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Current Evidence of Gait Modification with Real-time Biofeedback to Alter Kinetic, Temporospatial, and Function-Related Outcomes: A Review

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ABSTRACT

Background: Gait retraining using real-time biofeedback (RTB) may have positive outcomes in decreasing knee adduction moment (KAM) in healthy individuals and has shown equal likelihood in patients with knee osteoarthritis (OA). Currently, there is no consensus regarding the most effective gait modification strategy, mode of biofeedback or treatment dosage. **Objective:** The purpose of this review was: i) to assess if gait retraining interventions using RTB are valuable to reduce KAM, pain, and improve function in individuals with knee osteoarthritis, ii) to evaluate the effectiveness of different gait modifications and modes of RTB in reducing KAM in healthy individuals, and iii) to assess the impact of gait retraining interventions with RTB on other variables that may affect clinical outcomes. **Methods:** Seven electronic databases were searched using five search terms. Studies that utilized any form of gait retraining with RTB to improve one or a combination of the following measures were included: KAM, knee pain, and function. Twelve studies met the inclusion criteria, evaluating eleven distinctive gait modifications and three modes of RTB. **Results:** All but one study showed positive outcomes. Self-selected and multi-parameter gait modifications showed the greatest reductions in KAM with visual and haptic RTB being more effective than auditory. **Conclusions:** Current evidence suggests that gait modification using RTB can Positively alter KAM in asymptomatic and symptomatic participants. However, the existing literature is limited and of low quality, with the optimal combination strategies remaining unclear (gait and biofeedback mode). Future studies should employ randomized controlled study designs to compare the effects of different gait modification strategies and biofeedback modes on individuals with knee OA.

Key words: Gait Retraining, Real-time Biofeedback, Osteoarthritis, Knee Adduction Moment

INTRODUCTION

Osteoarthritis (OA) is one of the most common joint disorders in the U.S. (Allen & Golightly, 2015; Control & Prevention, 2013; Ma, Chan, & Carruthers, 2014; Neogi & Zhang, 2013). Over the past 20 years the incidence of symptomatic knee OA has risen dramatically (Nguyen et al., 2011), leading to $128 billion in annual healthcare and economic costs (Ma et al., 2014). Knee OA is the predominant form of the disease, with an estimated lifetime risk of developing knee OA of approximately 40% in men and 47% in women (Neogi & Zhang, 2013). The etiology of knee OA is multifactorial, with risk factors such as excessive bodyweight (Sharma, Lou, Cahue, & Dunlop, 2000), aging, varus alignment, and altered joint mechanics (Heijink et al., 2012). Knee OA most commonly occurs in the medial compartment (Dearborn, Eakin, & Skinner, 1996; Thomas, Resnick, Alazraki, Daniel, & Greenfield, 1975), where articular surface damage narrows the medial joint space resulting in an increased knee adduction moment (KAM) (Andriacchi & Mundermann, 2006; Andriacchi et al., 2004; Simon et al., 2015). Increased KAM has been associated with OA severity (Foroughi, Smith, & Vanwanseele, 2009), cartilage loss (Chang et al., 2015; Chehab, Favre, Erhart-Hledik, & Andriacchi, 2014) and static malalignment (Hurwitz, Ryals, Case, Block, & Andriacchi, 2002), and has been shown to be a reliable indicator of medial knee joint load and alignment (Miyazaki et al., 2002; Sharma et al., 1998; Zhao et al., 2007). Reducing KAM in individuals who have, or who are at elevated risk for knee OA may decrease pain (Amin et al., 2004)and reduce disease severity and progression (Miyazaki et al., 2002).

Numerous treatment and management options for knee OA have been recommended, including the use of orthotic, pharmacologic, and surgical interventions with the goal of reducing symptoms and medial compartment loads (Zhang et al., 2007). Gait retraining using real-time biofeedback is a

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conservative intervention that has shown positive outcomes in other pathologies (e.g., diabetes, stroke, Parkinson, joint replacement, etc.) (Mayr et al., 2007; Zalecki et al., 2013). It has been suggested that gait modification with RTB results in modest to sizable short-term treatment outcomes when compared to conventional therapy (Tate & Milner, 2010). Recent studies have demonstrated a similar effect of gait retraining and RTB on KAM (Simic, Hinman, Wrigley, Bennell, & Hunt, 2011).

A 6-week gait retraining using haptic RTB exhibited a 20% average reduction of peak KAM and a 30% improvement in pain and function in individuals with knee OA (Shull, Silder, et al., 2013). Reductions in peak KAM were also reported utilizing a medial knee thrust gait with visual RTB in healthy adults with varus malalignment (Barrios, Crossley, & Davis, 2010), while medial weight transfer of the foot resulted in reductions in peak KAM in healthy individuals with normal joint alignment (Dowling, Fisher, & Andriacchi, 2010). Other gait strategies that have been successfully implemented include lateral trunk lean (Simic, Hunt, Bennell, Hinman, & Wrigley, 2012), altered foot progression angle (Shull, Shultz, et al., 2013), multi-parameter (Shull, Lurie, Cutkosky, & Besier, 2011; Shull, Silder, et al., 2013), and self-selected gait strategies (van den Noort, Steenbrink, Roeles, & Harlaar, 2014; Wheeler, Shull, & Besier, 2011). Similarly, a wide variety of biofeedback delivery, including visual (van den Noort et al., 2014), auditory (Ferrigno, Stoller, Shakoor, Thorp, & Wimmer, 2016), and haptic (Shull et al., 2011) have reported positive outcomes.

Limitations of the current literature, however, constrain generalizability and clinical application. Research into the effects of gait retraining using RTB in patients with knee osteoarthritis is lacking. Methodological differences including strategy implemented, training methods, and evaluation of skill acquisition mean there is no clear consensus regarding the most effective gait strategy, mode of feedback, or treatment dosage (Simic et al., 2011). The long-term outcomes of gait modification using RTB are unclear at present. Early results indicate that positive changes can be maintained, at least for a month (Barrios et al., 2010; Shull, Silder, et al., 2013). However, based on current evidence and the limited amount of retention testing, it cannot be determined if motor learning adaptations occur (Tate & Milner, 2010).

A recent systematic review and meta-analysis evaluating the effects of gait retraining with real-time biofeedback on KAM and pain related outcome measures (PROM's) by concluded that despite these limitations, there is sufficient evidence to suggest that gait retraining with real-time biofeedback can be used to reduce KAM in healthy controls (Richards, van den Noort, Dekker, & Harlaar, 2017). However, the effects of gait modification using RTB on kinetic, kinematic, and temporospatial variables other than KAM that may be clinically relevant have largely been ignored (Simic et al., 2011). Unanticipated changes at the knee joint such as increased knee flexion moment (KFM) and KAM impulse may offset the benefits of reduced peak KAM by increasing joint compression (Manal, Gardinier, Buchanan, & Snyder-Mackler, 2015; Walter, D'Lima, Colwell, & Fregly, 2010), and time under loading (Kean et al., 2012). Additional variables such as stride speed (Browning & Kram, 2007) and length (Russell, Braun, & Hamill, 2010) that may also affect joint loading have not been adequately considered in prior reviews.

Therefore, the purpose of this systematic review was three-fold: (1) to determine if gait retraining interventions using RTB are beneficial to alter KAM, pain, and improve function in patients with knee OA (2) to evaluate the effectiveness of different gait modifications and modes of RTB in reducing KAM in both healthy and asymptomatic individuals. (3) to assess the impact of gait retraining interventions using RTB on other outcome variables that may affect clinical outcomes.

METHODS

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines for conducting and reporting on systematic reviews were followed. The search strategy identified all randomized, quasi-randomized, nonrandomized controlled, and uncontrolled trials, published in English language, that utilized a form of gait retraining with RTB to improve KAM, pain, and/or function. For randomized, quasi-randomized, and nonrandomized controlled trials, participants in the experimental group were diagnosed with knee OA (Altman, 1991), or self-reported OA based on knee chronic joint pain (Fransen et al., 2015). Gait retraining studies employing any mode of RTB (e.g., video, auditory, etc.) were included. If applicable, a control group was defined as a group not receiving gait retraining or any other type of intervention. Inclusion of uncontrolled trials, primarily focusing on interventions of healthy individuals, was considered relevant due to the information it can provide for future randomized controlled trials. Studies must have included one of the following outcomes: (1) KAM, (2) knee pain, (3) self-reported physical function (Bellamy et al., 1997).

