Archives of Rehabilitation Research and Clinical Translation (2019) 1, 100022

ACRM
AMERICAN CONGRESS OF REHABILITATION MEDICINE

Archives of Rehabilitation Research and Clinical Translation

Archives of Rehabilitation Research and Clinical Translation 2019;1:100022

Available online at www.sciencedirect.com

Systematic Review and Meta-Analysis

Does Gait Retraining Have the Potential to Reduce Medial Compartmental Loading in Individuals With Knee Osteoarthritis While Not Adversely Affecting the Other Lower Limb Joints? A Systematic Review

Jake Bowd, MSc [a,b], Paul Biggs, PhD [a,b], Cathy Holt, PhD [a,b], Gemma Whatling, PhD [a,b]

[a] *College of Physical Sciences and Engineering, Cardiff University, Cardiff, United Kingdom*
[b] *Biomechanics and Bioengineering Research Centre Versus Arthritis, Cardiff University, Cardiff, United Kingdom*

KEYWORDS
Gait;
Osteoarthritis, knee;
Rehabilitation;
Systematic review

Abstract *Objectives:* To review the literature regarding gait retraining to reduce knee adduction moments and their effects on hip and ankle biomechanics.
Data Sources: Twelve academic databases were searched from inception to January 2019. Key words "walk*" OR "gait," "knee" OR "adduction moment," "osteoarthriti*" OR "arthriti*" OR "osteo arthriti*" OR "OA," and "hip" OR "ankle" were combined with conjunction "and" in all fields.
Study Selection: Abstracts and full-text articles were assessed by 2 individuals against a predefined criterion.
Data Synthesis: Of the 11 studies, sample sizes varied from 8-40 participants. Eight different gait retraining styles were evaluated: hip internal rotation, lateral trunk lean, toe-in, toe-out, increased step width, medial thrust, contralateral pelvic drop, and medial foot weight transfer. Using the Black and Downs tool, the methodological quality of the included studies was fair to moderate ranging between 12 of 25 to 18 of 28. Trunk lean and medial thrust produced the biggest reductions in first peak knee adduction moment. Studies lacked collective sagittal and frontal plane hip and ankle joint biomechanics. Generally, studies had a low

List of abbreviations: EHAM, external hip adduction moment; EKAM, external knee adduction moment; OA, osteoarthritis; SMD, standardized mean difference.
Supported by the School of Engineering at Cardiff University in their commitment to the Biomechanics and Bioengineering Research Centre Versus Arthritis (BBRC VA) (Versus Arthritis [20781]) (PhD funding for Bowd). Funders were not involved with design and conduct of the study; collection, management, analysis, and interpretation of the data; and preparation, review, or approval of the manuscript.
Disclosures: none
Clinical Trial Registration No.: CRD42018085738.
Cite this article as: Arch Rehabil Res Clin Transl. 2019;1:100022.

https://doi.org/10.1016/j.arrct.2019.100022

sample size of healthy participants with no osteoarthritis and assessed gait retraining during 1 laboratory visit while not documenting the difficulty of the gait retraining style.

Conclusions: Gait retraining techniques may reduce knee joint loading; however, the biomechanical effects to the pelvis, hip, and ankle is unknown, and there is a lack of understanding for the ease of application of the gait retraining styles.

Overloading of the medial knee compartment has been strongly associated with osteoarthritis (OA) progression[1] and radiographic disease severity.[2] The parameter of most relevance to medial knee OA is the external knee adduction moment (EKAM).[3] This moment, which acts to force the tibia into varus, has been validated as a reliable indicator of medial knee load.[4] The EKAM reflects medial-to-lateral knee joint load distribution during gait.[5] In the presence of increased EKAM, the medial compartment of the tibial-femoral joint will typically experience increased load.[3]

Numerous potential gait modifications have been proposed to reduce EKAM.[3] These alterations include wide stance gait,[6] toe-out gait,[7,8] toe-in gait,[3] medial thrust gait,[9,10] trunk lean gait,[11] and medial foot weight transfer of the foot.[12] Consequently, gait modifying strategies have been proposed as a conservative strategy to reduce knee joint loading.[3]

The systematic review of Simic et al[3] analyzed gait modification strategies for altering medial knee joint load. Simic[3] concluded that different gait modifications exert different effects on dynamic knee load at varying points throughout the gait cycle. Of the 14 gait modifications identified, medial thrust and trunk lean most consistently reduced first peak EKAM. However, some of the reported results were conflicting and/or based on very few or single studies. In addition, sufficient data were not available to address whether there are any changes at other lower extremity joints with the implementation of gait modifications to reduce EKAM.[3] It has been suggested that an increased loading rate in the lower extremity joints may lead to a faster progression of existing OA and to the onset of OA at joints adjacent to the knee.[3] Therefore, any interventions for knee OA should be assessed for their effects on the mechanics of all joints of the lower extremity. This warrants the current review to establish the body of evidence on how changes to EKAM affects adjacent joints to the knee as a result of modifying an individual's gait. Richards et al[13] outlined the potential of direct feedback on modifying gait. In this study the authors considered the effects of reducing EKAM on the hip and ankle joints. Richards[13] concluded that external hip moments were not significantly increased with a modified gait, but small increases in external ankle adduction moment and external knee flexion moment were observed. The interaction between hip, knee, and ankle biomechanics is not well understood when modifying gait in patients with medial knee OA and needs to be reviewed to make clinical decisions on the role of gait retraining in reducing knee joint pain and discomfort,[13] justifying the necessity of a systematic review of the current literature.

Previous research has indicated that patients with knee OA experience abnormal loads of their major weight-bearing joints bilaterally, and abnormalities persist despite treatment of the affected limb.[13] Further treatment may be required if we are to protect the other major joints following joint arthroplasty. No systematic review has established what effects changing knee joint loading via gait style modification has on the other ipsilateral and contralateral joints in the lower limbs as well as trunk biomechanics. To lower knee joint loading, altered gait styles will undoubtedly change the kinematics and/or kinetics at the neighboring joints (eg, for toe-in gait the foot is at a more inverted position throughout the gait cycle). The clinical benefit of reducing the EKAM variables is questionable if there are detrimental consequences to other joints of the lower body. If the goal of gait retraining is to alleviate pain and slow down the deterioration of medial joint loading at the knee itself while not adversely affecting hip and ankle joint function, then an appreciation of what biomechanical changes are occurring at the hip and ankle joints is fundamental.

The objectives of this systematic review were (1) to identify the consequences of gait modifications on the biomechanics of the ankle and hip as well as trunk and pelvis biomechanics and (2) to establish whether gait styles and gait retraining can reduce medial knee loading as assessed by first and second peak EKAMs. Additionally, a third objective was to outline participant-reported outcomes on how easy the gait retraining style was to implement. This would aid the clinical translation of aforementioned gait retraining techniques.

Methods

Protocol and registration

In accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines[14] the protocol for this systematic review was registered with the International Prospective Register of Systematic Reviews on January 23, 2018 (registration ID: CRD42018085738) (available at https://www.crd.york.ac.uk/prospero/display_record.php?RecordID=85738).

Eligibility criteria

No study design, date, or language limits were applied. After the first search, only peer-reviewed quantitative academic articles published in English were considered.

Any study design that evaluated the effect of any gait retraining technique on EKAM while also evaluating at least 1 biomechanical variable at the ankle and/or hip was eligible for inclusion. There was no restriction on whether the participants of a study had to be clinically diagnosed as having medial knee OA. The reason for including studies involving gait retraining on healthy participants without OA was because of the anticipated lack of studies using participants with symptomatic knee OA, as evidenced in previous systematic reviews on similar topics.[3,15] In the interpretation of results, cohorts with and without OA are presented separately to establish any biomechanical differences between them when adopting a gait style.

Intervention

Gait retraining was defined as any researcher-initiated alteration of natural gait without the use of any devices or walking aids. Studies were included if they used 3-dimensional motion analysis and force plate—derived data during both natural and modified gait conditions as well as providing EKAM data. The altered gait style (intervention variable) was compared with the individual's natural level gait (control variable).

Studies evaluating post knee operations such as total knee replacements as well as studies that included participants with specific diseases and conditions that can affect the participant's gait were excluded.

Information sources

Database searches were undertaken by 1 reviewer (J.B.B.) with the assistance of 2 experienced librarians up to January 2019 on the following databases: Cumulative Index to Nursing and Allied Health (CINAHL, 1982-2019), EBSCO MEDLINE (MEDL) (1966-2019), Ovid Allied and Complementary Medicine Database (AMED) (1995-2019), Ovid EMCare (1995-2019), Ovid Joanna Briggs Institute (JBI) (1991-2019), Web of Science (1900-2019), BIOSIS Citation Index (Web of Science) (1926-2019), Scopus (1960-2019), Cochrane Library (Cochrane Library, DARE, and Central), ProQuest British Nursing Index (BNI) (1994-2019), Turning Research Into Practice Pro (TRIP PRO) (1997-2019), British Library e-theses online service (EThOS) (all years until 2019), and ProQuest Dissertations & Theses (1986-2019). Additionally, the International Prospective Register of Systematic Reviews was searched for ongoing or recently completed systematic reviews.

Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines[14] were used as guidelines of how to undertake this systematic review.

Search

To ensure maximum saturation of articles, the search strategy was purposely designed to be broad in its approach. The search strategy was designed by following the patient, intervention, comparison, and outcome model.[16]

The electronic databases were searched through using the combination of key search terms organized into sets and combined with the operators "AND" and "OR" (supplemental appendix S1, available online only at http://www.archives-pmr.org/).

Study selection

Titles were assessed by 1 author (J.B.B.). The principal investigators for each ClinicalTrials.gov identifier number (NCT number) were contacted to ascertain what peer-reviewed articles had been published from these clinical trials. Two authors assessed the abstracts of the remaining articles (P.R.B. and J.B.B.) independently. To ensure consistency and for expert advice, articles that were included in the systematic review were collectively reviewed by J.B.B., P.R.B., and C.A.H. During a meeting, the key data that were to be extracted from each study were determined.

