load associated with the separate systems due to distribution of information processing (Sigrist et al., 2013). Some of the included studies in this mapping review directly compared different feedback modes. Hirokawa and Matsumura (1989) and Shin and Chung (2017) found the best gait-related outcomes when using combined visual and auditory feedback, compared to each mode separately. However, it should be noted that different modes of feedback were used for different parameters: visual feedback for step length and auditory feedback for step duration. A study comparing visual, sensory and combined visual and sensory feedback on stride length in participants with incomplete spinal cord injury, found combined visual and sensory feedback to give significantly better results than the two modes presented separately (Yen et al., 2014). In this mapping review, multisensory feedback was only reported in 4% (n=6) of the studies. Future research on the effectiveness of different modes of feedback is therefore needed to help establish optimum feedback strategies for gait retraining applications within different populations. This suggestion supports previous research which has identified the need for research studies which directly compare different modes of feedback to further our knowledge in this area (Agresta and Brown, 2015; Sienko et al., 2017).

Kinematic variables were most frequently fed-back in the studies included in this mapping review. A previous systematic review on gait retraining found biofeedback of kinematic, kinetic and spatiotemporal parameters to show more promise than feedback on muscle activity, resulting in moderate to large short-term treatment effects in different patient groups (Tate and Milner, 2010). Feedback on muscle activity might be less effective since this mode of feedback focusses towards knowledge of performance. By moving away from knowledge of results and moving more towards knowledge of performance the learning response might be reduced (Winstein, 1991). Some studies included in this review support the suggestion that feedback on muscle activation results in smaller effects than feedback on other parameters. Franz et al. (2014) found that feedback on ground reaction forces (kinetic parameters) increased propulsive ground reaction forces and gastrocnemius muscle activity during push-off, while feedback on muscle activity only had no effect on the same gait related outcomes. In another study, feedback on muscle activity of the pretibial and calf muscles had no effect on walking speed, while feedback on ankle angle during heel-off and swing through (kinematic parameter) had a beneficial effect on the same gait related outcome (Mandel et al., 1990). However, a direct comparison between kinetic and kinematic parameters has not been reported in gait related studies, therefore it remains uncertain which group of variables may offer the best outcomes. A direct comparison between the different groups of parameters is needed to provide more insight into which parameter might be most effective at improving gait related outcomes.

Only 4 of the 173 studies gave feedback in the field, with a further 4 studies giving a combination of laboratory and field based training. Even though two previous reviews concluded that field based systems should be considered (Richards et al., 2016; Shull et al., 2014), to date the vast majority of published research is confined to laboratory settings. Presenting feedback in the field may facilitate the trend for healthcare to move away from a clinical model to a self-care model supported by technology (McCullagh et al., 2010), and it would also improve the representative design of experiments (Araújo et al., 2007). However, presenting feedback in the field does have some practical implementation issues. For example, visual feedback could be shown on a screen in the laboratory, but this would not be easily possible in the field. Auditory and sensory feedbacks are therefore easier to facilitate in field based settings.

Future research should also focus on the design of feedback interventions. Over half of the included studies reported one feedback training session. Since beneficial outcomes could be related to the duration of the intervention (Adamovich et al., 2009; Agresta and Brown, 2015), both the duration and number of sessions required for effective retraining should be explored. These findings are supported by a review of Gordt et al. (2017) on the effects of feedback of wearable sensor data on balance, gait and functional performance in both healthy and patient populations. These authors concluded that future randomised controlled trials should be designed with adequate intervention periods to enhance learning. In the current mapping review, only fifteen of the included studies used a faded feedback approach within their intervention. By gradually removing feedback over time, it is suggested that participants do not become dependent on the feedback, facilitating improved learning (Winstein, 1991). The majority of studies in this review had no retention test or a short term retention test within a week of the intervention finishing. Establishing the long term retention of any gait related changes represents a crucial step in prescribing gait retraining interventions as an effective alternate to existing treatment options (Agresta and Brown, 2015; Gordt et al. 2017, Stanton et al., 2017; Tate and Milner, 2010). Further, only thirteen studies combined having a retention test with having a control group. Of those thirteen studies, eleven studies reported beneficial effects of gait retraining when comparing baseline values to the retention values, four studies found significant differences between experimental and control groups. Therefore, the use of biofeedback shows promising results, since it has the same or a better effect compared to existing interventions, without the need for a health practitioner, or several trips to the clinic if field based feedback could be applied. However, at present there is a lack of well-designed studies that have established the long term efficacy of biofeedback for use in gait retraining interventions. Therefore, future work should focus on higher quality study designs, with a special focus on assessing the long term effects of any interventions.