An electronic search was conducted using the following databases: PubMed, EBSCO host (CINAHL, Medline, SPORTDiscus), Embase, PROQuest, and Cochrane [1970 to January 1, 2016]. Searches were limited to full-text accessible, peer-reviewed, and English-language results only. The results were collated and duplicates removed. A CONSORT flow chart depicts the process used (Figure 1). In each database, five search terms were utilized (1."gait AND (training OR retraining OR modification) AND (feedback OR biofeedback) AND (knee OR tibiofemoral)", 2. "gait AND (training OR retraining OR modification) AND (feedback OR biofeedback) AND (knee OR tibiofemoral) AND osteoarthritis", 3 ."gait AND (training OR retraining OR modification) AND (feedback OR biofeedback) AND (knee OR tibiofemoral) AND (load OR "adduction moment" OR "abduction moment")", 4."gait AND (training OR retraining OR modification) AND (feedback OR biofeedback) AND (knee OR tibiofemoral) AND (pain OR "quality of life")", 5. "gait AND (training OR retraining OR modification) AND

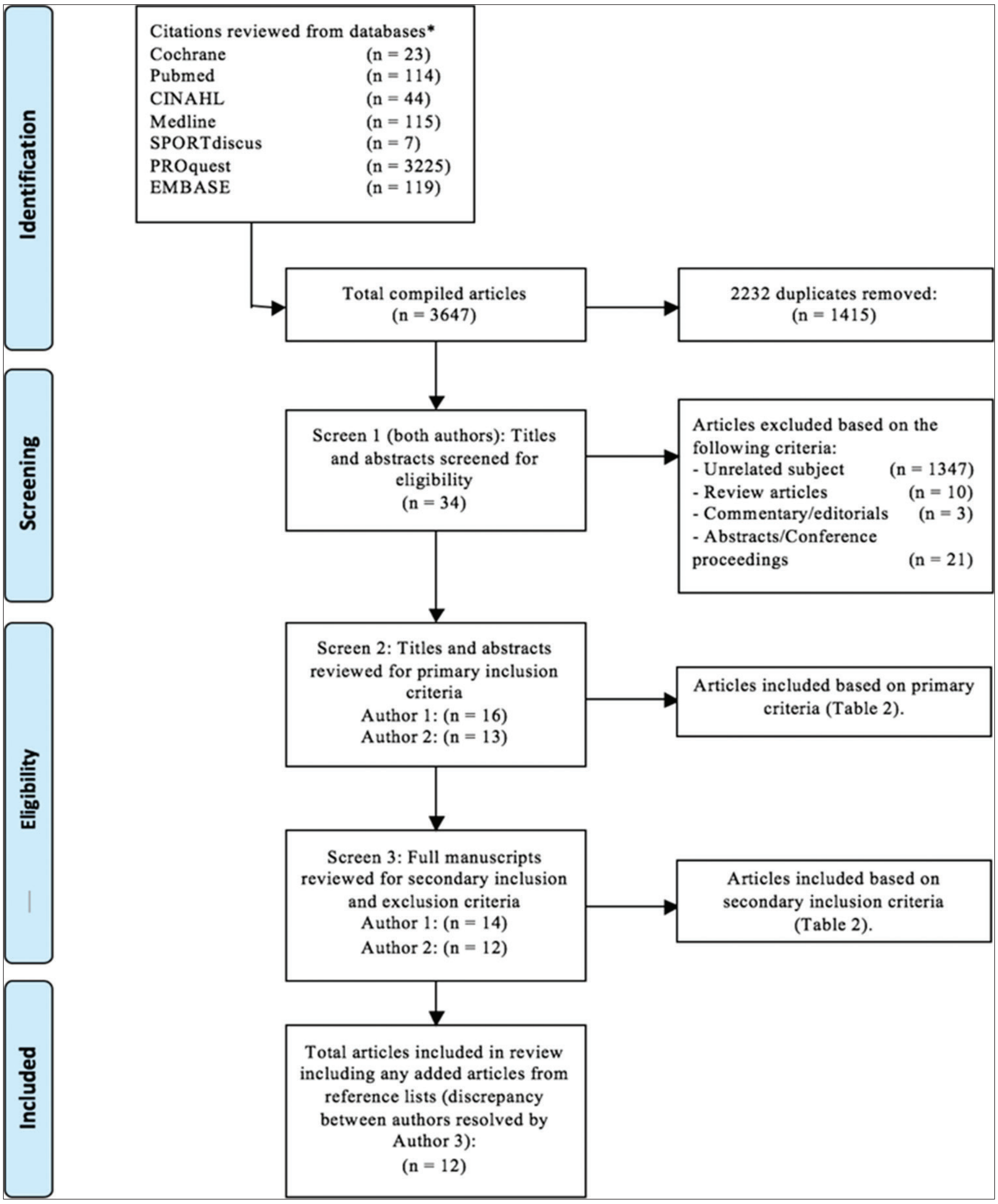

Figure 1. Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) Flow Diagram of search strategy

(feedback OR biofeedback) AND (knee OR tibiofemoral) AND osteoarthritis AND (load OR "knee adduction moment" OR "knee abduction moment") AND (pain OR "quality of life")."

The results of each search term combination were recorded and stored for each database in a bibliographic reference manager software. Duplicates were removed within each database and then across databases. Review articles, commentary/editorials, abstracts/conference proceedings, or articles that were pertaining to an unrelated topic were removed. Two authors independently screened titles and abstracts from the remaining list based on the primary inclusion criteria. Manuscripts of the remaining articles were independently reviewed for secondary inclusion and exclusion criteria. If there was a discrepancy in the articles selected for inclusion, a third author that was blinded from the search process reviewed the selected articles, and determined those that were appropriate for inclusion. Reference lists of the final selected articles were screened for additional articles that may have been missed in the initial search process but met the inclusion criteria, resulting in the final number included.

Methodological quality was assessed using the PEDro Scale which is a criteria list designed to help identify which of the reviewed experiments are likely to be externally valid (criteria 1), internally valid (criteria 2-9) and have sufficient statistical information to make their results interpretable (criteria 10-11) (Fitzpatrick, 2008). Two authors (BL and OE) independently reviewed and rated each study on both scales. Inter-rater disagreements were discussed and resolved in a consensus meeting. Unresolved items were evaluated by a third author (NC). Data were then extracted for each study.

RESULTS

Study Selection

A total of 3,647 citations were initially retrieved. After removal of duplicates, 1,415 citations were screened for initial eligibility. Of the remaining 34 articles, 12 met both primary and secondary inclusion and exclusion criteria. No additional articles were added from the reference lists of selected articles.

Study Characteristics

Eleven of the twelve studies included were designed to test the effects of a gait retraining intervention using RTB on measures of KAM, pain and/or function (Barrios et al., 2010; Dowling, Fisher, et al., 2010; Ferrigno et al., 2016; Hunt, Simic, Hinman, Bennell, & Wrigley, 2011; Segal et al., 2015; Shull et al., 2011; Shull, Shultz, et al., 2013; Shull, Silder, et al., 2013; Simic et al., 2012; van den Noort et al., 2014; Wheeler et al., 2011). The other study aimed to explore how training with a feedback-providing knee brace affected gait, rate of loading, and proprioception, but was included as KAM was reported as an outcome measure (Riskowski, 2010). Ten studies utilized a quasi-experimental within-subjects design (Barrios et al., 2010; Dowling, Corazza, Chaudhari, & Andriacchi, 2010; Ferrigno et al., 2016; Hunt et al., 2011; Riskowski, 2010; Shull et al., 2011; Shull, Shultz, et al., 2013; Shull, Silder, et al., 2013; Simic et al., 2012; van den Noort et al., 2014), while two employed true experimental designs (Segal et al., 2015; Wheeler et al., 2011), including one randomized controlled trial (Segal et al., 2015). Sample sizes ranged from 8 to 56 participants.