Data collection process

JBB extracted the data for the following items: study design, sample size, participant characteristics, gait modification and/or technique used, EKAM parameters evaluated, study duration, ankle and/or hip biomechanical analysis that was undertaken, and the main study findings.

Risk of bias in individual studies

Risk of bias was assessed using the Downs and Black quality index.[17] This is a validated index for nonrandomized trials[15] consisting of 27 items used to assess reporting quality (items 1-10), external validity (items 11-13), internal validity (items 14-26), and study power (item 27). The tool has been used in various modified forms for gait focusing on interventions aimed at individuals with knee OA.[3,18-21] Piloting of the tool and agreeing on interpretation of the questions were undertaken by 2 reviewers (J.B.B. and P.R.B.). Risk of bias scores for individual studies were rated in line with previous systematic reviews on similar topics.[3,15] Neither review explicitly defined their boundaries in their articles, so the authors of the current review have inferred that 10-14 and 15-20 correspond with fair and moderate scores, respectively.

Summary measures

The principal summary measure from each article was the within-group mean differences in hip and/or ankle data between natural level gait and the gait retraining intervention presented as a percentage difference from natural level gait. Summarized mean difference effect sizes were also calculated for these metrics.

EKAM has been used widely in the gait retraining literature as a surrogate measurement of medial knee joint loading.[3] For the purpose of this review, "natural level gait" is defined as an individual assessment of an individual walking without any instruction as to alter their ordinary walking pattern when being assessed in a motion capture laboratory. Finally, any data presented regarding participant

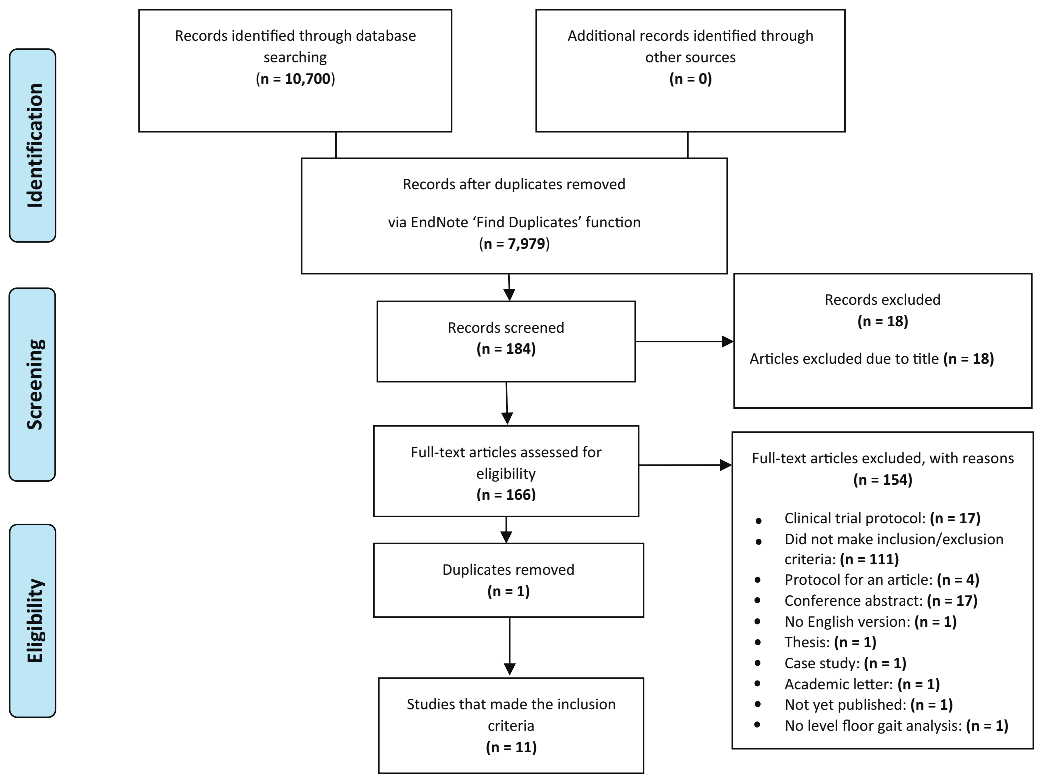

Fig 1 Flow diagram of search strategy.

perceptions on task difficulty were extracted to consider the practicality of translation to a clinical setting.

Changes from the original protocol

After analyzing the data from the 11 studies that met the inclusion criteria, there was enough evidence for trunk and pelvic biomechanical data to be included in the analysis. Therefore, this review has also documented trunk and pelvic biomechanical data. Additionally, the decision was made after the databases were searched to include any information on how easy the gait retraining was to implement.

Synthesis of results

A synthesis of results is provided with information presented in the text and tables to summarize and explain the main characteristics and findings of the included studies. The narrative synthesis explores the relationship of the findings between the included studies by way of gait style comparisons and methodological quality. The standardized mean difference (SMD) using the Hedges' *g* effect size was calculated for the change in EKAM and hip and/or ankle kinetic metrics. The SMDs were standardized according to small (0.2-0.5), medium (0.51-0.8), and large ($>$0.8).

Statistical analysis

Downs and Black scoring agreement between 2 reviewers (J.B.B. and P.R.B.) was assessed using a Cohen's kappa coefficient (κ) statistic, with reference to Landis and Koch's criteria where κ values $>$0.81 represent "almost perfect" agreement.[22] To estimate the SMD, the mean and standard deviation values were used. If mean and standard error mean data were provided in the studies, standard deviation was calculated as standard error mean multiplied by the square root of the sample size. SMDs were calculated using the Hedges' *g* effect size. All results are presented as forest plots. The 95% CI was calculated and presented for each effect size.

Results

Study selection

The search strategy resulted in a possible 184 studies to be included in the review, as shown in the Preferred Reporting Items for Systematic Reviews and Meta-Analyses flow diagram (fig 1). The reviewers showed substantial agreement in assessing the quality of each included study, κ=0.89. The 11 included articles focused on assessing the effects of gait modifications on reducing EKAM as well as documenting biomechanical variables for the pelvis, hip, and ankle joints. All data presented in this systematic review are from the medial knee OA ipsilateral limb for the patients. For healthy participants without OA, the data presented are for the side reported in the respective article.

Study characteristics

Table 1 outlines the group demographics. All studies, except that of Barrios et al,[9] used a within-subject design,

Table 1 Group demographics

Authors	Population	Gait Retraining Modification	Gait Speeds, mean ± SD (m/s)	Overground/ Treadmill Walking	n (M:F)	Age, mean ± SD (y)	Height, mean ± SD (m)	Mass, mean ± SD (kg)	BMI, mean ± SD
Shull et al[23]	Symptomatic knee OA (K/L grade≥1)	• T-I	1.23±0.21	Instrumented treadmill	12 (7:5)	59.8±12.0	1.71±0.8	77.7±18.0	26.5±4.2
Richards et al[18]	Symptomatic knee OA	• Self-selection combination of T-I, WS, and MT	NR	Instrumented treadmill	40 (15:25)	61.7±6.0	1.73±0.10	77.2±11.0	25.6±2.5
Erhart-Hledik et al[12]	Symptomatic knee OA and physician-diagnosed radiographic medial compartment knee OA (K/L grade≥1)	• Medial weight transfer at the foot	Control (natural speed [1.28±0.14]; fast speed [1.53±0.18]); active feedback (natural speed [1.31±0.12]; fast group [1.50±0.15])	Overground	10 (9:1)	65.3±9.8	NR	NR	27.8±3.0
Gerbrands et al[24]	Symptomatic knee OA; physician diagnosed with radiographic and fulfilment of the criteria by the American College of Rheumatology	• LT • MT	Comfortable walking (1.21±0.10); MT walking (1.02±0.19); TL walking (1.08±0.15)	Overground	30 (10:20)	61.0±6.2	1.71±0.1	75.7±13.1	NR
Charlton et al[25]	Radiographic medial compartment knee OA (K/L grade≥2)	• T-I • T-O	1.22±0.15	Overground and a treadmill	15 (6:9)	67.9±9.4	1.67±0.11	75.6±15.0	NR
Barrios et al[9]	Healthy without OA	• HIR strategy	1.46±2.5	Overground	8 (7:1)	21.4±1.6	1.75±0.07	71.7±8.8	NR
Hunt et al[26]	Healthy without OA	• LT	Natural TL (1.42±0.18); small TL (1.36±0.19); medium TL (1.36±0.19); large TL (1.40±0.19)	Overground	9 (3:6)	18.6±0.7	1.71±0.11	65.2±13.8	NR
Mündermann et al[27]	Healthy without OA	• Increased medio-lateral trunk sway	Natural gait (1.48±0.17); mediolateral trunk sway (1.44±0.15)	Overground	19 (12:7)	22.8±3.1	1.75±0.97	70.5±16.3	NR
van den Noort et al[28]	Healthy without OA	• HIR feedback	1.0±0.09	Instrumented treadmill	17 (8:7)	28.2±7.6	1.78±0.07	71.6±12.5	NR
Dunphy et al[29]	Healthy without OA	• Contralateral pelvic drop	1.31±0.12	Instrumented treadmill	15 (7:8)	25±2.65	1.73±0.08	76.7±16.5	25.7±5.06
Khan et al[30]	Healthy without OA	• T-O; • T-I	Slow (0.85); natural (1.18); fast (1.43)	Overground	20 (8:12)	29.0±4.10	1.65±0.11	59.3±10.4	NR

Abbreviations: BMI, body mass index (calculated as weight in kilograms divided by height in meters squared); F, female; HIR, hip internal rotation; K/L, Kellgren and Lawrence grade; LT, lateral trunk lean; M, male; MT, medial thrust; NR, not reported; T-I, toe-in gait; WS, wide stance gait.

