

GAIT MODIFICATION TO REDUCE LOWER EXTREMITY JOINT LOAD: A
REVIEW AND INVESTIGATION INTO UNINTENDED CONSEQUENCES

by

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A Dissertation
Submitted to the
Graduate Faculty
of
George Mason University
in Partial Fulfillment of
The Requirements for the Degree
of
Doctor of Philosophy
Education

Committee:

Chair

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Dean, College of Education
and Human Development

Date: _____

Summer Semester 2019
George Mason University
Fairfax, VA

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Acknowledgements

I would like to thank my advisors, colleagues, and undergraduate students in the Division of Health and Human Performance at George Mason University. Thank you to everyone involved with the SMART Lab, including faculty, Mason students, and summer interns. Finally, thanks go out to my research team for providing adequate and timely feedback.

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List of Abbreviations

Absolute sagittal plane moment.....	KFM _{abs}
Analysis of variance.....	ANOVA
External knee adductor moment	KAM
External knee flexor moment.....	KFM
Ground reaction force	GRF
Internal knee abductor moment	KabM
Internal knee extensor moment.....	KEM
Knee Injury/Osteoarthritis Outcome.....	KOOS
Late-Life Function and Disability Basic Lower Limb Function	LLFDI
Magnetic resonance imaging	MRI
Medial knee contact force.....	MCF
Medial knee contact force.....	MCF
Osteoarthritis.....	OA
Pain-related outcome measures.....	PROMs
Patellofemoral joint.....	PFJ
Preferred Reporting Items for Systematic Reviews and Meta-Analyses.....	PRISMA
Rate of loading.....	ROL
Real-time biofeedback	RTB
Standard deviation	SD
Tibiofemoral joint	TFJ
Visual analog pain scales.....	VAS
Western Ontario and McMaster Universities Arthritis.....	WOMAC

Abstract

GAIT MODIFICATION TO REDUCE LOWER EXTREMITY JOINT LOAD: A REVIEW AND INVESTIGATION INTO UNINTENDED CONSEQUENCES

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George Mason University, 2019

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Gait modification using real-time biofeedback may positively alter mechanical load at the knee. Currently, there is no consensus regarding the most effective gait-modification strategy, magnitude of modification, or mode of biofeedback. The effects on the biomechanical parameters of the non-modified limb also remain unclear. Additionally, trunk modifications are associated with frontal plane knee moment reductions ranging from 9% to 65%, and involve a shift of the center of mass to the implicated side. Increased trunk dynamics are associated with increased spinal load, and implicated in the pathomechanics of lower back pain. Three studies were conducted to achieve the objective of this dissertation. Their purposes were to (1) systematically assess the efficacy of gait modification using real-time biofeedback for reducing frontal plane knee moment; (2) investigate the acute changes in the biomechanical parameters of the non-modified side in individuals undergoing unilaterally implemented medial knee thrust, lateral trunk lean, and toe-in foot progression gait modification; and (3) to investigate the

effects of subject-specific trunk lean gait modification on trunk kinetics. Overall, the findings of this dissertation inform gait-retraining-related research. Gait modification produced frontal plane knee moment reductions, although available evidence was of low quality. During the medial knee thrust gait modification, the loading environment of the non-modified knee for our healthy cohort appeared compromised. We further found increased spinal load throughout the gait cycle during the lateral trunk lean gait condition. Future experimental studies using experimental designs should investigate acute and chronic adaptations to gait modification within both healthy and pathological populations.

Chapter One. Overview

Introduction to the Problem

Osteoarthritis (OA) is one of the most common joint disorders in the U.S.¹⁻⁴ It has been projected that by 2040, 26% of the adult population will be diagnosed with OA.⁵ The economic cost for OA continues to rise, with costs not just limited to treatment but also attributed to indirect expenses as a result of lost wages.⁶ Knee OA is an often-diagnosed form of the disease,⁴ and the knee is the most injured lower extremity joint.⁷ Symptoms associated with knee OA include: pain, joint stiffness, and functional instability, resulting in reductions in patients' abilities to perform activities of daily living.⁸ Due to the nature of the disease and the associated comorbidities, it is considered a major contributor to years of life lived with disability.⁸ The etiology of knee OA is multifactorial, with risk factors that include excessive bodyweight/obesity,⁴ aging,⁴ varus alignment,⁴ and altered joint mechanics.^{4,9}