Four tested individuals with knee OA (Segal et al., 2015; Shull, Shultz, et al., 2013; Shull, Silder, et al., 2013; Simic et al., 2012); the remaining eight tested healthy individuals with the goal of developing and informing future studies to be conducted in symptomatic individuals (Barrios et al., 2010; Dowling, Corazza, et al., 2010; Ferrigno et al., 2016; Hunt et al., 2011; Riskowski, 2010; Shull et al., 2011; van den Noort et al., 2014; Wheeler et al., 2011). In studies evaluating symptomatic individuals, radiographic evidence of medial compartment OA was used to confirm the presence and severity of the disease using the Kellgren and Lawrence scale (Shull, Shultz, et al., 2013; Shull, Silder, et al., 2013). A verbal confirmation of knee pain was an additional diagnostic criterion (Segal et al., 2015; Shull, Silder, et al., 2013; Simic et al., 2012). Nine studies employed a single session design (Dowling, Corazza, et al., 2010; Ferrigno et al., 2016; Hunt et al., 2011; Riskowski, 2010; Shull et al., 2011; Shull, Shultz, et al., 2013; Simic et al., 2012; van den Noort et al., 2014; Wheeler et al., 2011) with three performing a single intervention trial (Riskowski, 2010; Shull, Shultz, et al., 2013; Wheeler et al., 2011). Six of these studies tested gait under multiple conditions to compare different types of gait strategies (Ferrigno et al., 2016; Shull et al., 2011) and feedback (Dowling, Fisher, et al., 2010; van den Noort et al., 2014), as well as varying magnitudes (Hunt et al., 2011; Simic et al., 2012). Only three studies were conducted over multiple sessions and included follow-up testing to assess retention (Barrios et al., 2010; Segal et al., 2015; Shull, Silder, et al., 2013).

Gait Retraining Interventions

Eleven gait modification strategies were identified across the twelve studies. Four studies evaluated the effects of modifying trunk position (Hunt et al., 2011; Shull et al., 2011; Shull, Silder, et al., 2013; Simic et al., 2012) with two testing trunk sway (Shull et al., 2011; Shull, Silder, et al., 2013), and two evaluating trunk lean (Hunt et al., 2011; Simic et al., 2012). Three studies investigated reduced foot progression angle (Shull et al., 2011; Shull, Shultz, et al., 2013; Shull, Silder, et al., 2013), two studies utilized a weight shift to the medial side of the foot during the stance portion of gait (Dowling, Corazza, et al., 2010; Ferrigno et al., 2016), and two allowed participants to self-select the kinematic adjustment to reduce KAM (van den Noort et al., 2014; Wheeler et al., 2011).

Other gait modification strategies included medial knee thrust (Barrios et al., 2010); reduced rate of loading through increased knee flexion and decreased vertical acceleration (Riskowski, 2010); gait retraining towards symmetrical and typical displacements of the trunk and pelvis (Segal et al., 2015), and multi-parameter gait retraining through a combination of altered foot progression angle, increased trunk sway, and increased tibia angle (Shull et al., 2011).

Biofeedback

Visual, haptic, and auditory real-time biofeedback or a combination was used to implement gait modification strategies. The two most common biofeedback techniques were visual (Barrios et al., 2010; Hunt et al., 2011; Segal et al., 2015; Shull et al., 2011; Simic et al., 2012; van den Noort et al., 2014; Wheeler et al., 2011) and haptic (Dowling, Corazza, et al., 2010; Shull et al., 2011; Shull, Shultz, et al., 2013; Shull, Silder, et al., 2013; Wheeler et al., 2011). Two studies employed auditory biofeedback (Ferrigno et al., 2016; Riskowski, 2010).

Outcome Assessment

Ten studies reported KAM as the primary outcome measure (Barrios et al., 2010; Dowling, Corazza, et al., 2010; Ferrigno et al., 2016; Hunt et al., 2011; Shull et al., 2011; Shull, Shultz, et al., 2013; Shull, Silder, et al., 2013; Simic et al., 2012; van den Noort et al., 2014; Wheeler et al., 2011). Of these, three studies with OA participants reported measures of pain, and function such as the Western Ontario McMaster Universities OA Index (WOMAC) and visual analog pain scales (VAS) (Hunt et al., 2011; Shull, Silder, et al., 2013; Simic et al., 2012). Seven studies reported additional kinetic and temporospatial variables including KFM (Ferrigno et al., 2016; Riskowski, 2010; Shull, Shultz, et al., 2013; Shull, Silder, et al., 2013), KAM impulse (Simic et al., 2012; van den Noort et al., 2014), stride speed (Ferrigno et al., 2016; Hunt et al., 2014; Riskowski, 2010; Simic et al., 2012), and stride length (Ferrigno et al., 2016; Riskowski, 2010; Simic et al., 2012). Four studies using healthy participants reported numerical ratings (0-10) of awkwardness and difficulty in adopting gait modifications (Barrios et al., 2010; Hunt et al., 2011; van den Noort et al., 2014; Wheeler et al., 2011). Two studies did not report KAM as the primary outcome measure (Riskowski, 2010; Segal et al., 2015). One reported proprioceptive acuity and rate of loading (ROL) as primary outcome measures with KAM being used to determine differences in training gait with and without a feedback based knee brace (Riskowski, 2010). The other did not measure KAM, instead focusing on outcome measures associated with pain and function such as Late-Life Function and Disability Basic Lower Limb Function (LLFDI) score, Knee Injury/Osteoarthritis Outcome (KOOS) score, and mobility tests (Segal et al., 2015). All eleven studies that reported KAM evaluated the overall or first peak during stance. Four studies also reported second peak KAM (Ferrigno et al., 2016; Hunt et al., 2011; Shull, Shultz, et al., 2013; Simic et al., 2012), and one study reported peak KAM at mid-stance in addition to first and second peak KAM (van den Noort et al., 2014).

Quality and Bias Assessment

The mean (±SD) PEDro score was 6.1±0.7 out of a possible 11 (Table 1). While most studies scored well regarding external validity (criterion 1) and statistical information (criteria 10 and 11), internal validity was poor across all studies (criteria 2 through 9). Specifically, all studies scored a zero on blinding of subjects, therapists, and assessors (criteria 5, 6, and 7, respectively). Additionally, eight studies scored a zero on random allocation (criterion 2), while eleven studies scored zeros on allocation concealment (criterion 3).

Definition of criteria as in Fitzpatrick 2008

1. Eligibility criteria were specified
2. Subjects were randomly allocated to groups (in a cross-over study, subjects were randomly allocated an order in which treatments were received)
3. Allocation was concealed
4. The groups were similar at baseline regarding the most important prognostic indicators
5. There was blinding of all subjects
6. There was blinding of all therapists who administered the therapy
7. There was blinding of all assessors who measured at least one key outcome
8. Measures of at least one key outcome were obtained from more than 85% of the subjects initially allocated to groups
9. All subjects for whom outcome measures were available received the treatment or control condition as allocated, or where this was not the case, data for at least one key outcome was analyzed by "intention to treat"
10. The results of between-group statistical comparisons are reported for at least one key outcome
11. The study provides both point measures and measures of variability for at least one key outcome

Synthesis of Results

Benefit of gait retraining using RTB on individuals with knee OA

Three (Shull, Shultz, et al., 2013; Shull, Silder, et al., 2013; Simic et al., 2012) of the four studies conducted on OA patients reported smaller but still significant reductions in KAM compared to healthy individuals, ranging from 9.3% (Simic et al., 2012) to a maximum of 20% (Shull, Silder, et al., 2013) (Table 2). Of these studies, self-selected gait retraining that Allowed participants to choose between using a combination of both altered foot progression and trunk sway angle or only altered foot or trunk sway angle, resulted in the greatest average reduction in KAM (Shull, Silder, et al., 2013). Increased trunk lean resulted in average KAM reductions between 9.3% and 14.9% depending on the magnitude of lean (Simic et al., 2012) while toe-in gait reduced KAM by 13% (Shull, Shultz, et al., 2013). Two studies employed real-time visual feedback (Shull, Shultz, et al., 2013; Shull, Silder, e ., 2013) while the other two used real-time haptic feedback (Segal et al., 2015; Simic et al., 2012) with participants responding equally well to both modes of feedback. All four studies measured pain and function related outcome measures including WOMAC (Shull, Silder, et al., 2013), KOOS (Segal 2015), LLFDI (Segal et al., 2015), and VAS scales (Shull, Silder, et al., 2013; Simic et al., 2012) (Table 3). Ratings of pain and function were significantly improved in all studies but one which was a single session design (Simic et al., 2012). Improvements in WOMAC pain and function were retained at the 1-month