Table 2 Disease severity

Authors	Population	K/L Grade	PROMs
Shull et al[23]	Symptomatic knee OA	II: 4, III: 7, IV: 1	WOMAC pain, mean ± SD: 74.2±19.0 (max 100) WOMAC function, mean ± SD: 81.7±21.6 (max 100)
Richards et al[18]	Symptomatic knee OA	I: 19, II: 8, III: 9, IV: 4	WOMAC pain, mean ± SD: 5.35±3.13 (max 20) WOMAC function, mean ± SD: 19.10±12.08 (max 68) WOMAC stiffness: 3.25±1.96 (max 8) Baseline pain: 3.05±2.16 (max 10)
Gerbrands et al[24]	Symptomatic knee OA	NR	KOOS pain (%): 57.5 (13.4) KOOS function (%): 62.3 (14.1)
Erhart-Hledik et al[12]	Symptomatic knee OA	All>I.	Daily pain score: 3.2 (3.6)
Charlton et al[25]	Radiographic knee OA	II: 7; III: 8	WOMAC pain, mean ± SD: 4±2.2 (max 20) WOMAC stiffness, mean ± SD: 3.0±1.3 (max 8) WOMAC function, mean ± SD: 15.4±8.0 (max 68
Hunt et al[26]	Healthy with no OA	NR	NR
Barrios et al[9]	Healthy with no OA	NR	KOOS-SR score, mean ± SD: 0.7±0.9 (max 20)
Mundermann et al[27]	Healthy with no OA	NR	NR
van den Noort et al[28]	Healthy with no OA	NR	NR
Dunphy et al[29]	Healthy with no OA	NR	NR
Khan et al[30]	Healthy with no OA	NR	NR

Abbreviations: K/L, Kellgren and Lawrence grade; KOOS, Knee Injury and Osteoarthritis Outcome Score; NR, not reported; PROM, patient-reported outcome measure; SR, function in Sport and Recreation; WOMAC, Western Ontario and McMaster Universities Osteoarthritis Index.

and most studies evaluated the immediate within-session effect and potential benefits of gait retraining. Sample sizes varied from 8-40 participants. Six of the 11 studies assessed healthy participants without OA, and 5 included participants with knee OA. In the systematic review of Simic et al[3] there was only study of interest to be included in the current systematic review.[27] Table 2 presents the Kellgren and Lawrence grade and patient-reported outcome measures on knee OA disease severity for the articles that included patients with knee OA in their research.

Risk of bias within studies

The methodological quality of the included studies was fair to moderate. The quality indices of included articles ranged from 12 of 25 to 18 of 28 with a mean of 15.0 (table 3). Studies assessing participants with OA ranged from 14-17, while the studies of healthy cohorts without OA had a wider range of methodological quality ranging from 12-18. All studies that involved OA participants had high reporting scores, low external validity scores, 4 of 6 for internal validity (bias), low scoring 0-2 of 6 for internal validity (confounding), and scored for power reporting. Studies that used a healthy cohort without OA varied in their reporting (6-10 of 10), 0 of 3 for external validity, mixed scores for internal validity (confounding) (1-3 of 6), and varied in reporting the sample power of the respective study. Average interrater reliability between the 2 independent reviewers (J.B.B. and P.R.B.) across all questions was very strong (κ=0.89) (supplemental appendix S2, available online only at http://www.archives-pmr.org/). Table 3 outlines J.B.B.'s scoring for the risk of bias for each study.

Results of individual studies

Overall gait retraining style strategies

SMDs were calculated using the Hedges' *g* effect size. All results are presented as forest plots in figures 2-6 for EKAM 1 and 2, hip kinetics, hip kinematics, ankle kinetics, and ankle kinematics, respectively. Eight different gait retraining styles were evaluated (see table 1): hip internal rotation,[9,24] trunk lean,[24,26,27] toe-in gait,[23,25,30] contralateral pelvic drop,[29] medial thrust gait,[24] medial weight transfer at the foot,[12] toe-out gait,[25,30] and self-selected combination of toe-in, wide stance, and medial thrust.[18] Individual studies assessing these various gait style interventions also varied in terms of study quality. Two studies assessing toe-in gait had scores of 12 and 14 of 25 for study quality,[23,30] respectively. One hip internal rotation study[28] scored 14 of 25 while another scored 18 of 28.[9] The SMD effect size varied across studies for a given measured variable as well as varying 95% CI for the effect size.

Biomechanical variables reported

Primary analysis: hip kinetic biomechanics

Peak external abduction moment was addressed in 2 studies. One study showed a null to small effect due to a trunk lean intervention for all 3 trunk lean angles assessed,[26] with the small effect resulting from the largest of the 3 trunk leans assessed (~12°) (SMD, 0.23; CI, −0.69 to 1.16). This is compared with a large increase due to a trunk lean (~10°) intervention in another study[27] (SMD, 0.89; CI, 0.23-1.56). These findings indicate that there may be a dose-response effect on trunk lean angle and an increase in peak external hip abduction moment. Both studies assessed healthy participants without OA and

Table 3 Risk of bias within studies

Authors	Population	Reporting (n=1-10)	External Validity (n=11-13)	Internal Validity: Bias (n=14-20)	Internal Validity: Confounding (n=21-26)	Power (n=27)	Methodological Score (/25 or /28)
Shull et al[23]	Symptomatic knee OA	9	0	4	0	1	14/25
Richards et al[18]	Symptomatic knee OA	8	0	4	2	1	15/25
Gerbrands et al[24]	Symptomatic knee OA	9	0	4	1	1	15/25
Erhart-Hledik et al[12]	Symptomatic knee OA	9	1	4	2	1	17/25
Charlton et al[25]	Radiographic knee OA	9	0	4	1	1	15/25
Barrios et al[9]	Healthy with no OA	10	0	4	3	1	18/28
Hunt et al[26]	Healthy with no OA	9	0	4	2	0	15/25
Mundermann et al[27]	Healthy with no OA	8	0	4	2	1	15/25
van den Noort et al[28]	Healthy with no OA	7	0	4	3	0	14/25
Dunphy et al[29]	Healthy with no OA	9	0	4	2	0	15/25
Khan et al[30]	Healthy with no OA	6	0	4	1	1	12/25

NOTE. Barrios et al[9] used the KOOS-SR score (Function in Sport and Recreation), which ranged from 0-20, a score of 0 indicating no difficulty. Shull et al[23] measured WOMAC levels on the day of assessment, with the scale ranging from 0-100 with 100 indicating no pain and perfect function. Richards et al[18] measured WOMAC levels on the day of assessment, evaluating the pain and function of the participant in the past week, with the lower the scoring of pain out of 20 equating to the lower the pain, and the lower the score out of a maximum of 68 being the better the function of the participant. Gerbrands et al[24] assessed pain and function using the KOOS; scores are presented as a percentage, where 0% represents extreme problems and 100% represents no problems. Daily pain score ranged from 0-10, with 0 indicating no pain and 10 indicating worst pain.
Abbreviations: K/L grade, Kellgren and Lawrence system; KOOS, Knee injury and Osteoarthritis Outcome Score; NR, not reported; OA, osteoarthritis; PROM, patient-reported outcome measure; WOMAC, The Western Ontario and McMaster Universities Osteoarthritis Index.

lacked external validity, which severely hinders any inferences to gait alterations on peak external hip abduction moments in a population with medial knee OA.

Peak external hip adduction moment (EHAM) was assessed by 1 study,[18] which indicated a null effect (SMD <0.2) when using various feedback mechanisms to reduce EKAM 1. Richards et al[18] evaluated the effect of real-time feedback on a population with OA. First and/or early peak EHAM was assessed in 3 trunk lean studies showing conflicting effects.[24,26,27] The conflicting findings may be because 1 study used a cohort group with OA[24] (indicating a small effect increase (SMD, 0.36; CI, −0.15 to 0.87) and the other 2 assessed a healthy cohort without OA[26,27] (indicating a small and a large effect size decrease in late stance EHAM).

Late stance peak EHAM changes due to a trunk lean intervention indicate that the greater the trunk lean implemented, the lower the reduction in late stance peak EHAM with increasingly higher effect size associated with the change accordingly to the increase in trunk lean angle. However, caution must be had because 1 study assessed a patient population[24] while the other assessed a healthy group of participants without OA.[26] This change in late stance peak EHAM for a trunk lean intervention appears to be different from the use of a medial thrust gait style, which indicates a small effect size increase (SMD, 0.25; CI, −0.26 to 0.75).

In terms of sagittal plane hip kinetics, only 1 study[18] assessed peak external hip flexion moment, indicating a null effect for all 4 different feedback mechanisms (SMD<0.2). Maximum hip axial loading rates were assessed by 1 study,[9] which indicated a null effect (SMD, −0.08; CI, −0.72 to 0.55).

Overall, reporting of hip kinetic data is lacking across the studies. Caution must be had when interpreting these results because of the lack of external validity and the different population groups assessed in each study. Additionally, the 95% CI was large for all variables assessed, with most metrics 95% CI measured crossing the line of null effect.

Primary analysis: ankle kinetic biomechanics

Early and late stance peak external inversion moment were assessed in 1 study.[24] In the early stance, a null effect for trunk lean was calculated (SMD, 0; CI, −0.51 to 0.51) but potentially increasing when adopting a medial thrust gait (SMD, 0.49; CI, −0.02 to 1.01). Late stance[24] indicated null effect for trunk lean (SMD, 0.15; CI, −0.66 to 0.36) and