This review has some limitations that are noteworthy: we used a selection of terms combined with feedback (as stated in the methods, section 2.2), since feedback is too broad as a term and would therefore have led to too many results. By using a selection of terms instead of feedback, there is a possibility that we missed some articles. However, we covered the area which we were interested in by a wide selection of terms and we further searched the reference list of reviews we found as well to make sure no articles were missed. Another limitation is the risk of publication bias, which might inflate the number of beneficial effects reported for the main outcome. Publication bias could mean that studies are less likely to be published when they have not found beneficial results. By choosing a mapping review instead of a systematic review we chose not to assess quality, assessing of the quality could have reduced the publication bias. However, in the current review the focus was on assessing the body of literature on the use of biofeedback to alter gait-related outcomes and the methods used; for this a mapping review was the most appropriate approach.

5. Conclusion

There is a growing body of research on the use of biofeedback in gait retaining. This mapping review has identified several areas within the current body of research that warrant further work. Future research should focus on direct comparisons between groups of parameters and feedback modes for specific gait retraining applications. Furthermore, researchers should seek to produce high quality well designed studies that explore the fading of feedback, the appropriate number of sessions as well as include a control group as assessing the long-term benefits of any intervention. Finally, researchers should seek to develop and assess the efficacy of field-based gait retraining systems using experimental designs more representative of real life situations.