Table 1. PEDro scores of included studies in systematic review (Fitzpatrick, 2008)

	1	2	3	4	5	6	7	8	9	10	11	Total
Barrios et al. (2010)	1	0	0	1	0	0	0	1	1	1	1	6
Dowling et al. (2010)	1	1	0	1	0	0	0	1	1	1	1	7
Ferrigno et al. (2016)	1	1	0	1	0	0	0	1	1	1	1	7
Hunt et al. (2011)	1	0	0	1	0	0	0	1	1	1	1	6
Riskowski (2010)	1	0	0	1	0	0	0	1	1	1	1	6
Segal et al. (2015)	1	1	1	1	0	0	0	0	1	1	1	7
Shull et al. (2011)	0	0	0	1	0	0	0	1	1	1	1	5
Shull et al. (2013a)	1	0	0	1	0	0	0	1	1	1	1	6
Shull et al. (2013b)	1	0	0	1	0	0	0	1	1	1	1	6
Simic et al. (2012)	1	0	0	1	0	0	0	1	1	1	1	6
Van den Noort et al. (2014)	0	0	0	1	0	0	0	1	1	1	1	5
Wheeler et al. (2011)	0	1	0	1	0	0	0	1	1	1	1	6

Table 2. Extracted data from included studies

Author (year)	Gait modification	Natural Gait: Mean value of target parameter	Modified gait: Mean value of target parameter	KAM unit of measure	Biofeedback variable	KAM outcome reported	Natural gait: mean±SD KAM	Modified gait: mean±SD KAM	Calculated % KAM change	Primary Findings
Barrios et al. (2010)	Medial knee thrust	Knee adduction angle: 6.8±2.4°	Post-training: Natural: 6.2±2.2° Modified: 5.0±2.1° 1-month: Natural: 6.6±1.4° Modified: 5.5±2.2°	Nm/kg*Ht	Visual; knee angle	KAM	0.43±0.07	Post-training: Natural: 0.42±0.05 Modified: 0.34±0.07 1-month: Natural: 0.44±0.06 Modified: 0.34±0.07	 –2* –20 2* –20	Medial knee thrust significantly reduced KEAM, however at 1-month natural gait remained unchanged although participants could replicate learned gait with similar reductions in KEAM found at post-training.
Dowling et al. (2010)	Weight transfer to medial foot	NR	NR	%BW*Ht	Haptic; lateral foot pressure	KAM 1	Haptic feedback group: 2.54±0.56 Verbal instruction group: 2.48±0.40	2.18±0.57 2.29±0.55	–14.2 –8.3	A slight weight bearing shift to the medial side of the foot during gait using real-time haptic biofeedback reduced first peak KAM.
Ferrigno et al. (2016)	Medial thrust gait and limited lateral foot pressure via pressure based feedback	NR	NR	%BW*Ht	Auditory; lateral foot pressure	KAM, KAM 1, KAM 2	3.03±0.86 1.74±0.76 2.99±0.88	Medial thrust: KAM: 2.66±0.95 KAM 1: 1.08±0.72 KAM 2: 2.64±0.98 Pressure based feedback: KAM: 2.66±0.85 KAM 1: 1.58±0.72 KAM 2: 2.63±0.87	 –12 –38 –11.7 –12 –9.2 –12	Pressure-based feedback is equally effective as 'medial thrust gait' in lowering KAM in healthy subjects without the unknown and potentially negative outcomes of other gait modifications.
Hunt et al. (2011)	Lateral trunk lean	Lateral trunk lean 2.6±1.6°	4° lean: 5.0±0.87° 8° lean: 8.34±1.61° 12° lean: 12.88±1.91°	Nm/BW*Ht%	Visual; trunk angle	KAM 1, KAM 2	4.07±1.64 1.89±0.77	KAM 1: 4° lean: 3.82±1.77 8° lean: 3.37±1.72 12° lean: 3.26±1.64 KAM 2: 4° lean: 1.64±0.96 8° lean: 1.64±1.02 12° lean: 1.60±0.90	Average peak KAM: 4° lean: –7 8° lean: –21 12° lean: –25	A gait pattern incorporating at least 8° of lateral trunk lean is successful in lowering early stance peak KAM compared to normal walking and can be achieved quickly by young healthy individuals using real-time visual biofeedback.

(*Contd...*)

Table 2. (*Continued*)

Author (year)	Gait modification	Natural Gait: Mean value of target parameter	Modified gait: Mean value of target parameter	KAM unit of measure	Biofeedback variable	KAM outcome reported	Natural gait: mean±SD KAM	Modified gait: mean±SD KAM	Calculated % KAM change	Primary Findings
Riskowski (2010)	Reduced rate of loading (ROL)	IC Knee flexion: 1.2±2.2° IC Vertical acceleration: -5.87±1.51°	Training gait (with brace): IC knee flexion: 7.2±1.4° IC vertical acceleration: –4.97±1.29 Post-training (no brace): IC knee flexion: 5.4±1.5° IC vertical acceleration: –4.89±1.05°	BW*Ht	Auditory; knee flexion and vertical acceleration	KAM	0.51±0.07	Training gait (with brace): 0.62±0.05 Post-training (no brace): 0.57±0.07	12.16* 11.18*	Gait retraining with a feedback-based gait monitoring knee brace demonstrated short-term gait and neuromuscular effects while reducing ROL and increasing proprioceptive awareness. However, a concomitant increase in KAM limits the effectiveness of the brace particularly in those with OA.
Segal et al. (2015)	Increased proportioned displacements of the trunk and pelvis for the frontal and transverse axes.	NR	NR	NR	Visual; kinematic measures	NR	NR	NR	NR	In comparison with usual care, three months of individualized physical therapist-supervised gait training reduced self-reported outcomes in older adults with symptomatic knee OA immediately after post-intervention, but it was not retained at 6 or 12-months post-intervention.
Shull et al. (2011)	Foot progression, Trunk sway, Tibia angle using single and multi-parameter models.	Tibia angle: –4.2° Foot progression angle: –5.9° Trunk sway angle: 1.5°	Tibia angle: 3.0° Foot progression angle: 8.4° Trunk sway angle: 9.9°	%BW*Ht	Haptic; trunk, tibia, and foot progression angles	KAM 1	4.1 ± 0.6	2.7±0.6	–36.6*	Data-driven gaits were identified and trained in a single session, lead to a 20-48% reduction in KAM. These findings upkeep the use of localized linear modeling for altered gait identification and real-time haptic feedback.

(*Contd...*)

Table 2. (Continued)

Author (year)	Gait modification	Natural Gait: Mean value of target parameter	Modified gait: Mean value of target parameter	KAM unit of measure	Biofeedback variable	KAM outcome reported	Natural gait: mean±SD KAM	Modified gait: mean±SD KAM	Calculated % KAM change	Primary Findings
										While the change was overall positive, the magnitude of changed varied significantly.
Shull et al. (2013a)	Toe-in gait.	Foot progression angle: KAM 1: 3.3° KAM 2: 3.9°	Foot progression angle: KAM 1: -2.1° KAM 2: -1.4°	%BW*Ht	Haptic; tibia angle	KAM 1, KAM 2	3.28±1.37 1.98±1.14	2.90±1.38 1.94±1.09	–13 –2*	Toe-in gait significantly reduced the first peak of the knee adduction moment, which occurred as the knee joint center shifted medially and the center of pressure shifted laterally. Peak external flexion moment was not increased by toe-in gait modification.
Shull et al. (2013b)	Single and/or multi-gait parameter data driven gait retraining	Foot progression angle: 2.1±4.0° Trunk sway angle: 1.0±2.1°	Foot progression angle: Post-training: –5.1±5.1° 1-month follow-up: –6.0±4.7° Trunk sway angle: Post-training: 0.7±1.6° 1-month follow-up: 0.7±1.5°	%BW*Ht	Haptic; trunk and foot progression angles	KAM 1	3.11±1.40	Post-training: 2.61±1.47 1-month follow-up: 2.67±1.41	–20 –14.1*	The 20% reduction in KAM achieved post-training and 14.1% reduction at follow up shows that the effects of gait modification can be retained over time. No association was found between KAM decrease and knee flexion moment increase. Generally, increased knee flexion moment may eradicate the potential medial compartment force reduction that derives from the decrease in KAM.