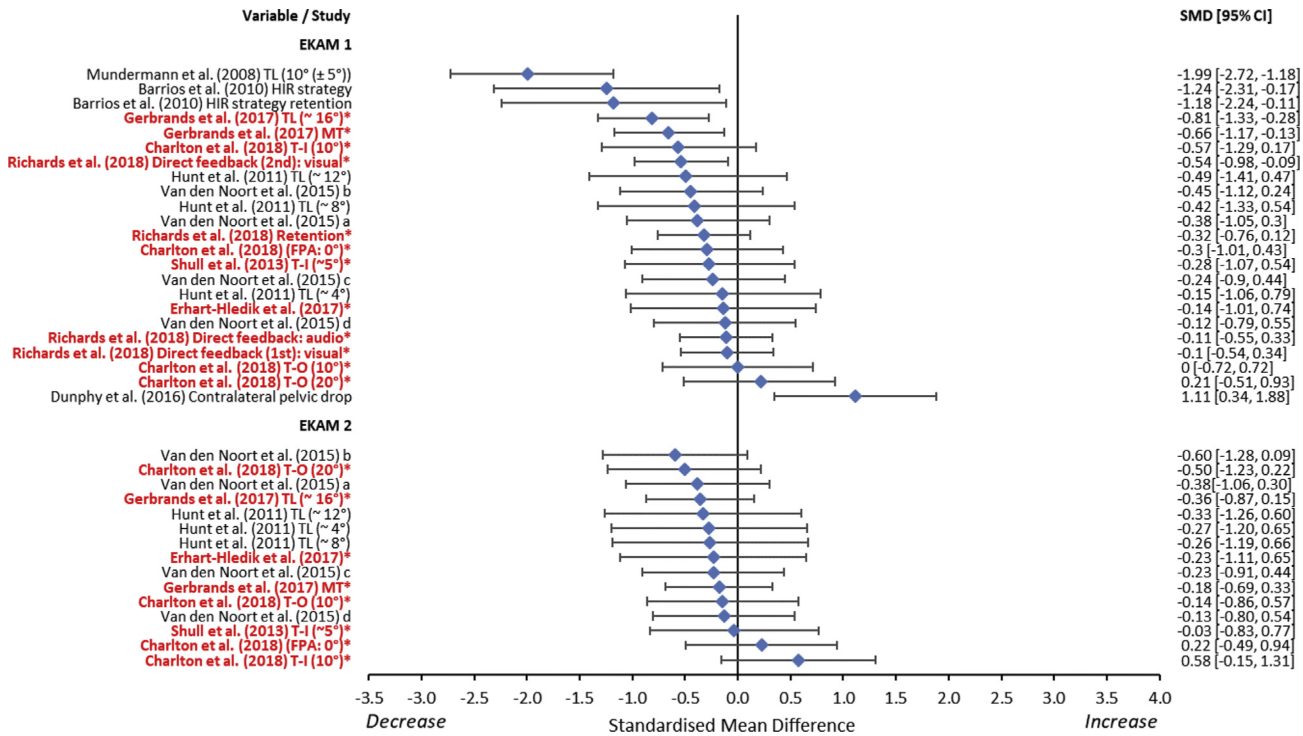

Fig 2 Forest plot of EKAM 1 and EKAM 2 comparing the given study intervention with normal gait. Articles bold, in red, with an * indicate studies that assessed participants with knee OA.

small effect medial thrust (SMD, 0.33; CI, −0.84 to 0.18) reductions in peak external inversion moment. This study was rated as moderate (15/25) and assessed a population with OA.

Peak frontal and sagittal plane external moments were assessed by 1 study.[18] In the frontal plane, the effect sizes should be interpreted with caution because of the very high standard deviation. Sagittal plane moment indicated a null

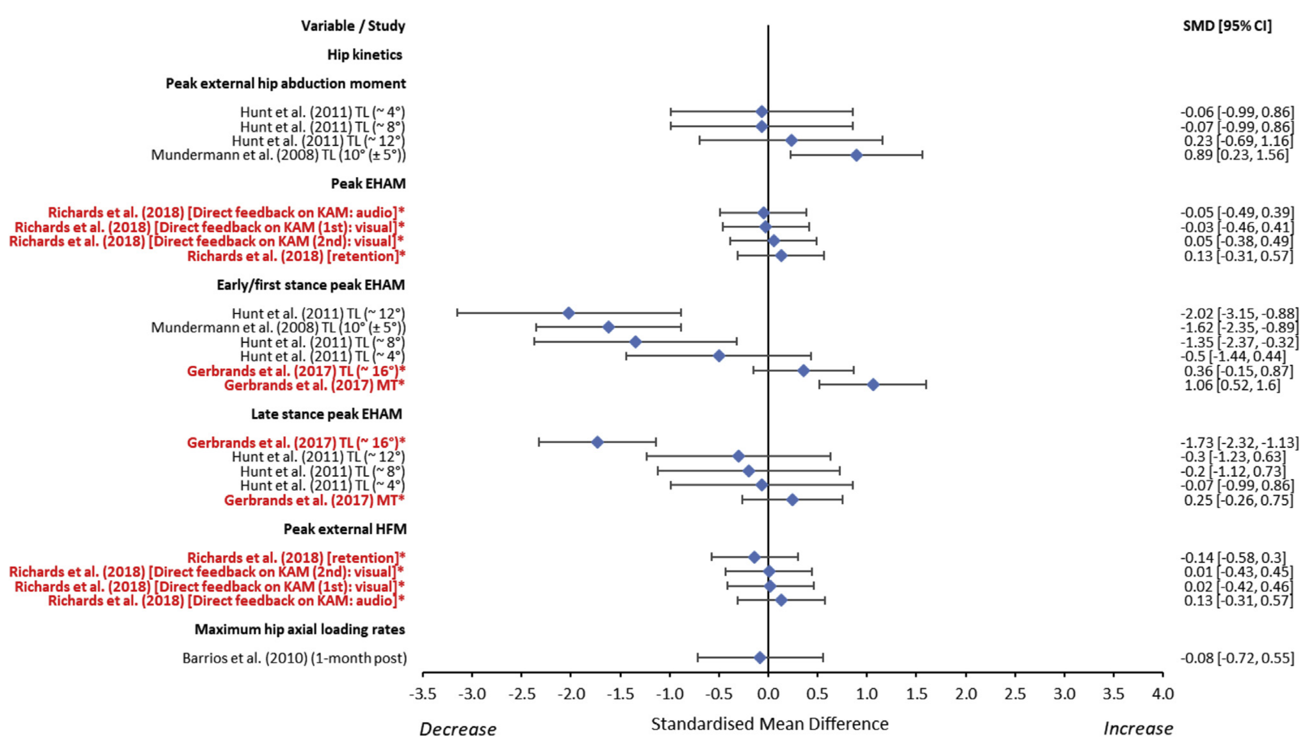

Fig 3 Forest plot of hip kinetic metrics comparing the given study intervention with normal gait. Articles bold, in red, with an * indicate studies that assessed participants with knee OA. Abbreviation: HFM, hip flexion moment.

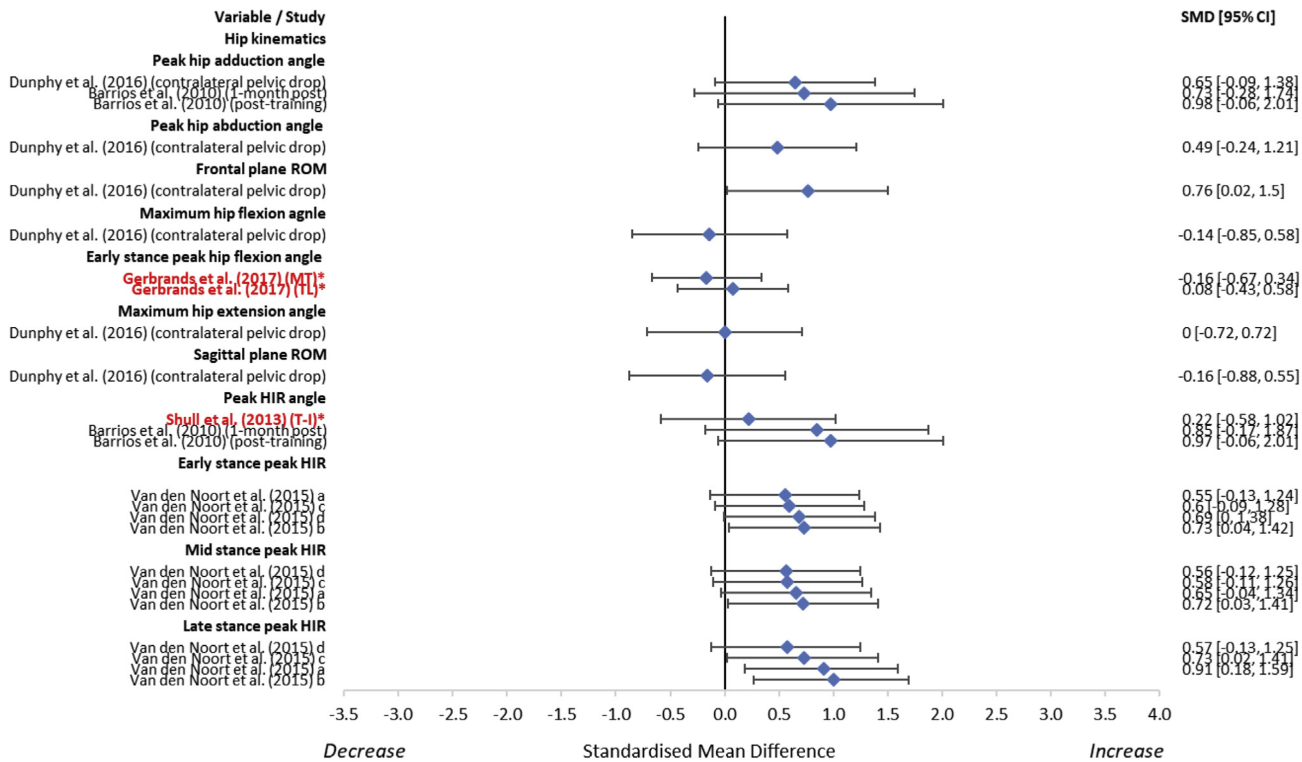

Fig 4 Forest plot of hip kinematic metrics comparing the given study intervention with normal gait. Articles bold, in red, with an * indicate studies that assessed participants with knee OA. Abbreviations: HIR, hip internal rotation; MT, medial thrust; ROM, range of motion; TL, trunk lean. Van den Noort et al[28] **(A)** bar visual feedback on HIR. Van den Noort et al[28] **(B)** polar visual feedback on HIR. Van den Noort et al[28] **(C)** color visual feedback on HIR. Van den Noort et al[28] **(D)** graph visual feedback on HIR.

effect for the various intervention types used by Richards et al.[18] This study was rated as moderate (15/25) and assessed a population with OA.