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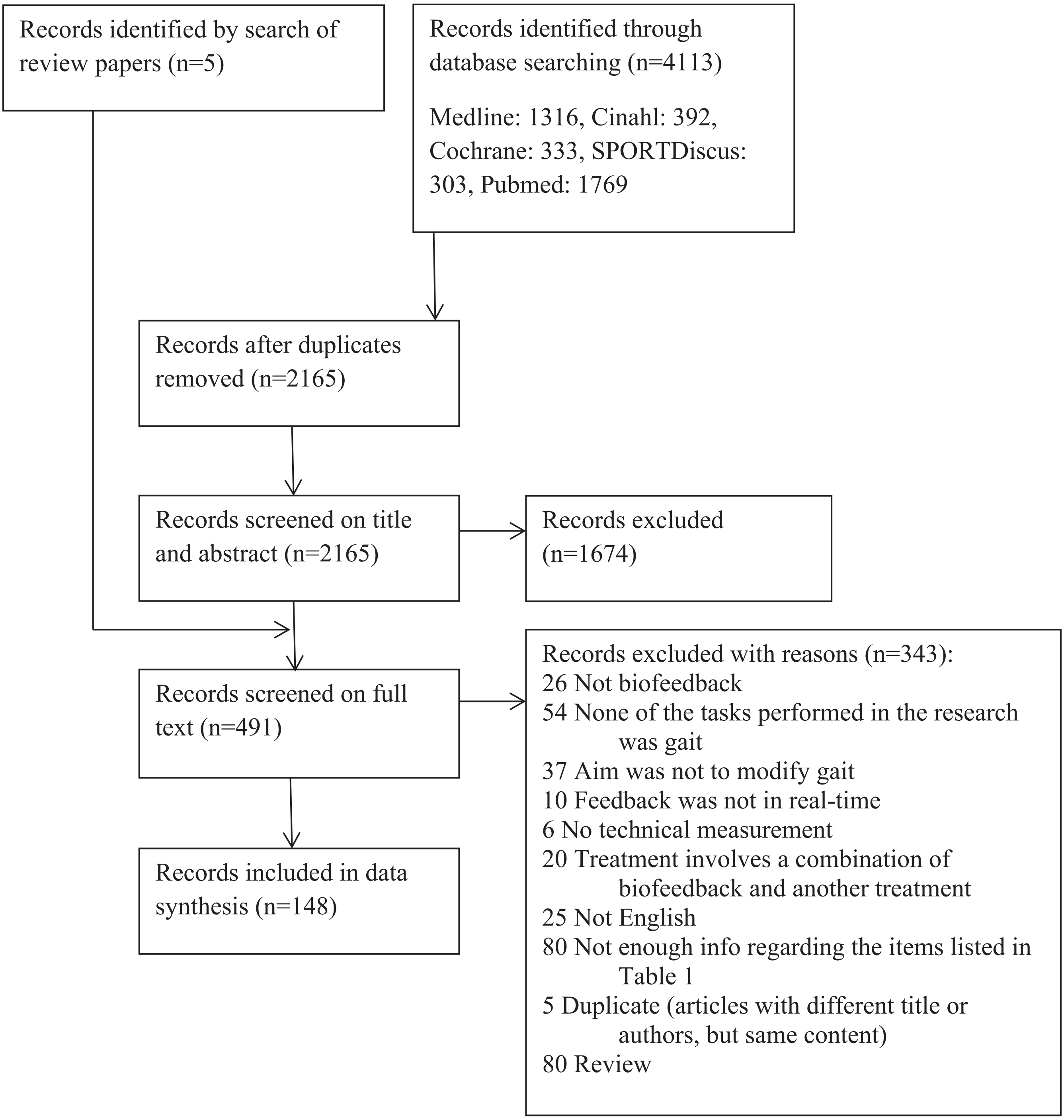
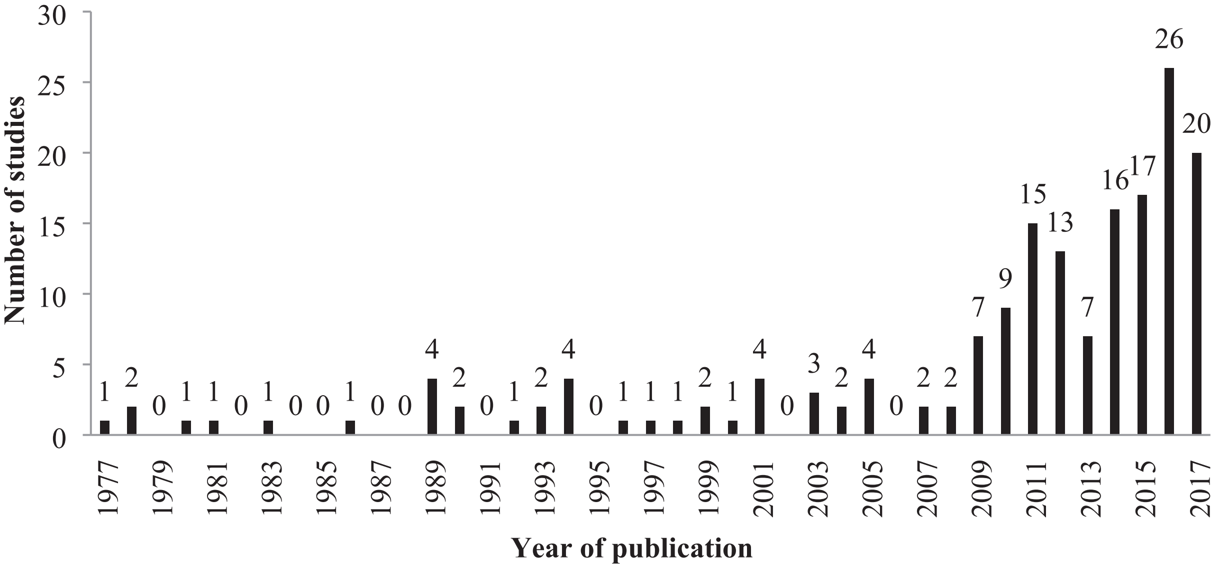

Records identified by search of review papers (n=5)
Records identified through database searching (n=4113)
Medline: 1316, Cinahl: 392, Cochrane: 333, SPORTDiscus: 303, Pubmed: 1769
Records after duplicates removed (n=2165)
Records screened on title and abstract (n=2165)
Records excluded (n=1674)
Records screened on full text (n=491)
Records excluded with reasons (n=343):
26 Not biofeedback
54 None of the tasks performed in the research was gait
37 Aim was not to modify gait
10 Feedback was not in real-time
6 No technical measurement
20 Treatment involves a combination of biofeedback and another treatment
25 Not English
80 Not enough info regarding the items listed in Table 1
5 Duplicate (articles with different title or authors, but same content)
80 Review
Records included in data synthesis (n=148)