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Table 2. (Continued)

Author (year)	Gait modification	Natural Gait: Mean value of target parameter	Modified gait: Mean value of target parameter	KAM unit of measure	Biofeedback variable	KAM outcome reported	Natural gait: mean±SD KAM	Modified gait: mean±SD KAM	Calculated % KAM change	Primary Findings
Simic et al. (2012)	Trunk lean (a peak of 6° lean, 9° lean, and 12° lean)	Peak lateral trunk lean: 2.0° Early stance trunk lean: 0.9° Late stance trunk lean: 0.8°	Peak trunk lean: 6° lean: 6.1° 9° lean: 8.7° 12° lean: 11.1° Early Stance: 6° lean: 5.1° 9° lean: 7.6° 12° lean: 9.3° Late Stance: 6° lean: 3.0° 9° lean: 4.4° 12° lean: 5.6°	Nm/%BW*Ht	Visual; trunk angle	KAM 1 KAM 2	3.75 2.05	KAM 1: 6° lean: 3.40 9° lean: 3.33 12° lean: 3.19 KAM 2: 6° lean: 1.71 9° lean: 1.69 12° lean: 1.56	KAM 1: 6° lean: –9.3* 9° lean: –11.5* 12° lean: –14.9* KAM 2: 6° lean: –17.1* 9° lean: -18* 12° lean: –23.9*	Increasing lateral trunk lean on the knee OA side can positively reduce the knee load throughout the stance phase of gait.
Van den Noort et al. (2014)	Self-selected gait to reduce KAM and HIR	Early HIR: 1.98±2.69° Mid HIR: 2.52±2.83° Late HIR: 1.92±2.53°	Bar Early: 8.26±2.69° Bar Late: 11.40±2.53° Bar Mid: 10.33±2.83° Polar Early: 10.41±2.78° Polar Late: 12.52±2.61° Polar Mid: 11.27±2.92° Color Early: 8.99±2.78° Color Late: 9.81±2.69° Color Mid: 9.66±3.02° Graph Early: 9.97±2.69° Graph Late: 7.90±2.53° Graph Mid: 9.26±2.83°	%BW*Ht	Visual; KAM and HIR	KAM 1, KAM 2, KAM 3	HIR Feedback: Early: 2.14±0.20 Late: 1.91±0.29 Mid: 1.72±0.22	HIR Feedback: Bar Early: 1.79±0.24 Bar Late: 1.41±0.33 Bar Mid: 1.86±0.25 Polar Early: 1.73±0.24 Polar Late: 1.14±0.32 Polar Mid: 1.54±0.24 Color Early: 1.92±0.25 Color Late: 1.60±0.34 Color Mid: 1.96±0.27 Graph Early: 2.03±0.23 Graph Late: 1.74±0.32 Graph Mid: 1.97±0.24	Bar Early: –16.19 Bar Late: –26.04 Bar Mid: 8.05 Polar Early: –19.22 Polar Late: –40.32 Polar Mid: –10.64 Color Early: –10.07 Color Late: –16.45 Color Mid: 13.75 Graph Early: –4.91 Graph Late: –8.77 Graph Mid: 14.47	Results showed that the gait pattern of healthy subjects can be effectively modified using real-time visual feedback, independently of the type of feedback, however, direct visual feedback of the KAM resulted in greater reductions in peak KAM compared to indirect feedback of HIR. The direction of the gait modifications was also in agreement with the presented modification using visual feedback. Both KAM and HIR were significantly affected during with visual feedback, which decreased KAM by about 50% and the HIR by 6°–10° when compared to baseline

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Table 2. (Continued)

Author (year)	Gait modification	Natural Gait: Mean value of target parameter	Modified gait: Mean value of target parameter	KAM unit of measure	Biofeedback variable	KAM outcome reported	Natural gait: mean±SD KAM	Modified gait: mean±SD KAM	Calculated % KAM change	Primary Findings
							KAM feedback: Early: 2.17±0.25 Late: 2.10±0.16 Mid: 1.91±0.30	KAM feedback: Bar Early: 1.17±0.25 Bar Late: 0.94±0.39 Bar Mid: 0.94±0.30 Polar Early: 0.96±0.26 Polar Late: 0.94±0.34 Polar Mid: 0.94±32 Color Early: 1.20±0.27 Color Late: 0.98±0.36 Color Mid: 0.98±0.33 Graph Early: 1.10±0.26 Graph Late: 1.23±0.30 Graph Mid: 1.23±0.32	Bar Early: -46.08% Bar Late: –55.21% Bar Mid: –50.80% Polar Early: –55.84 Polar Late: –55.00 Polar Mid: –50.57 Color Early: –44.72 Color Late: –53.40 Color Mid: –48.82 Graph Early: –49.48 Graph Late: –41.40 Graph Mid: –35.63	
Wheeler et al. (2011)	Self-selected	NR	NR	%BW*Ht	Visual and haptic; KAM	KAM 1	All participants: 3.98±0.90 Visual: 4.07±0.89 Haptic: 3.90±0.96	All participants: 3.19 ± 0.93 Visual: 3.29±0.98 Haptic: 3.09±0.94	All participants: –20.67% Visual: –20.24 Haptic: –21.11	The study showed that providing real-time feedback of the KAM and allowing subjects to self-select gait modifications was an effective gait retraining method for reducing the KAM.

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Table 2. (Continued)

Author (year)	Gait modification	Natural Gait: Mean value of target parameter	Modified gait: Mean value of target parameter	KAM unit of measure	Biofeedback variable	KAM outcome reported	Natural gait: mean±SD KAM	Modified gait: mean±SD KAM	Calculated % KAM change	Primary Findings

- BW – Body weight
- Ht – Height
- OA – Osteoarthritis
- SD – Standard deviation
- KAM – overall peak knee adduction moment
- KAM 1 – peak knee adduction moment in first half of stance
- KAM 2 – peak knee adduction moment in second half of stance
- KAM 3 – peak knee adduction moment in midstance
- IC – initial contact
- HIR – hip internal rotation angle
- NR – not reported
- * – calculated from data provided

follow up, while improvements in KOOS pain and function and LLFDI scores were retained 12-months post-intervention. Three studies using OA patients measured additional kinetic and temporospatial variables. Two studies reported a reduction in KFM post-training (Shull, Shultz, et al., 2013; Shull, Silder, et al., 2013) that, when tested, was retained at the 1-month follow-up (Shull, Silder, et al., 2013). Lateral trunk lean reduced KAM impulse but did not significantly alter stride speed or length (Simic et al., 2012).