Peak external ankle eversion/inversion and plantarflexion/dorsiflexion moments were assessed in 1 study,[25] all of which had a 95% CI crossing the line of null effect. This indicates that caution should be taken when interpreting the SMD effect size in isolation. This was also true for peak external ankle plantarflexion/dorsiflexion moment impulses,[25] again limiting the interpretation of the SMD value. However, for toe-out gait peak external ankle eversion moment impulse appears to reduce while having a null effect for toe-in gait. For the peak external ankle inversion moment impulse, there appears to be a large effect size indicating an increased load when adopting a toe-in gait compared with natural gait (SMD, 1.43; CI, 0.6-2.26). This study was rated as moderate (15/25) and assessed a population with OA.

Center of pressure at EKAM 1 and EKAM 2 was only assessed for toe-in gait,[23]; both indicating no effect size (SMD$<$0.2) when adopting a toe-in gait style. First and second half of stance center of pressure were assessed in 1 study,[12] which reported a large effect size increase in the first half of stance center of pressure because of the intervention and small size increase in the second half of stance center of pressure (SMD, 0.85 and 0.28, respectively). However, the 95% CI for these 2 variables cross the line of null effect, so caution must be taken in the interpretation of these findings. Maximum ankle axial loading rates was assessed by 1 study,[9] which indicated a null effect (SMD, $-$0.15; CI, $-$0.79 to 0.49).

All ankle kinetic data presented above used a population with OA within their studies, with varying methodological scores (14-17 of 25), having scored low on external validity. Caution should be had when assessing the effect sizes alone because the 95% CI tends to cross the line of null effect. Therefore, interpretation should always consider the 95% CI values when making conclusions for a gait style.

Trunk and pelvis biomechanics

Six studies reported various pelvic and/or trunk biomechanics data[23,24,26-29] (table 4). Shull et al[23] did not find any significant changes in lateral trunk sway at first or second peak EKAM between natural gait and a toe-in gait modification. Gerbrands et al[24] reported a significant increase in peak trunk angle between natural gait to both trunk lean and medial thrust gait modifications. The trunk biomechanics presented by Hunt et al[26] and Mündermann et al[27] describe the mean $\pm$ SD trunk lean angles for the gait styles performed. Van den Noort et al[28] outlines a number of trunk and hip changes with and without hip internal rotation feedback on hip internal rotation. Dunphy et al[29] studied the influence of contralateral pelvic drop and noted the differences in pelvic drop angle between natural gait and contralateral pelvic drop gait style.

External knee adduction moment

Trunk lean ($\sim$10°)[27] had the biggest reduction in EKAM 1 compared with natural walking (SMD, $-$1.99; CI, $-$2.72 to

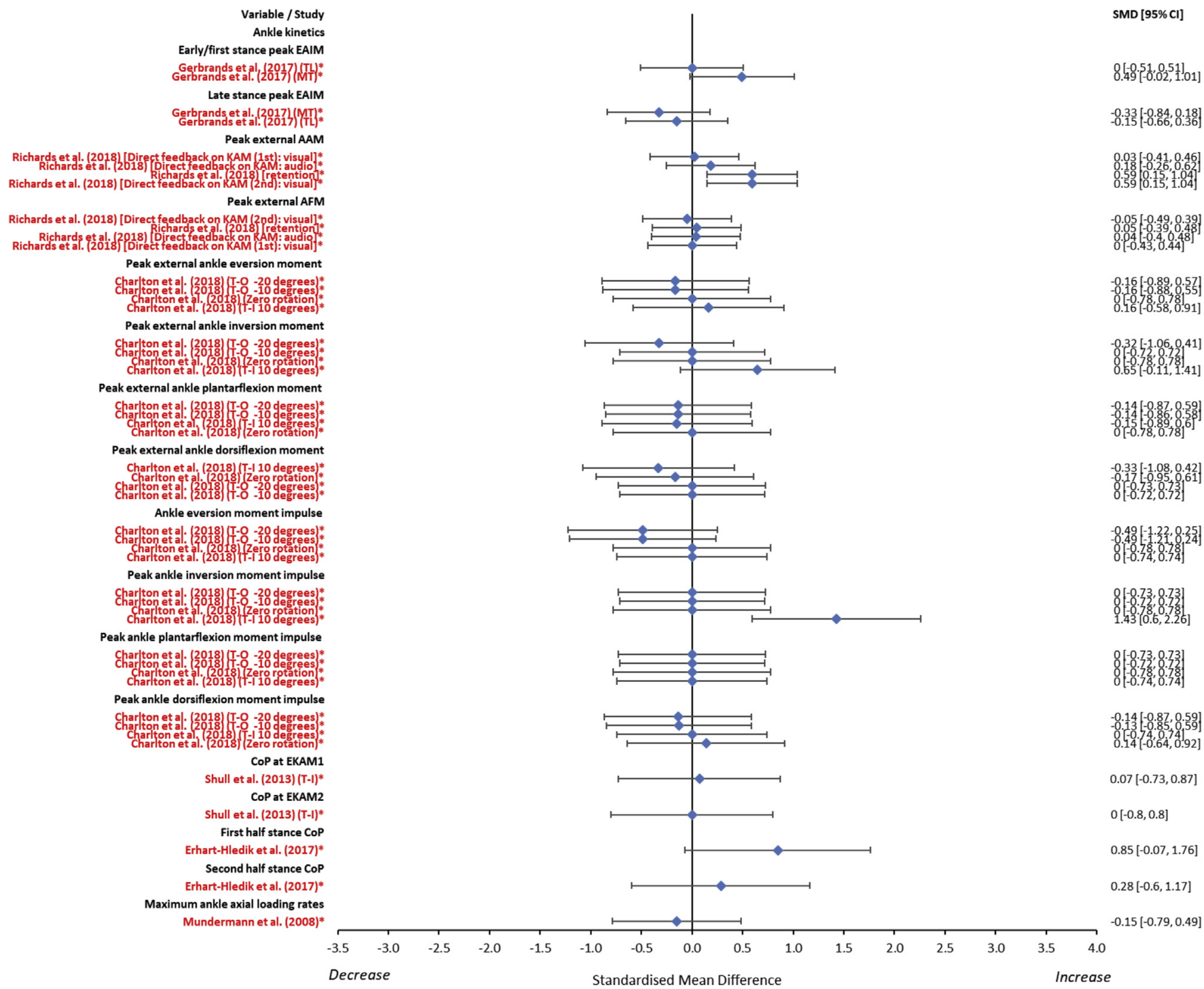

Fig 5 Forest plot of ankle kinetic metrics comparing the given study intervention with normal gait. Articles bold, in red, with an * indicate studies that assessed participants with knee OA. Abbreviations: CoP, center of pressure; MT, medial thrust; T-I, toe in; TL, trunk lean; T-O, toe out.

−1.18). In addition, other studies assessing trunk lean indicated large reductions in EKAM 1[24] (SMD, −1.18; CI, −2.24 to −0.11)[26] (SMD, −0.45; CI, −1.12 to 0.24). Trunk lean also appears to be dose dependent—the larger the degree of trunk lean, the larger the reduction in EKAM 1. Hip internal rotation[9] (SMD, −1.24; CI, −2.31 to −0.17), medial thrust[24] (SMD, −0.66; CI, −1.17 to −0.13), toe-in gait (SMD, −0.57; CI, −1.29 to 0.17),[25] and a self-selection of a combination of toe-in, wider stance, and medialization of the knee position while receiving visual direct feedback on EKAM (SMD, −0.54; CI, −0.98 to −0.09) also had medium to large effect size on reducing EKAM 1.

The effects of gait styles on EKAM 2 were less pronounced, with only 2 studies showing a medium effect size reduction, using polar visual feedback on hip internal rotation (SMD, −0.60; CI, −1.28 to 0.09)[25] and toe-out gait (~20°)[25] (SMD, −0.50; CI, −1.23 to 0.22). All studies that assessed a gait style compared with natural gait for EKAM 2 had a CI that crossed the line of null effect.

Ease of adapting gait style

After the review protocol was made available, the authors of the review decided that it would enrich the study to extract additional information to establish the ease of adopting a given gait style. Five studies included subjective commentary on how easy the gait retraining was to implement,[9,23-26,28] with 3 of them[9,25,28] asking the participants for their feedback. Barrios et al[9] found that effort and how natural the retraining was to implement improved from sessions 1 to 8. In the study by van den Noort et al,[28] the intuitiveness of the type of feedback was verbally tested after each trial by a subjective score on the question, "How well were you able to modify your gait pattern?" There were no significant differences between subjective scoring of the intuitiveness for all visual feedback trials. Therefore, the type of visual feedback is not of primary concern when aiming to modify gait.[28] In the study by Charlton et al,[25] discontent levels were low across the