Medial compartment OA, also referred to as tibiofemoral joint (TFJ) OA, is the most common form of the disease.^{10,11} This is where the articular surface damage results in the narrowing of the medial joint space, and an increased frontal plane knee moment.¹²⁻¹⁴ The external knee adductor moment (KAM) or internal knee abductor (KabM) are frontal plane knee moments used to non-invasively quantify medial compartment knee load. KAM and KabM are fundamentally equal with the internal

moments resisting the actions of external moments. The relationship can be thought of as equal, but with opposing signs. An increase in the net frontal plane knee moment acts to force the tibia into varus and is a reliable indicator of medial compartment load.¹⁵⁻¹⁷ Repetitive loading of the varus aligned knee has been suggested to contribute to higher load at the medial knee joint resulting in medial compartment articular surface damage.^{18,19} Reducing peak frontal plane knee moment in individuals with elevated risk for knee OA has been proposed to result in reduced pain via decreased TFJ load.

Currently numerous options exist for disease treatment and management, and they include the use of drug therapy, external devices, and surgical interventions.²⁰ Other available treatment options include total or partial knee replacement, osteotomy, and the use of external aids including lateral shoes wedges and walking poles. Current treatments have had limited impact on the prognosis of the disease, and forecasted prevalence for the disease is on a precipitous rise.⁵ Gait modification using real-time biofeedback (RTB) is an emerging treatment option that has garnered attention for altering gait mechanics and reducing frontal plane knee moment.²¹

Gait modification using RTB has been implemented effectively for various pathologies such as for: diabetic, post stroke, Parkinson's, and joint replacement patients.^{22,23,23} Gait modification is associated with reduced pain,²⁴ improved function,²⁵ and task retention.²³ Reports indicate greater success for RTB than for conventional physical therapy in certain pathologies.²³ Early evidence supports the usefulness of gait modification using RTB in achieving moderate to large reductions in frontal plane knee moment. However, limitations of the current literature constrain the generalizability and

clinical application. Methodological differences including strategy implemented, training methods, and evaluation of skill acquisition means there is no clear consensus regarding the most effective gait strategy, mode of feedback, or treatment dosage.¹⁷

Frequently investigated gait-modification strategies include toe-in foot progression,²⁶ toe-out foot progression,²⁷ medial knee trust,²⁸ and trunk modification.^{21,29} Secondary changes as a result of implementing gait modification have, however, received limited attention. Gait modification is usually implemented in the dominant limb for healthy participants, or the most symptomatic side for arthritic patients. A previous study investigated contralateral limb toe-in foot rotation during unilaterally implemented toe-in foot progression.³⁰ The authors reported a significant increase in contralateral foot rotation during gait-modification trials compared to baseline.³⁰ Potential changes in the kinetic parameters of the contralateral limb were not investigated. When introducing gait modification unilaterally, it may be important to investigate potential load redistribution, specifically at lower extremity load-bearing joints that have been indicated to be most susceptible to degenerative changes, as well as the spine. Increasing trunk motion, particularly medio-laterally, has been associated with increased trunk moment,³¹ muscle activity,³² and spinal load.^{31,33} Excessive trunk movement is implicated in the etiology of lower back pain.^{31,33} While it is important to understand the effectiveness and long-term benefit of gait modification, there is a concurrent need to better understand the potential effect of these modifications throughout the kinetic chain. To date, however, the effects of gait modification on the loading environment of the spine and contralateral side are yet to be explored.

Statement of the Research Problem and Purpose

The main purpose of this PhD dissertation was to assess the efficacy of gait modification using real-time biofeedback for reducing frontal plane knee moment, pain, and for improving function in both healthy individuals and individuals with knee OA, and to investigate acute changes in the biomechanical parameters of the trunk and non-modified side in participants undergoing unilaterally implemented gait modification. To accomplish this, a systematic review and a within-subject repeated measures study were conducted. Each study has its own specific research question and hypothesis based on scientific rationale. This is presented through 3 scientific studies that are either published or under review.