Effects of different gait modifications and modes of biofeedback on healthy individuals

Seven of the eight studies conducted using healthy participants reported a significant reduction in KAM compared to baseline (Barrios et al., 2010; Dowling, Fisher, et al., 2010; Ferrigno et al., 2016; Hunt et al., 2014; Shull et al., 2011; van den Noort et al., 2014; Wheeler et al., 2011). KAM reduction ranged from 7% (Hunt et al., 2014) to 55.8% (van den Noort et al., 2014) with the magnitude of change differing based on gait modification used, mode of biofeedback and study design. Self-selected gait modification showed the greatest reductions in KAM in healthy individuals (van den Noort et al., 2014; Wheeler et al., 2011). Participants who were free to determine their own gait strategy without instruction reduced KAM by an average of 49% (van den Noort et al., 2014), while those who were instructed to select one or any combination of previously studied gait modifications decreased KAM 20.7% (Wheeler et al., 2011). Multi-parameter gait retraining also resulted in a large average reduction in KAM of 36.6% in healthy participants (Shull et al., 2011). Using a data-driven model, Shull et al. (2011) prescribed individual modifications to foot progression, trunk sway, and tibia angle resulting in reductions ranging from 29%-48%. Lateral trunk lean showed increasing reductions in KAM from 7% to 25% based on magnitude of lean (Hunt). Medial knee thrust resulted in an average KAM reduction of 20% which was replicated upon request 1-month post-intervention (Barrios et al., 2010). Gait modifications involving the foot resulted in smaller but still significant reductions in KAM between 9.2% (Ferrigno et al., 2016) and 14.2% (Dowling, Fisher, et al., 2010). An increase in first peak KAM of 12% after training with a feedback-based gait monitoring knee brace was reported (Riskowski, 2010). Of the eight studies investigating healthy participants, three employed visual feedback (Barrios et al., 2010; Hunt et al., 2014; van den Noort et al., 2014), two used haptic (Dowling, Fisher, et al., 2010; Shull et al., 2011), two used auditory (Ferrigno et al., 2016; Riskowski, 2010), and one compared visual and haptic feedback between groups (Wheeler et al., 2011). Participants responded well to both visual and haptic feedback but displayed lesser reductions in KAM with auditory feedback. (Table 2). Only two of the eight studies used direct biofeedback, meaning feedback provided was the dependent variable of interest (KAM) (van den Noort et al., 2014; Wheeler et al., 2011). The remaining studies employed indirect feedback whereby participants were provided feedback based on kinematic measures such as joint angle (Barrios et al., 2010; Hunt et al., 2014; Riskowski, 2010; Shull

Table 3. Extracted data from other outcome measures

Outcome measure	Author (year)	Natural gait: Mean value of target variable	Modified gait: Mean value of target variable	Calculated % change	Findings
Kinetic:					
KFM (%BW*Ht)	Ferrigno et al. (2016)	3.01±1.50	Medial knee thrust: 4.02±1.98 Pressure based feedback: 2.79±1.25	33.55* −7.31*	KFM was reduced concomitantly with peak KAM during toe-in gait, medial weight shift gait, and multi-parameter gait (option of altering foot progression or trunk sway angle). Similar to KAM, KFM showed a continued reduction 1-month post-training following multi-parameter gait retraining. In comparison, medial knee thrust gait, and altered gait using a feedback-based monitoring knee brace increased KFM suggesting that different gait modifications may have different effects on KFM.
	Riskowski (2010)	0.29±0.05	Training gait (with brace): 0.31±0.03 Post-training (no brace): 0.31±0.04	6.9* 6.9*	
	Shull et al. (2013a)	1.48±1.45	1.29±1.39	−12.84*	
	Shull et al. (2013b)	1.95±0.76	Post-training: 1.67±0.75 One-month: 1.43±0.70	−14.36* −26.66*	
KAM impulse (Nm.s/%BW*Ht)	Simic et al. (2012)	1.22	6° lean: 1.05 9° lean: 1.03 12° lean: 0.96	−13.95* −15.57* −21.31*	KAM impulse was reduced when walking with increased lateral trunk lean and during self-selected gait. Like KAM, the reductions in KAM impulse increase with increasing magnitude of trunk lean. During self-selected gait, reductions in KAM impulse were similar to those seen in KAM with direct visual feedback (KAM) providing the greatest reductions in KAM impulse.
	Van den Noort et al. (2014)	KAM feedback: 1.21±0.17 HIR feedback: 1.17±0.13	KAM feedback: Bar: 0.63±0.17 Polar: 0.47±0.18 Color: 0.67±0.19 Graph: 0.62±0.18 HIR feedback: Bar: 0.98±0.15 Polar: 0.90±0.15 Color: 1.10±0.16 Graph: 1.17±0.15	 −48.17 −61.02 −44.81 −49.24 −16.77 −23.26 −6.38 −0.34	
Temporospatial:					
Stride speed (m/s)	Ferrigno et al. (2016)	1.31±0.13	Medial knee thrust: 1.17±0.15 Pressure based feedback: 1.26±0.15	−10.69* −3.82*	Stride speed was minimally reduced during all gait modifications apart from a small increase during increased lateral trunk lean of 6° and more significantly during medial knee thrust. The complexity of medial knee thrust suggests that more difficult gait modifications may require a slower speed.
	Hunt et al. (2011)	1.42 ±0.18	4° lean: 1.36±0.19 8° lean: 1.36±0.19 12° lean: 1.40±0.19	−4.23* −4.23* −1.41*	

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Table 3. (Continued)

Outcome measure	Author (year)	Natural gait: Mean value of target variable	Modified gait: Mean value of target variable	Calculated % change	Findings
	Riskowski (2010)	1.28±0.05	Training gait (with brace): 1.26±0.04 Post-training (no brace): 1.27±0.03	1.56* –0.78*	
	Simic et al. (2012)	1.24	6° lean: 1.25 9° lean: 1.24 12° lean: 1.23	0.81* –0* –0.81*	
Stride length (m)	Ferrigno et al. (2016)	1.37±0.12	Medial knee thrust: 1.32±0.12 Pressure based feedback: 1.35±0.12	–3.64* –1.46*	Stride length was minimally reduced but not significantly altered across all gait modifications studied.
	Riskowski (2010)	1.35±0.12	Training gait (with brace): 1.30±0.08 Post-training (no brace): 1.30±0.14	–3.70* –3.70*	
	Simic et al. (2012)	1.35	6° lean: 1.33 9° lean: 1.34 12° lean: 1.34	–1.48* –0.74* –0.74*	
Subjective Rating:					
Difficulty/effort (0/10)	Barrios et al. (2010) 0 – "Effortless" 10 – "Max effort"	Session 1: 6.63±1.83†	Session 8: 2.94±0.94†	–55.66*	Participants reported moderate difficulty adopting medial knee thrust, lateral trunk lean, and self-selected gait. However, by the last session of an 8-week intervention using medial knee thrust, participants reported reduced ratings of difficulty, suggesting that walking with a new gait should become easier with practice.
	Hunt et al. (2011) 0 – "No difficulty" 10 – "Max difficulty"	N/A	4° lean: 3±3 8° lean: 3±1 12° lean: 4±2	N/A N/A N/A	
	Van den Noort et al. (2014) 1 – "Very difficult" 10 – "Very easy"	N/A	KAM feedback: Bar: 6.3±1.5 Polar: 5.8±2.0 Color: 6.8±1.8 Graph: 5.9±2.3	N/A N/A N/A N/A	

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Table 3. (Continued)

Outcome measure	Author (year)	Natural gait: Mean value of target variable	Modified gait: Mean value of target variable	Calculated % change	Findings
			HIR feedback: Bar: 6.0±1.7 Polar: 6.1±2.5 Color: 5.9±2.4 Graph: 6.4±1.8	 N/A N/A N/A N/A	
Awkwardness/ Intuitive (0/10)	Barrios et al. (2010) 0 – "Natural" 10 – "Maximally unnatural"	Session 1: 7.06±0.78†	Last session: 3.88±1.64†	–45.04*	Participants reported altered gait as moderately awkward during both medial knee thrust and self-selected gait suggesting that adopting a new gait may feel equally as awkward if it is prescribed or chosen by the participant. Similar to ratings of difficulty/effort,
	Wheeler et al. (2011) 0 – "No different" 10 – "Extremely awkward"	N/A	All participants: 5.31±2.27 Visual: 5.25±1.98 Haptic: 5.38±2.67	N/A N/A N/A	
PROM:					
KOOS pain	Segal et al. (2015)	62.7±10.8	3-month: 70.9 6-month: 68.1 12-month: 72.8	13.07* 8.61* 16.12*	Participant reporting of knee pain, symptoms, and lower extremity function were improved across all conditions. These improvements were retained at 1, 3, 6, and 12-months post-intervention, however, improvements in LLFDI and KOOS symptoms scores were no different between the intervention and control group past 3 months.
KOOS symptoms	Segal et al. (2015)	60.1±16.8	3-month: 71.6 6-month: 68.2 12-month: 68.6	19.13* 13.48* 14.14*	
LLFDI	Segal et al. (2015)	65.8±9.2	3-month: 69.1 6-month: 68.9 12-month: 69.7	5.02* 4.71* 5.93*	These results suggest that gait retraining interventions designed to reduce KAM can translate to improvements in patient reported pain and function. These changes can also be retained over time but may trend back towards baseline values if the new gait is not continually used.
WOMAC pain	Shull et al. (2013b)	70.5†	Post-training: 85.0† One-month: 90.0†	20.57* 27.66*	
WOMAC function	Shull et al. (2013b)	77.4†	Post-training: 91.7† One-month: 91.7†	18.48* 18.48*	