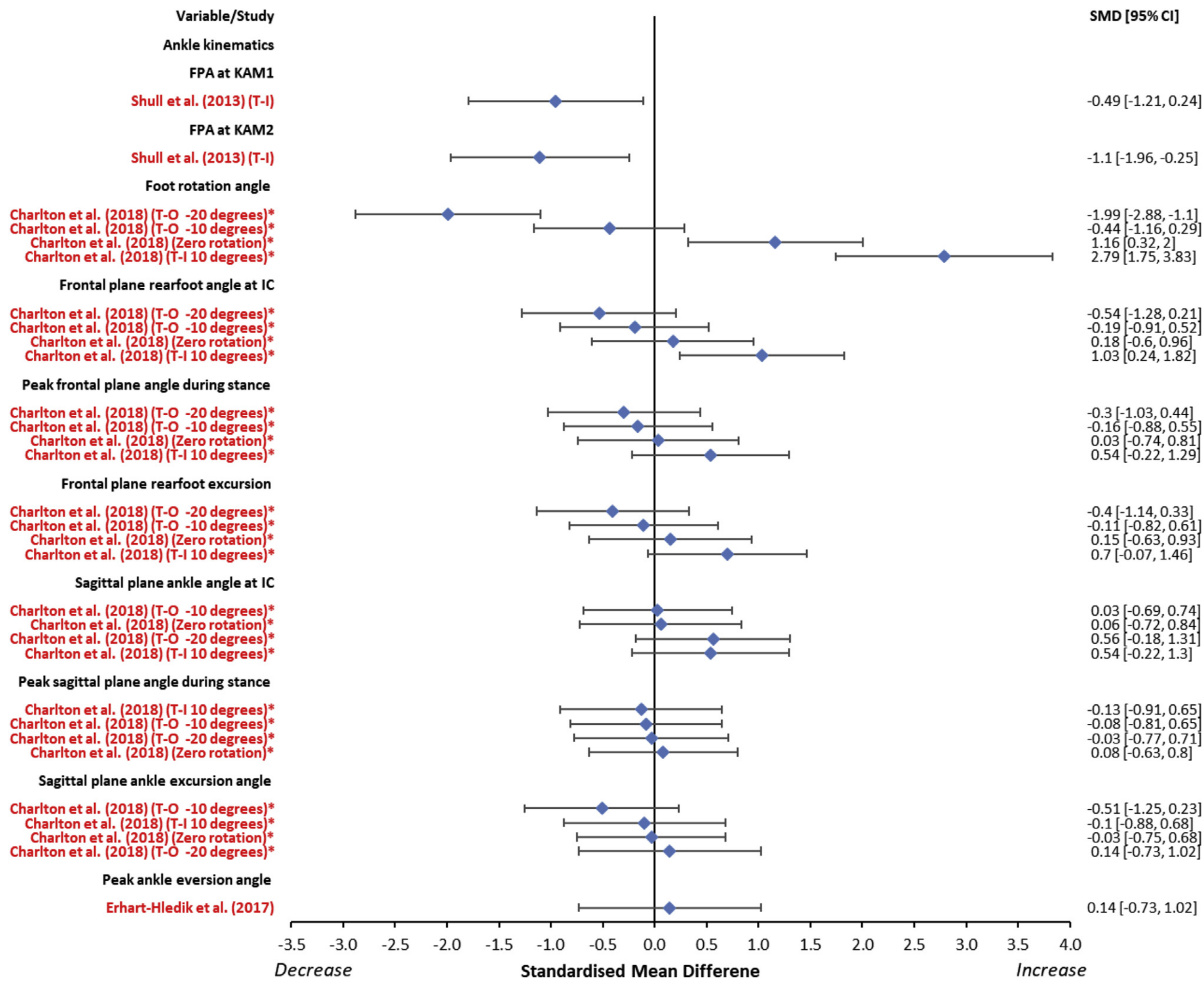

Fig 6 Forest plot of ankle kinematic metrics comparing the given study intervention with normal gait. Abbreviations: FPA, foot progression angle; IC, initial contact; T-I, toe in; T-O, toe out.

toe-in, natural, and toe-out walks for the ankle and/or foot, knee, and hip. All participants in the study by Hunt et al[26] reported at least some difficulty in performing the increased trunk lean walking trials. Shull et al[23] commented on the ease of learning toe-in gait only within the article's discussion section. Subjectively, participants in the aforementioned study appeared to walk naturally with toe-in gait.

Study quality assessment

The methodologic quality of included studies could be considered fair to moderate. Overall, 2 studies were rated fair, and 9 studies were moderately rated (see table 3). Studies lacked external validity and internal validity (confounding). In addition to the methodological issues highlighted by the Downs and Black tool, other methodologic issues included the failure to thoroughly control extraneous variables such as speed and step length, inadequate standardization of gait modification magnitudes, and small sample sizes. Also, to assess the efficacy of gait modifications it is necessary to capture the immediate and long-term effects on patient-reported pain, function, and discomfort.

Discussion

Summary of evidence

This systematic review evaluated whether gait retraining can reduce EKAM while not affecting adjacent joints. This is the first systematic review that has evidenced a lack of reporting of hip and/or ankle joint biomechanics when altered knee joint loading is targeted during gait retraining protocols. On the evidence currently available in the gait retraining literature we cannot not confirm whether there is an adverse effect on adjacent joints to the knee when adopting a gait style because of the lack of evidence and conflicting evidence presented.

This systematic review suggests that different gait retraining strategies may have different knee joint loading

Table 4 Percentage change in EKAM parameter measured between normal gait and gait retraining intervention

Authors	1st Peak EKAM Values (presented as %BW*H unless otherwise stated)	2nd Peak EKAM Values (%BW*H)	% Change in 1st Peak EKAM	% Change in 2nd Peak EKAM
Shull et al[23]	Baseline: 3.28 (1.37); T-I: 2.90 (1.38)[†]	Baseline: 1.98 (1.14); T-I: 1.94 (1.09)	T-I: −13%	NS
Richards et al[18]	Combination of WS, T-I, and MT gait modifications with real-time feedback. Baseline: 3.29 (1.00); visual feedback with self-selected combination of WS, T-I, and MT gait: 2.82 (0.71)[†]; retention: 3.00 (0.77)[†]	NR	Visual feedback: −14% Retention: −9%	NR
Gerbrands et al[24]	Baseline: 0.24 (0.12); TL: 0.15 (0.10)[†]; MT: 0.17 (0.09)[†]	Baseline: 0.19 (0.12); TL:0.15 (0.10)[†]; MT: 0.17 (0.10)	TL: −38% MT: −29%	TL: −21% MT: NS
Erhart-Hledik et al[12]	Baseline: 2.41 (1.10); medial weight transfer at the foot: 2.26 (1.04)[†] Baseline, fast walking: 2.90 (1.28); medial weight transfer at the foot, fast walking: 2.63 (1.35)[†]	Baseline: 1.71 (1.01); medial weight transfer at the foot, normal gait: 1.47 (0.96)[†] Medial weight transfer at the foot, fast gait: 1.50 (1.13)	Medial weight transfer at the foot: −6% Medial weight transfer at the foot, fast gait: −9%	Medial weight transfer at the foot, normal gait: −14% Medial weight transfer at the foot, fast gait: NS
Charlton et al[25]	Baseline: 0.48 (0.14) (N m/kg); T-I: 0.4 (0.14) (N m/kg); zero rotation: 0.44 (0.13) (N m/kg); T-O (10°) 0.48 (0.14) (N m/kg); T-O (20°) 0.51 (0.14) (N m/kg)	Baseline: 0.39 (0.14) (N m/kg); T-I: 0.47 (0.13) (N m/kg); zero rotation: 0.42 (0.12) (N m/kg); T-O (10°) 0.37 (0.13) (N m/kg); T-O (20°) 0.32 (0.14) (N m/kg)	T-I: −20% zero rotation: −9% T-O (10°): 0% T-O (20°): +6%	T-I: +17% zero rotation: +7% T-O (10°): −5% T-O (20°): +22%
Barrios et al[9]	Baseline visit: 0.426 (0.065) (N m/kg); post training: 0.34 (0.66)[*] (N m/kg); 1-month post: 0.34 (0.073)[*] (N m/kg)	NR	Post training: −20% 1 month post: −20%	NR
Hunt et al[26]	Baseline: 4.07 (1.64); small lean: 3.82 (1.77); medium lean: 3.37 (1.72)[*]; large lean: 3.26 (1.64)[*]	Baseline: 1.89 (0.77); small lean: 1.64 (0.96); medium lean: 1.64 (1.02); large lean: 1.60 (0.90)	Small lean: NS Medium lean: −21% Large lean: −25%	NS
Mundermann et al[27]	Baseline: 2.0 (0.7); increased trunk sway: 0.7 (0.6)[†]	NR	Increased trunk sway: −65%	NR
van den Noort et al[28]	Baseline: 2.14 (0.20); HIR color feedback: 1.92 (0.25); HIR polar feedback: 1.73 (0.24)	Baseline: 1.91 (0.29); HIR color: 1.60 (0.34); HIR polar: 1.14 (0.32)[†]	HIR color: NS HIR polar: NS	HIR color: NS HIR polar: −40.32 %
Dunphy et al[29]	Baseline: 0.41 (0.03); contralateral pelvic drop: 0.56 (0.04)[*]	NR	Contralateral pelvic drop: +37%	NR
Khan et al[30]	Slow, ST: 1.81 (NR); slow, T-I: 1.82 (NR); slow, T-O: 2.28 (NR)[*]; Normal, ST: 1.96 (NR); normal, T-I: 1.80 (NR)[*]; normal, T-O: 2.81 (NR)[*] fast, ST: 2.70 (NR); fast, T-I: 2.23 (NR)[*]; fast, T-O: 3.08 (NR)[*]	Slow, ST: 1.28 (NR); slow, T-I: 1.64 (NR)[*]; slow, T-O: 1.13 (NR)[*]; Normal, ST: 1.42 (NR); normal, T-I: 1.70 (NR)[*]; normal, T-O: 1.06 (NR)[*]; Fast, ST: 1.56 (NR); fast, T-I: 1.60 (NR); fast, T-O: 1.22 (NR)[*]	Slow, T-I: NS; normal, T-I: −9%; fast, T-I: −21% Slow, T-O: +26%; normal, T-O: +43%; fast, T-O: +14%	Slow, T-I: +22%; normal, T-I: + 20%; fast, T-I: NS Slow, T-O: −12%; normal, T-O: −25%; fast, T-O: −22%

Abbreviations: baseline, normal gait; HIR, hip internal rotation; medium lean, 8 °; large lean, 12 °; MT, medial thrust; small lean, 4 °; NR, not reported; NS, not significant, $P>.05$; %BW*H, percent body weight multiplied by height; ST, straight-toe gait; T-I, toe-in gait; T-L, trunk lean; T-O, toe-out gait; WS, wide stance gait.

* $P<.05$.

† $P<.01$.