Study 1. Title: Current Evidence of Gait Modification with Real-Time Biofeedback to Alter Kinetic, Temporospatial, and Function-Related Outcomes: A Review

Status: Published

Rationale: Gait modification using real-time biofeedback (RTB) has been credited with positive outcomes for various pathologies. Early evidence from studies investigating the effectiveness of the intervention support its usefulness for reducing frontal plane knee moment. The effects of gait modification using RTB on kinetic, kinematic, and temporospatial variables other than the frontal plane knee moment that may be clinically relevant have largely been ignored. Unanticipated changes at the knee joint such as increased knee flexion moment (KFM) and KAM/KabM angular impulse may offset the

benefits of reduced peak frontal plane knee moment by increasing joint compression, and time under loading.

Research questions: (1) Are gait-retraining interventions using RTB beneficial to alter frontal plane knee moment, pain, and improve function in patients with knee OA? (2) Are the various gait-modification strategies along with modes of RTB reported in the literature effective for reducing the frontal plane knee moment in both healthy and symptomatic individuals? (3) What are the impacts of gait-retraining interventions using RTB on other outcome variables that may affect clinical outcomes?

Study 2. Title: Unintended Changes in the Contralateral Limb as a Result of Gait Modification

Status: Under review

Rationale: Based on the findings of the systematic review, a question that emerged was related to unintended secondary changes following gait modification. Chronic adaptations to gait asymmetries observed in patients with unilateral symptomatic knee OA may be responsible for the reported contralateral knee joint degeneration. The effect of unilaterally implemented medial knee thrust, lateral trunk lean, and toe-in foot progression on the biomechanical parameters of the non-modified limb remains unclear.

Research question: Are there acute changes in the biomechanical parameters of the non-modified side in participants undergoing dose-specific medial knee thrust, lateral trunk lean, and toe-in foot progression gait modification?

Hypothesis: Implementing gait-modification strategies would increase the joint moments at the non-modified knee and hip as a result of the introduced asymmetry.

Study 3. Title: Increased Trunk Kinetics Observed During Subject-Specific Lateral Trunk Lean Gait Modification

Status: Submitted

Rationale: Trunk modifications are associated with frontal plane knee moment reductions ranging from 9% to 65%. Lateral trunk lean is a commonly implemented trunk modification that involves a unilateral shift of the center of mass to the implicated side, which serves to move the ground reaction force (GRF) closer to the stance knee joint center, and results in reduced frontal plane knee moment. Evidence suggests that increased trunk motion is associated with increased trunk moment, which is associated with increased spinal load, and muscle activation. Increased structural load at the spine has been identified as proximate cause of low back pain and can be estimated using trunk kinetics.

Research question: Would implementing subject-specific lateral trunk lean gait modification result in increased trunk load during ipsilateral and/or contralateral stance phases in healthy participants?

Hypothesis: Implementing subject-specific lateral trunk lean would not result in significant increase in trunk kinetics due to the conservative trunk movement associated with the approach.

Operational Definitions

- Gait modification: A transient change in kinematic or temporospatial variable to achieve an intended goal.

- Osteoarthritis: A degenerative disease and the most common form of arthritis, which commonly occurs at the hands, hip, and knee.³⁴
- Medial compartment osteoarthritis: The most common form of knee OA, as a consequence of articular damage that results in narrowing of the joint space.^{12–14}
- Internal moment: The external joint moment balances the internal moment produced by the muscles and ligaments. They are fundamentally equal but have opposite signs.³⁵
- Frontal plane knee moment: A proxy used to assess knee compartmental loading.³⁶ Reduced KAM/KabM in individuals with knee OA have been suggested to result in decreased pain,⁹ disease severity,³⁷ and disease progression.³⁸
- Frontal plane knee moment angular impulse: The area under the KAM/KabM waveform, which represents total exposure of the medial compartment to load both by magnitude and duration.³⁹
- Knee flexor moment: A measure of sagittal plane load, reported to contribute significantly to medial compartment load.⁴⁰ It provides an estimate of mechanical loading at the tibiofemoral and patellofemoral joints.^{40,41}
- Inverse dynamics: The process of determining joint reaction forces and muscle moments through the use of link-segment modeling.⁴²
- Joint contact force: Net loading at the joint as a result of muscle forces, gravitational forces, inertial forces, GRF, and moments.⁴³

Assumptions.***Study 2.***

1. The convenient sample used is representative of the population.
2. Biomechanical changes observed in healthy individuals are comparable to what is expected in patients with symptomatic knee OA.
3. There is no significant variability in the frontal plane knee moment over longer walking periods.

Study 3.

1. The convenient sample used is representative of the population.
2. Biomechanical changes observed in healthy individuals are comparable to what is expected in patients with symptomatic knee OA.