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Table 3. (Continued)

Outcome measure	Author (year)	Natural gait: Mean value of target variable	Modified gait: Mean value of target variable	Calculated % change	Findings
VAS (0/10)	Shull et al. (2013b) 0 – “No hurt” 10 – “Hurts worst”	3.2	Post-training: 1.4 1-month: 1.0	–56.25*	Participant reporting of knee pain and discomfort using visual analogue pain scales were not significantly altered over a single day intervention using increased lateral trunk lean, however, over a 6-week intervention pain ratings were more than halved.
	Simic et al. (2012) 0 – “No pain/ discomfort” 10 – “Worst pain/ discomfort”	2.2	6° lean: 2.3 9° lean: 2.2 12° lean: 2.1	4.54* 0* –4.54*	

- BW – Body weight
- Ht – Height
- KFM – Overall peak knee flexion moment during stance
- KAM – Knee adduction moment
- HIR – Hip internal rotation angle
- ROL – rate of loading
- PROM – Pain related outcome measure
- KOOS – Knee injury and osteoarthritis outcome score (scale from 0-100, a score of 100 indicating no symptoms and a score of 0 indicating extreme symptoms)
- LLFDI – Late-life function and disability instrument (scored on a 0 to 100 scale, with higher scores indicating higher levels of function)
- WOMAC – Western Ontario and McCaster Universities Osteoarthritis Index (scale from 0-100, a score of 100 indicating no symptoms and a score of 0 indicating extreme symptoms)
- VAS – Visual analogue scale
- N/A – not applicable
- ± - standard deviation (if reported)
- * – calculated from data provided
- † – Author contacted for data

et al., 2011) and foot pressure (Dowling, Fisher, et al., 2010; Ferrigno et al., 2016).

Half of the studies involving healthy participants also reported subjective ratings of gait modification using visual analogue scales (0/10) (Barrios et al., 2010; Hunt et al., 2014; van den Noort et al., 2014; Wheeler et al., 2011) (Table 3). Three studies showed moderate ratings of difficulty and effort between 3-6.8/10 when adopting a modified gait (Barrios et al., 2010; Hunt et al., 2014; van den Noort et al., 2014) with a third of healthy participants in one study reporting some form of pain or discomfort during the intervention (Hunt et al., 2014). Participants in two studies rated how awkward and or unnatural adopting a modified gait was with scores ranging from 5.25-7/10 (Barrios et al., 2010; Wheeler et al., 2011). However, participants using medial knee thrust reported that both effort and naturalness of the new gait improved by greater than 3/10 by the end of the 8-week intervention (Barrios et al., 2010).

Four studies using healthy participants measured additional kinetic and temporospatial variables. One study reported an increase in KFM during and after using a feedback providing knee brace designed to reduce rate of loading (ROL) (Riskowski, 2010), while a second study showed a reduction in KFM when using pressure-based feedback to reduce lateral plantar pressure, but an increase in KFM during medial knee thrust gait (Ferrigno et al., 2016). KAM impulse was reduced with both lateral trunk lean (Simic et al., 2012), and self-selected gait (van den Noort et al., 2014). Stride speed and length were minimally reduced, but not significantly changed (Hunt et al., 2014; Riskowski, 2010) except with medial knee thrust which reduced gait speed by an average of 10.69% (Ferrigno et al., 2016).

DISCUSSION

The first aim of this review is to determine if gait retraining using real-time biofeedback are beneficial in reducing KAM, pain, and improving function in patients with knee OA. Analysis of the available literature revealed a lack of high quality evidence, as most studies employed lower level of evidence designs (e.g., quasi-experimental) using young, healthy individuals, with only a few experimental designs studying symptomatic populations. A high degree of heterogeneity was also noted among the studies, with multiple gait modification strategies and real-time feedback modes being employed. Nonetheless, all studies that measured KAM in OA participants (n=4) reported significant reductions post-training (Shull, Shultz, et al., 2013; Shull, Silder, et al., 2013; Simic et al., 2012) suggesting that gait retraining using real-time biofeedback can be beneficial in reducing KAM in some patients with knee OA. There is also limited evidence that gait modification using RTB can reduce pain, and improve function in individuals with knee OA (Segal et al., 2015; Shull, Silder, et al., 2013). The only randomized controlled trial included in the review reported significant improvements in knee pain, symptoms and functional tasks after a 12-week intervention involving intermittent visual RTB designed to make postural adjustment and reinforce correct gait patterns (Segal et al., 2015). WOMAC pain and function scores showed similar improvements after a 6-week intervention also using visual RTB (Shull, Silder, et al., 2013). These effects lasted up to 12 and 1 months, respectively, suggesting that gait retraining with RTB can have long-term clinical benefits in OA patients. The present evidence is limited to 2 studies and 66 participants, however, and therefore must be interpreted with caution. Future studies should focus on longitudinal designs assessing the short and long-term functional outcomes of OA patients after gait retraining interventions using RTB.

The second aim of this review was to evaluate the effectiveness of different gait modifications and modes of RTB in reducing KAM in healthy individuals. Self-selected gait displayed the greatest change in KAM in healthy individuals. Evidence suggests that reduction in KAM per unit of gait modification is highly variable among participants, signifying that individual dose-response relationships exist (Favre, Erhart-Hledik, Chehab, & Andriacchi, 2016; Gerbrands, Pisters, & Vanwanseele, 2014). As an example, individual reductions in KAM ranged from as little as 3% to more than 50% within the same gait retraining protocol (Wheeler et al., 2011). These results indicate that the optimal gait modification strategy will differ between individuals, meaning interventions may be most effective when adapted to each patient. Entire adaptability to self-select gait modification may not be clinically beneficial, however, as patients may adopt highly variable and inefficient strategies that are not sustainable and increase other biomechanical measures associated with the development of knee OA (Walter et al., 2010). Participants that self-selected their gait modification strategy without further instruction, exhibited 35% of additional modifications such as increased or decreased foot progression angle greater than 15°, increasing step width by greater than 10 cm, and larger knee flexion, hip abduction, and pelvic protraction (van den Noort et al., 2014). Gait modifications to moderate KAM have been shown to have kinematic, kinetic, and spatiotemporal effects across the kinetic chain, yet long-term outcomes due to these changes remain poorly understood (Simic et al., 2011).

Multi-parameter gait modification showed greater reductions in KAM when compared to single parameter and may offer a practical and effective medium between self-selected and single-parameter gait. Recently, it was reported that secondary changes such as increased step width occurred with up to 60% of the amplitude of the instructed modification when using a single parameter strategy (Favre et al., 2016). When participants combined three gait modifications (toe-in, increased step width, and increased trunk sway) a decrease in first peak KAM of approximately 49% was reported, leading the authors to suggest that gait retraining should be addressed as a general scheme as opposed to focusing on a single gait modification (Favre et al., 2016). Multi-parameter strategies may represent an optimum approach to a natural concomitant relationship of the kinetic chain, whereas employing a single variable self-selected strategy appears to lead to unanticipated and unintended outcomes. Single parameter strategies, such as lateral trunk lean, medial knee thrust, and medial weight shift were less effective in reducing KAM than both self-selected and multi-parameter strategies. Employing lateral trunk lean and medial knee thrust, which require substantial and complex adjustments may be less clinically beneficial due to the difficulty of adoption, particularly with OA participants (Barrios et al., 2010; Hunt et al., 2011; Shull et al., 2011; Shull, Silder, et al., 2013). In comparison, medial weight transfer is easier to adopt as it requires only a subtle change in gait and has not been associated with a concomitant increase in KFM unlike other gait modification strategies (Ferrigno et al., 2016; Gerbrands et al., 2014; Walter et al., 2010). Nonetheless, reported reductions in KAM of 9% to 14% when using medial weight transfer is only slightly greater than those observed in orthotic interventions, reducing clinical impact compared to other modification strategies (Hinman, Bowles, Payne, & Bennell, 2008; Kean, Bennell, Wrigley, & Hinman, 2013).