Table 5 Biomechanical consequences of gait retraining at the trunk, hip, ankle, foot, and CoP

Authors	Trunk and Pelvis	Hip	Ankle, Foot, and CoP
Shull et al[23]	• NS LT sway between T-I gait (0.2 [2.0]) and normal gait (0.5 [2.3]) at first peak EKAM, $P=.44$; • NS LT sway between T-I gait (0.4 [1.3]) and normal gait (0.6 [1.2]) at second peak EKAM, $P=.48$; • NS peak lateral trunk sway angle between normal gait (1.5° [1.6°]) and T-I gait (1.3° [0.5°]), $P=.49$.	• NS findings for peak HIR angle between normal gait (3.2° [3.8°]) and T-I gait (4.1° [4.1°]), $P=.18$.	• Significant difference between normal gait FPA at first (3.3° [4.5°]) and second (3.9° [4.6°]) peak EKAM compared with FPA for T-I gait at first (−2.6° [6.3°]) and second (−1.4° [6.4°]) peak EKAM; • Early stance, the CoP shifted laterally from normal gait (27 [77]mm) compared with 33 (79) mm, $P=.04$; • Late stance CoP did not significantly change between normal gait (30 [83]mm) and T-I gait (30 [83]mm), $P=.96$.
Richards et al[18]	• NR	• NS changes in the peak EHAM, $P=.083$; • NS changes in peak HFM between normal gait and gait modifications, $P=.182$.	• Peak EAAM was significantly increased compared with baseline during the second peak EKAM visual feedback trial and the final retention trial, $P<.001$; • NS in peak EAFM for any condition, $P>.058$; • FPA significantly more internally rotated during second EKAM visual feedback and retention trials, $P<.001$; • Patients significantly increased their step widths during all trials.
Gerbrands et al[24]	• During the MT the peak trunk angle significantly increased to 5.5° (3.7°), and during the TL the peak trunk angle significantly increased to 16.1° (5.5°) compared with normal walking trunk angle of 3.4° (1.8°), $P<.05$.	• Early stance peak hip flexion angle significantly increased from normal walking (15.3° [37.7°]) to 18.2° [37.2°] during TL, $P<.05$. NS in early stance peak hip flexion angle between normal walking (15.3° [37.7°]) and MT (10.2° [21.1°]), $P>.05$; • NS findings in EHAM between baseline walking trials and neither the TL or MT gait retraining trials at both the first and second peak EKAM, $P>.05$.	• Significant reductions were found for late stance peak ankle inversion moment of 3% during MT gait compared with normal walking ($P<.05$). Peaks did not increase significantly for plantar and dorsal ankle moments between the 2 different walking styles.
Erhart-Hledik et al[12]	• NR	• NR	• NS changes in peak ankle eversion angle in stance between control (13.9° [5.4°]) and active feedback (14.7° [5.3°]), $P=.193$ for normal walking speed. • Average foot CoP in the first half of stance phase in the medial/lateral direction was significantly different between control (43.1 [5.6]mm) and active feedback (49.0 [7.6]mm), $P=.011$ for normal walking speed. Average foot CoP in the second half of stance phase was significantly different between control (28.3 [9.5]mm) and active feedback (31.8 [13.7]mm), $P=.079$;

(*continued on next page*)

Table 5 (*continued*)

Authors	Trunk and Pelvis	Hip	Ankle, Foot, and CoP
			• Average foot CoP in the first half of stance phase was significantly different between control (43.9 [6.0]mm) and active feedback (47.5 [6.7]mm), $P=.006$, for fast walking speed. NS CoP findings in the second half of stance phase for fast walking speed.
Charlton et al[25]	• NR	• NR	• T-I 10° significantly increased rearfoot inversion angles by 68%, 139%, and 289% for ZR, T-O 10°, and T-O 20°, respectively. T-O 20° resulted in significantly decreased rearfoot inversion angles by −57% compared with natural gait. • Significant peak frontal plane rearfoot angles during stance. T-I 10° significantly decreased rearfoot eversion by −48%, −57%, and −61% compared with all the other conditions. Significant differences in frontal plane ankle rearfoot excursion was observed. T-I 10° significantly increased frontal plane rearfoot excursion by 20%, 32%, and 50% compared with all the other conditions. Also, ZR resulted in significantly increased frontal plane rearfoot angle excursion by 25% compared with T-O 20°. • Significant differences for sagittal plane ankle angles at IC was observed. Angles at IC during T-I 10° were significantly more dorsiflexed by 129% compared with T-O 10°. Additionally, T-O 20° was significantly more dorsiflexed by 138% and 136% compared with ZR and T-O 10°. No main effects could be detected for peak sagittal plane ankle angles during stance or for sagittal plane ankle angle excursion. • The foot rotation conditions resulted in different EKAM magnitudes, evidenced by the significant main effect for early and late stance peak EKAM. • NS findings for ankle eversion moment impulse after post hoc correction. No main effect for ankle inversion moment impulse could be detected. • A main effect for step width was found across conditions ($P=.001$). Pairwise comparisons revealed that T-I 10° increased step width compared with all the other conditions.

Barrios et al[9]	• NR	• Significant increase between baseline natural gait peak HIR: 5.3° (7.4°); posttraining modified peak HIR: 13.5° (8.5°); 1-month post modified peak HIR: 12.8° (9.2°); • NS change in peak hip adduction angle (P=.073); baseline natural gait hip adduction angle: 9.2° (2.4°).	• NR
Hunt et al[26]	• Normal gait TL 2.61° (1.64°); • Small TL 5° (0.87); • Medium TL 8.34° (1.61); • Large TL 12.88° (1.91).	• Significant early stance peak EHAM differences were observed between all TL conditions (5.22 [0.99], 4.61 [0.65], 4.09 [0.61] for small, medium, and large TL, respectively) compared with normal walking (5.72 [0.90], with greater early stance peak EHAM reductions associated with increasing amounts of TL, P<.001; • NS differences in late stance peak EHAM for any TL gait modification compared with normal gait (4.16 [1.13]), P>.05; • NS differences observed in peak hip abduction moment for any TL gait modifications compared with normal gait (1.38 [1.10]).	• NR
Mundermann et al[27]	• Increased mediolateral trunk sway (10° [5]).	• NS differences were observed for the maximum axial loading rates at the hip joint for normal gait (1286 [488]%Bw/s) and trunk sway (1250 [371]%Bw/s), P=.763; • Significant increase in maximum hip abduction moment of 55.3% between normal gait (2.0 [1.1]) and increased trunk sway (3.1 [1.3]), P<.001; • First peak EHAM was significantly reduced by 57.1% for the increased mediolateral trunk sway trial (1.8 [1.5]) compared with normal gait (4.2 [1.4]), P<.001.	• NS differences we observed for the maximum axial loading rates at the ankle joint for normal gait (1280 [490]%Bw/s) and trunk sway (1214 [356]%Bw/s), P=.568.
van den Noort et al[28]	• Pelvis lift decreased by more than 5° in 6 participants (NS at group level), pelvis protraction increased (4-6°, only significant for graph P=.03), and ipsilateral trunk sway decreased (2-3°, P<.01 except for color); • With HIR feedback, maximal hip extension decreased (5-6°, P<.05 for bar and polar), and pelvis protraction increased by >5° in 6 participants (but NS at group level).	• Hip angle feedback, HIR in the early stance phase increased significantly compared with baseline levels (bar 8°, P<.01; polar 10°, P<.01; color 8°, P<.01, graph 7°, P<.01). The bar, polar, and color showed the largest change in late stance (9° [P=.01], 11° [P<.01], and 8° [P=.03], respectively); • The kinematic changes that occurred while visual feedback on EKAM was provided included a decreased hip adduction (5°, polar P=.01, graph P=.02) and a maximal hip	• Kinematic changes that occurred while visual feedback on EKAM was provided included an increased T-I angle of more than 5° in 8 participants (on average: 2-7° at group level but NS), an increased step width (6-7cm, P<.03 for all feedback conditions); • While HIR feedback was provided, apart from significant changes in the HIR, participants also showed a significant increase in WS (7-10cm). Furthermore, 6 participants showed an increased T-I angle >5°, and 5 participants

(*continued on next page*)

Table 5 (*continued*)

Authors	Trunk and Pelvis	Hip	Ankle, Foot, and CoP
		extension decrease (4-5°, $P<.03$ except for color).	showed an increased T-O angle (on average 3-7° increase in T-I angle in group level but NS).
Dunphy et al[29]	• Significant differences were observed in maximum pelvic drop angle between normal gait (3° [1°]) and contralateral pelvic gait (7° [1°]), $P<.001$; • The correlation between change in pelvic drop and change in EKAM peak was $r=0.88$ ($P<.001$).	• Significant differences were observed in maximum hip adduction angle between normal gait (0° [2°]) and contralateral pelvic gait (4° [2°]), $P<.001$; • The correlation between change in peak hip adduction angle and change in EKAM peak was $r=0.83$ ($P<.001$); • NS differences in hip flexion/extension between normal gait and contralateral pelvic drop gait trials.	• NR
Khan et al[30]	• NR	• Through the entire range from T-I to T-O, the hip joint's contribution to the total limb work decreased significantly at slow speed from 35.00% to 22.00%; • The hip joint increased its contribution at normal gait speed (26%–37%) through T-I to T-O. • At T-O, significant increase of hip joint's contribution from 22% to 37% in slow to normal walking speeds; • At T-I, the contribution of hip joint decreased from 35% to 26% in slow to normal walking speeds.	• The mean ± SD of self-selected FPAs for ST, T-O, and T-I were 12.91 (4.78) cm, 31.56 (7.51) cm, and 13.43 (3.39) cm, respectively; • NS findings in ankle joint contribution by the speed transitions, except at T-I in slow to fast gait speeds. The ankle joint's contribution remained consistent except at slow speeds (decreased from 43.00% to 37.00%) from T-I to T-O gait.

Abbreviations: %Bw/s, percentage of body weight per second; CoP, center of pressure; EAAM, external ankle adduction moment; EAFM, ankle flexion moment; FPA, foot progression angle; HFM, hip flexion moment; HIR, hip internal rotation; IC, initial contact; LT, lateral trunk lean ; MT, medial thrust; NR, not reported; NS, nonsignificant; ST, straight-toe gait; T-I, toe-in gait; T-L, trunk lean; T-O, toe-out gait; ZR, zero rotation.

alterations. Strategies that reduced first peak EKAM the most were an increased trunk lean, hip internal rotation, and medial thrust gait (table 5). Conclusions are based on a very limited number of studies included within this review, emphasizing the need for further exploratory studies to be undertaken. In addition to the small number of included studies, the quality of the trunk lean gait style and medial thrust gait style studies was 15 of 25, indicating moderate methodological quality. These findings agree with the systematic review by Simic et al,[3] with medial thrust and trunk lean showing the highest reductions in early stance EKAM (see table 5). All studies lacked external validity, so the conclusions of these individual studies cannot be generalized to other populations. This systematic review has highlighted the need for further studies to assess the effect of gait retraining styles on a population group with OA.