Delimitations.***Study 2.***

1. A single-session within-person repeated measures study design was employed. The reported changes are acute by nature and may not persist over time.
2. Conservative magnitudes of modification were implemented.

Study 3.

1. A single-session within-person repeated measures study design was employed. The reported changes are acute by nature and may not persist over time.
2. Conservative magnitudes of modification were implemented.

Chapter Two. Literature Review

The purpose of this chapter is to provide a review of literature relevant to this dissertation. In order to fully appreciate the economical burden of OA and the significance of cost-effective treatment, one must have an understanding of the prevalence of the disease as well as the risk factors and limitations of current treatment options. Therefore, the first section of this chapter covers the epidemiology and economic cost of OA, followed by a focus on the different types of knee OA and the identified risk factors for the disease. The next section within the chapter discusses current treatment options, and introduces gait modification as a viable option for slowing down disease progression. The remainder of the chapter covers potential implications of implementing gait modification, such as biomechanical considerations for the trunk and non-modified limb.

This chapter presents information on the various gait-modification strategies, and their effectiveness in reducing frontal plane knee moment, frontal plane knee moment angular impulse, and effect on KFM. The chapter concludes with a discussion of the efficacy of gait modification to reduce biomechanical risk factors associated with OA progression, and investigating potential unanticipated changes in the kinetic chain as a consequence of introducing gait modification.

Osteoarthritis

OA is one of the most common joint disorders in the U.S.⁴ with the total attributable cost for OA ranging between \$303.5 and \$326.9 billion in 2013.⁶ OA is reported to affect almost 15% of the population,^{1,8} and has an incidence rate that has risen dramatically over the last 20 years.⁴⁵ In the arthritic joint, the activities of the degradative enzymes are greater than those of the anabolic factors.⁴⁶ The associated imbalance in the cartilage enzyme activities triggers an inflammation cascade, accelerating both cartilage degeneration and damage to the joint structure. OA is a leading cause of pain and disability among adults, and impacts many health outcomes.¹ As a result of the graying of America, the projected impact of OA will be significant. The hip and knee are the most common lower extremity sites for disease occurrence,^{4,8} and the disease can be characterized as either radiographic or symptomatic.⁸ Radiographic OA includes diagnosis solely based on X-ray evidence, while diagnosis of symptomatic OA involves both radiographic evidence, as well as clinical diagnosis of pain and loss of function.⁸

Knee osteoarthritis. Knee OA is a common form of the disease,⁴ and the knee is the most injured joint of the lower extremity.⁷ Knee OA is associated with reduced quality of life, and inherent comorbidities as a consequence reduce participation in physical activity.⁴ Comorbidities such as obesity resulting from physical inactivity create a vicious disease cycle, because obesity is one of the leading risk factors for developing knee OA.⁴⁷ The economic cost for knee OA has continuously risen, with cost not just limited to treatment but also attributed to indirect expenses as a result of lost wages. The estimated lifetime risk of developing knee OA is approximately 40% in men and 47% in

women, with over half of all persons with symptomatic knee OA younger than 65 years of age.^{4,48} The symptoms of knee OA include pain, joint stiffness, and functional instability which reduces patients' abilities to perform activities of daily living and making it a major contributor to years of life lived with disability.⁸ The etiology of knee OA as described above is multifactorial, with risk factors that include excessive bodyweight/obesity,⁴⁷ aging, varus alignment, and altered joint mechanics.⁴⁹

Tibiofemoral joint OA. Knee OA most commonly occurs in the medial compartment of the knee,^{10,11} where articular surface damage narrows the medial joint space, resulting in increased frontal plane knee moment.¹²⁻¹⁴ Repetitive loading of the knee with varus alignment has been reported to result in higher loads at the medial knee joint causing medial compartment articular surface damage,^{18,19} and resulting in greater forces at the knee. Reducing peak frontal plane knee moment in individuals who have or are at elevated risk for TFJ OA has been suggested to result in decreased pain, via reductions in TFJ load.

In a study investigating 56 arthritic knees, 25% were diagnosed with unicompartmental OA, 61% with bicompartamental OA, and 14% with tricompartmental OA.¹¹ It has been reported that less than 50% of people diagnosed with radiographic OA have symptoms related to the findings.⁵⁰ The cartilage does not contain pain receptors, which means the source of the diagnosed pain is currently unexplained.