Number of studies
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25
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10
5
0
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1977
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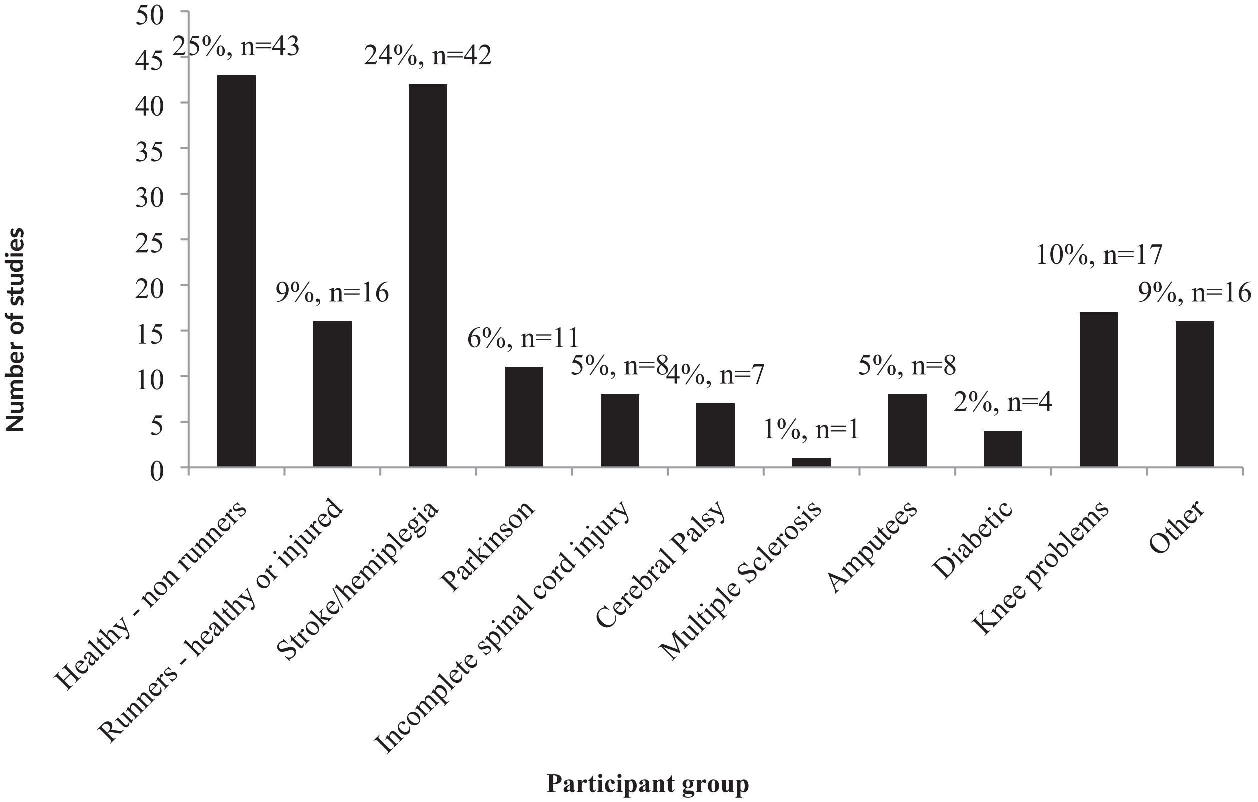
Number of studies
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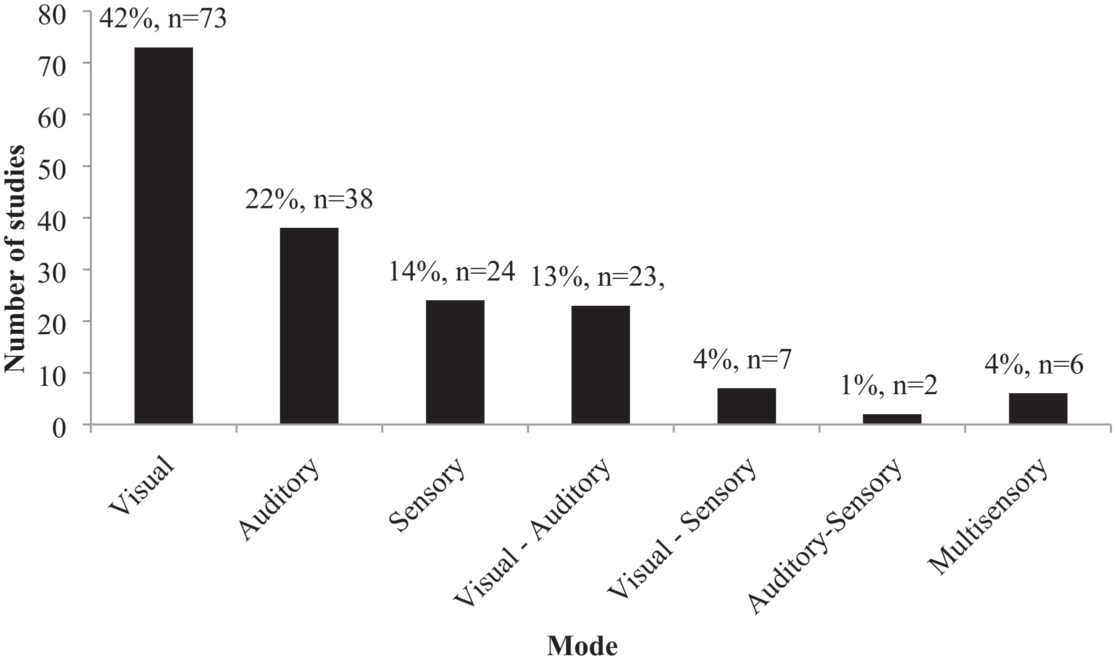
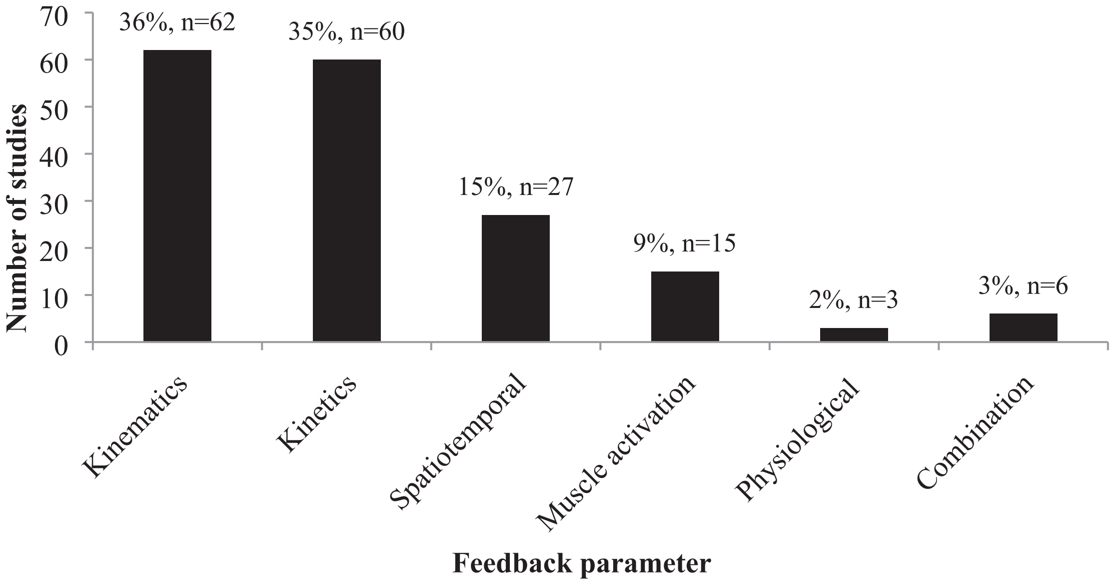
45
40
35
30
25
20
15
10
5
0
25%, n=43
9%, n=16
24%, n=42
6%, n=11
5%, n=8
4%, n=7
1%, n=1
5%, n=8
2%, n=4
10%, n=17
9%, n=16
Healthy - non runners
Runners - healthy or injured
Stroke/hemiplegia
Parkinson
Incomplete spinal cord injury
Cerebral Palsy
Multiple Sclerosis
Amputees
Diabetic
Knee problems
Other
Participant group


Number of studies
80
70
60
50
40
30
20
10
0
42%, n=73
22%, n=38
14%, n=24
13%, n=23,
4%, n=7
1%, n=2
4%, n=6
Visual
Auditory
Sensory
Visual - Auditory
Visual - Sensory
Auditory-Sensory
Multisensory
Mode


Number of studies
70
60
50
40
30
20
10
0
36%, n=62
35%, n=60
15%, n=27
9%, n=15
2%, n=3
3%, n=6
Kinematics
Kinetics
Spatiotemporal
Muscle activation
Physiological
Combination
Feedback parameter

Declarations of interest statement:

Declarations of interest: none

Figure legends

Fig 1. Flow diagram of search strategy

Fig 2. Number of studies published each year

Fig 3. The number of studies published for each participant group

Fig 4. The number of studies published for each mode of feedback

Fig 5. The numbers of studies published for each parameter which was fed-back

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