Visual biofeedback provided the greatest reduction in KAM in healthy individuals. Concurrent visual feedback has been effective in rehabilitation of complex motor skills (J. Y. Chang, Chang, Chien, Chung, & Hsu, 2007; Snodgrass, Rivett, Robertson, & Stojanovski, 2010). Yet, the guidance hypothesis states that continued concurrent feedback can be detrimental for long-term retention and that terminal feedback must be introduced to encourage internalization of the new skill (Bernier, Chua, & Franks, 2005; Heuer & Hegele, 2008; Sülzenbrück & Heuer, 2011). Considering this factor, Barrios et al. implemented a fading feedback paradigm and reported no changes in KAM from post-training to 1-month post-training, showing that participants retained the reductions in KAM from gait retraining. For older adults, more susceptible of knee OA, it has been described that they may benefit from receiving only concurrent visual feedback as they remain in an attention-demanding phase of learning longer than their younger counterparts (Wishart, Lee, Cunningham, & Murdoch, 2002). We did not find any studies directly comparing visual, haptic, and auditory feedback, but prior motor learning research suggests that concurrent visual feedback to be preferable for older adults attempting to learn a complex motor skill (Sigrist, Rauter, Riener, & Wolf, 2013). Surprisingly, only two studies used KAM as the biofeedback variable (van den Noort et al., 2014; Wheeler et al., 2011); the majority used kinematic measures (Barrios et al., 2010; Ferrigno et al., 2016; Hunt et al., 2011; Segal et al., 2015; Shull et al., 2011; Shull, Shultz, et al., 2013; Shull, Silder, et al., 2013; Simic et al., 2012). Studies employing KAM as the biofeedback variable resulted in the greatest reductions in KAM, suggesting a better response to biofeedback based on the target kinetic parameter, compared to a surrogate kinematic measure.

The final aim of this review was to assess the impact of gait retraining interventions using RTB on other variables that may affect clinical outcomes. Additional outcome variables that were clinically relevant and were reported in at least more than one study were identified (Table 3). Increased KFM compressive loads at the knee joint (Walter et al., 2010) and is a significant predictor of joint load even after accounting for variance attributed to KAM (Manal et al., 2015). Reductions in KFM were seen with self-selected (Shull, Silder, et al., 2013) and toe-in gait (Shull, Shultz, et al., 2013) in OA participants and with medial weight shift in healthy individuals (Ferrigno et al., 2016). In contrast, walking with a feedback monitoring knee brace designed to reduce ROL (Riskowski, 2010) and medial knee thrust (Ferrigno et al., 2016) increased KFM. The increase in KFM seen with the use of the feedback monitoring brace may be explained by the fact that the primary purpose of the study was to explore how training with the knee brace affected ROL and proprioceptive acuity, with KAM only being a secondary outcome measure (Riskowski, 2010). However, participants who performed both medial knee thrust and medial weight shift gait in the same study showed opposing effects on KFM despite the fact both interventions were designed to reduce KAM (Ferrigno et al., 2016). This supports the finding that KAM and KFM are not correlated (Manal et al., 2015), suggesting that different gait modifications, regardless of similar effects on KAM, can have varying effects on KFM. It is important that gait retraining interventions do not offset the benefits of reduced KAM with equal or greater increases in KFM. Future research should identify which strategies are most beneficial in terms of both KAM and KFM. KAM impulse integrates the magnitude of KAM and the duration over which KAM acts providing a measure of total mechanical loading during walking as opposed to load only at one instance in time (Creaby et al., 2010; Kean et al., 2012). Similar to KFM, it is important that reduction in KAM does not coincide with increased KAM impulse as it has been associated with the severity and prevalence of cartilage defects (Creaby et al., 2010) as well as knee pain (Robbins et al., 2011). Both increased lateral trunk lean in OA participants (Simic et al., 2012) and self-selected gait in healthy participants (van den Noort et al., 2014) reduced KAM impulse. Though evidence is limited, this suggests that KAM impulse may be more closely correlated with KAM than KFM. More research is needed to determine the relationship between these variables and the impact different gait modifications have on KAM impulse. Stride speed and length remained relatively unchanged across all studied gait modifications (Hunt et al., 2014; Riskowski, 2010; Simic et al., 2012) apart from medial knee thrust (Ferrigno et al., 2016). This can be attributed to the fact that gait speed was controlled to be within 5% of self-selected baseline speeds (Hunt et al., 2014; Riskowski, 2010; Simic et al., 2012). The one study that did not control for gait speed showed a significant reduction during medial knee thrust gait. This may be attributable to the complexity of the gait modification which involves participants to adduct and generate an internal rotation of the hip while concurrently increasing hip, knee, and ankle flexion angles. Reduced stride speed has been argued to be both beneficial and detrimental to patients with knee OA. It has been theorized that slower gait speed may reduce KAM by altering vertical and frontal plane center of mass acceleration, thus reducing the magnitude of the ground reaction force (Browning & Kram, 2007). However, study results do not consistently support this (Simic et al., 2012), as others report that slower gait speeds increase KAM impulse (Robbins & Maly, 2009). Reduced stride length, on the other hand, has been suggested to provide small reductions in KAM impulse due to less time spent during stance in gait (Russell et al., 2010). Similar to gait speed, stride length was not significantly changed as a result of gait retraining. However, future studies should investigate if there is a significant change in these parameters when gait speed is not controlled for, such as the results seen during medial knee thrust, as gait speed is not easily controlled outside of the lab. Limitations of the included studies weakens the clinical applications of these findings. Most studies included in this review provided low quality evidence due to methodological decisions; study design, lack of controls, and small sample sizes. Eight studies recruited young, healthy participants diminishing generalizability to symptomatic individuals (Barrios et al., 2010; Dowling, Corazza, et al., 2010; Ferrigno et al., 2016; Hunt et al., 2011; Riskowski, 2010; Shull et al., 2011; van den Noort et al., 2014; Wheeler et al., 2011). Participant follow-up was limited to three studies, one of which reported the average percentage of time healthy participants spent walking with the modified gait outside of the lab at only 11% (Barrios et al., 2010). Participants reported completing 97% (Shull, Silder, et al., 2013) and 92.4% (Segal et al., 2015) of prescribed at-home gait training in the other two studies, suggesting participant compliance is feasible in long-term interventions. Almost all studies scored poorly regarding internal validity. These scores reflect the quasi-randomized and uncontrolled nature of most of the included studies. The sole RCT included in this review did not require blinding of participants or testers (Segal et al., 2015), and of the four studies to employ random allocation in their study design, none concealed allocation to groups (Dowling, Corazza, et al., 2010; Ferrigno et al., 2016; Segal et al., 2015; Wheeler et al., 2011). Interaction effects make it difficult to separately assess the magnitude of KAM reduction by gait modification type and mode of RTB as the RTB mode may appear to reduce KAM more because of the gait modification it was combined with and vice versa. Publication bias may also have affected the results of this review as studies that report significant or positive results are more likely to be published (Dwan, Gamble, Williamson, & Kirkham, 2013).

CONCLUSION

First peak KAM has been repeatedly associated with knee OA progression, therefore, a non-surgical intervention capable of reducing KAM has profound clinical implications on patients suffering from or at risk of knee OA. Overall, the evidence presented in this review demonstrates that gait modification with RTB may successfully reduce KAM in both symptomatic and asymptomatic participants. However, the existing literature is limited and of low quality, denoting that combination of modification strategy and biofeedback remains uncertain. Future studies should employ randomized, controlled study designs to compare the effects of different gait modification strategies and biofeedback modes across groups (healthy and knee OA) while including additional outcome measures that may affect clinical outcomes. The currently available evidence suggests that self-selected gait modification using multiple gait variables in conjunction with visual RTB may provide the greatest reductions in KAM in healthy individuals.

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