The feasibility of applying these strategies in daily life might depend greatly on changes in the loading of joints, ligaments, and muscles throughout the kinematic chain, a potential increase of energy expenditure, and the aesthetics of the resulting gait.[24] Other studies outside of this review have indicated that trunk lean can increase energy expenditure, which may lead to fatigue and discomfort for the individual.[31,32] So, while trunk lean may aim have the biggest change in effect size to reduce knee joint loading, there may be changes in terms of energy expenditure that may be counterproductive.

In this systematic review, many studies reported very little evidence of the biomechanical effect of gait retraining on the hip and/or ankle joints. Accordingly, the adverse effects of the proposed gait retraining strategies cannot be thoroughly evaluated and should be addressed in future studies. This is an area of research that needs to be reviewed for future research before gait retraining can be recommended as a clinical intervention.

Despite the limited research available that has highlighted the consequences of reducing first peak EKAM from gait retraining interventions and its effects on the hip and ankle joints, the reduction in knee joint loading may be clinically important. However, any recommendations made must be made with caution because of the lack of available hip and ankle data as well as the lack of external validity within the studies. Hunt et al[26] outlined a pathway toward clinical translation of their findings, such as examining the biomechanical effects at other joints and overcoming potential barriers to using this intervention in individuals with knee OA. Van den Noort et al[28] suggested future research should focus on modification of gait patterns to the extent that a clinically significant reduction in the EKAM (and not a maximum) is achieved and a sustainable gait pattern is developed that can be maintained by patients with knee OA in daily life. Erhart-Hledik[12] states that the sustainability of the gait retraining and tolerability for longer-term clinical implementation requires future consideration. While the results are promising and the gait modification was readily achieved, a longitudinal study would be required to determine the feasibility of the gait modification to improve joint loading in the long term as well as evaluate potential improvements in clinical outcomes such as pain and function.

Study limitations

Only 11 studies were identified in this review, which varied in the consistency of biomechanics reported for the hip and ankle joints, and conclusive interpretation is limited. It is imperative to understand the consequences an altered gait has on the hip and ankle joints when considering a gait alteration for a clinical purpose, and future studies should aim to incorporate this into their study design. This lack in consistent reporting across the 11 studies also prevented the current systematic review in undertaking a meta-analysis on the current literature.

Of the 11 included studies, the majority had a low number of participants and involved 1 visit. Additionally, most studies used healthy participants without OA, so the translation of the findings to patients with medial OA is limited. Future studies should aim to evaluate gait retraining potential on individuals with medial knee OA and to analyze the effects of such retraining longitudinally over multiple visits. Finally, the participant's perspective on how difficult the gait retraining style is to perform should be assessed in future studies along with studies indicating the clinical translation of the retraining.

Conclusions

In conclusion, to our knowledge, this is the first systematic review that has focused on assessing gait retraining and its effects on first and second peak EKAMs as well as evaluating the biomechanical consequences to the hip and/or ankle biomechanics. This systematic review highlights the lack of studies that have included hip and/or ankle biomechanical consequences when altering an individual's gait with the objective of lowering knee joint loading. In addition, studies lacked external validity and were scored fair to moderate in their study quality. The findings from this systematic review should direct future research to undertake gait retraining research using patients with knee OA over multiple visits as well as analyzing the potential changes of the gait retraining strategy to the other lower limb joints. Without a thorough understanding of the biomechanical consequences of a gait retraining style at the hip and/or ankle joints, the clinical value of such gait styles cannot be determined.

Corresponding author

Jake Bowd, MSc, Cardiff School of Engineering, Cardiff University, Queens Buildings, The Parade, Cardiff, CF24 3AA. *E-mail address:* BOWDJB@cardiff.ac.uk.

Acknowledgments

Search strategy and database searches were assisted by 2 librarians at Cardiff University, Nicola Jones, BSc, PG Dip (School of Engineering) and Jonathan Jones, BA, MA (School of Healthcare Sciences).

References

1. Miyazaki T, Wada M, Kawahara H, Sato M, Baba H, Shimada S. Dynamic load at baseline can predict radiographic disease progression in medial compartment knee osteoarthritis. Ann Rheum Dis 2002;61:617-22.
2. Sharma L, et al. Knee adduction moment, serum hyaluronan level, and disease severity in medial tibiofemoral osteoarthritis. Arthritis Rheum 1998;41:1233-40.
3. Simic M, Hinman R, Wrigley T, Bennell K, Hunt M. Gait modification strategies for altering medial knee joint load: a systematic review. Arthritis Care Res 2011;63:405-26.
4. Birmingham TB, Hunt MA, Jones IC, Jenkyn TR, Giffin JR. Test-retest reliability of the peak knee adduction moment during walking in patients with medial compartment knee osteoarthritis. Arthritis Rheum 2007;57:1012-7.
5. Chang A, et al. External knee adduction and flexion moments during gait and medial tibiofemoral disease progression in knee osteoarthritis. Osteoarthr Cartil 2015;23:1099-106.
6. Reinbolt J, Haftka R, Chmielewski T, Fregly B. A computational framework to predict post-treatment outcome for gait-related disorders. Med Eng Phys 2008;30:434-43.
7. Whelton C, et al. Combined effect of toe out gait and high tibial osteotomy on knee adduction moment in patients with varus knee deformity. Clin Biomech 2017;43:109-14.
8. Hunt M, Charlton J, Krowchuk N, Tse C, Hatfield GL. Clinical and biomechanical changes following a 4-month toe-out gait modification program for people with medial knee osteoarthritis: a randomized controlled trial. Osteoarthr Cartil 2018;26:903-11.
9. Barrios J, Crossley K, Davis I. Gait retraining to reduce the knee adduction moment through real-time visual feedback of dynamic knee alignment. J Biomech 2010;43:2208-13.
10. Fregly B, D'Lima D, Colwell C. Effective gait patterns for offloading the medial compartment of the knee. J Orthop Res 2009;27:1016-21.
11. Simic M, Hunt M, Bennell K, Hinman R, Wrigley T. Trunk lean gait modification and knee joint load in people with medial knee osteoarthritis: the effect of varying trunk lean angles. Arthritis Care Res (Hoboken) 2012;64:1545-53.
12. Erhart-Hledik J, Asay J, Clancy C, Chu C. Effects of active feedback gait retraining to produce a medial weight transfer at the foot in subjects with symptomatic medial knee osteoarthritis. J Orthop Res 2017;35:2251-9.
13. Metcalfe A, et al. Abnormal loading of the major joints in knee osteoarthritis and the response to knee replacement. Gait Posture 2013;37:32-6.
14. Moher D, Liberati A, Tetzlaff J, Altman D. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. PLoS Med 2009;6:1-6.
15. Richards R, van den Noort J, Dekker J, Harlaar J. Gait retraining with real-time biofeedback to reduce knee adduction moment: systematic review of effects and methods used. Arch Phys Med Rehabil 2017;98:137-50.
16. Huang X, Lin J, Demner-Fushman D. Evaluation of PICO as a knowledge representation for clinical questions. AMIA Annu Symp Proc 2006:359-63.
17. Downs S, Black N. The feasibility of creating a checklist for the assessment of the methodological quality both of randomised and non-randomised studies of health care interventions. J Epidemiol Community Heal 1998;52:377-84.
18. Richards R, van den Noort J, van der Esch M, Booij M, Harlaar J. Effect of real-time biofeedback on peak knee adduction moment in patients with medial knee osteoarthritis: is direct feedback effective? Clin Biomech 2018;57:150-8.
19. McClelland J, Webster K, Feller J. Gait analysis of patients following total knee replacement: a systematic review. Knee 2007;14:253-63.
20. Moyer R, Birmingham T, Bryant D, Giffin J, Marriott K, Leitch K. Biomechanical effects of valgus knee bracing: a systematic review and meta-analysis. Osteoarthr Cartil 2015;23:178-88.
21. Shaw K, et al. The effects of shoe-worn insoles on gait biomechanics in people with knee osteoarthritis: a systematic review and meta-analysis. Br J Sports Med 2017;52:238-53.
22. Landis J, Koch G. The measurement of observer agreement for categorical data. Biometrics 1977;33:159-74.
23. Shull P, et al. Toe-in gait reduces the first peak knee adduction moment in patients with medial compartment knee osteoarthritis. J Biomech 2013;46:122-8.
24. Gerbrands T, Pisters M, Theeven P, Verschueren S, Vanwanseele B. Lateral trunk lean and medializing the knee as gait strategies for knee osteoarthritis. Gait Posture 2017;51:247-53.
25. Charlton JM, Hatfield GL, Guenette JA, Hunt MA. Ankle joint and rearfoot biomechanics during toe-in and toe-out walking in people with medial compartment knee osteoarthritis. PM R 2019;11:503-11.
26. Hunt M, Simic M, Hinman R, Bennell K, Wrigley T. Feasibility of a gait retraining strategy for reducing knee joint loading: increased trunk lean guided by real-time biofeedback. J Biomech 2011;44:943-7.
27. Mündermann A, Asay J, Mündermann L. Implications of increased medio-lateral trunk sway for ambulatory mechanics. J Biomech 2008;41:165-70.
28. van den Noort J, Steenbrink F, Roeles S, Harlaar J. Real-time visual feedback for gait retraining: toward application in knee osteoarthritis. Med Biol Eng Comput 2015;53:275-86.
29. Dunphy C, Casey S, Lomond A, Rutherford D. Contralateral pelvic drop during gait increases knee adduction moments of asymptomatic individuals. Hum Mov Sci 2016;49:27-35.
30. Khan S, Khan S, Usman J. Effects of toe-out and toe-in gait with varying walking speeds on knee joint mechanics and lower limb energetics. Gait Posture 2017;53:185-92.
31. Caldwell L, Laubach L, Barrios J. Effect of specific gait modifications on medial knee loading, metabolic cost and perception of task difficulty. Clin Biomech 2013;28:649-54.
32. Takacs J, et al. Lateral trunk lean gait modification increases the energy cost of treadmill walking in those with knee osteoarthritis. Osteoarthr Cartil 2014;22:203-9.