Patellofemoral joint OA. Patellofemoral joint (PFJ) OA is another type of knee OA associated with pain and dysfunction.^{50,51} An increase in severity of isolated PFJ OA is associated with greater levels of pain, stiffness, and functional limitation, after

adjusting for age, gender, and BMI.⁵¹ Radiographic and magnetic resonance imaging (MRI) reports from previous studies indicated that approximately 64% of the adults studied over 50 years of age have PFJ OA, a third of whom were classified as having isolated PFJ OA.⁴¹

Teng et al. suggested that the prevalence of PFJ OA is as high, if not higher than, TFJ OA. It is theorized that the reduction in cartilage tissue alters the joint loads through the retropatellar surface, placing greater deforming stress upon the underlying subchondral bone.⁵⁰ Increased late stance external KFM and KFM impulse have been associated with higher PFJ reaction force and joint stress.⁴¹ An increase in these biomechanical parameters was associated with knee cartilage deterioration in patients with PFJ OA when assessed via magnetic resonance imaging 1 year later.⁴¹

Risk factors. Risk factors for knee OA can be classified as person-level factors or joint-level factors.⁴ Person-level factors include sex, age, obesity, genetic, ethnicity, and bone metabolism.⁴ Identified joint-level factors include a history of previous knee injury, and varus alignment.^{4,49,52,53} Improving joint mechanics by reducing the frontal plane knee moment in individuals with TFJ OA has been suggested to result in decreased pain,⁹ reduced disease severity,³⁷ and slower disease progression.³⁸ Increased peak frontal plane knee moment is associated with TFJ OA severity,⁵² cartilage loss,^{40,54} static malalignment,⁵⁵ and has been shown to be a reliable indicator of medial knee joint load and alignment.^{37,38,56} Other personal-level risk factors include the individual's profession as some physical job requirements introduce unique stress to the musculoskeletal system compared to others.

Lower extremity gait biomechanics. Increased knee extension at initial contact, reduced knee flexion throughout stance, altered hip angle, and reduced gait speed have been observed in symptomatic patients.⁵⁷ The reported adaptations are related to disease severity,⁵⁷ and pain level.⁵⁸ Individuals with less disease severity and/or on pain medication presented with more pronounced kinematic changes compared to control, and patients with more severe diagnosis.⁵⁷ Additionally, reduced pain in symptomatic individuals was reported to result in increased knee joint loads.⁵⁸

The medial knee contact force (MCF) is a measure of the internal knee loads contributing to the detrimental biomechanics associated with cartilage loss.⁴³ Peak frontal plane knee moment can be assessed non-invasively, and is an accepted surrogate for the MCF. Including both the absolute sagittal plane moment (KFM_{abs}) and the frontal plane knee moment in regression equations significantly improves the prediction of internal loading (MCF) using external moments. Miyazaki et al. reported that a 25% increase in overall magnitude of the peak frontal plane knee moment at baseline was associated with 6.6-fold increase in the risk of radiographic medial compartment disease progression over 6 years.³⁸ Peak frontal plane knee moment is a measure associated with a single time point. Frontal plane knee moment angular impulse is defined as the total area under the frontal plane knee moment time curve, and has been reported to be predictive of cartilage volume loss over 12 months using MRI.⁵⁹ Frontal plane knee moment angular impulse takes into account not just the magnitude of load at an instance in time but also the duration of stance, and has been suggested to be a more comprehensive proxy of the medial compartment loading.⁶⁰

Absolute sagittal plane moment. The absolute values of the first and second KFM/knee extensor moment (KEM) peaks have been suggested to contribute to increased joint compression via an increase in either the flexion or extension moment. Regression models that use both the frontal plane knee moment and absolute KFM to predict MCF are more strongly correlated to *in vivo* measured MCF ($r^2 = 0.85\text{--}0.93$) than those that use the frontal plane knee moment alone ($r^2 = 0.63\text{--}0.68$).^{61,62} Regression analyses show that peak values of MCF were best fitted by a combination of peak values of the frontal plane knee moment and KFM_{abs}. Regardless of the direction of the sagittal plane moment, an increase is detrimental to knee joint health.

Increased knee flexor/extensor moment has been previously associated with changes in cartilage thickness and is suggested to attenuate expected reductions in joint load via frontal plane knee moment reduction.^{40,62} It is suggested that a reduction in the frontal plane knee moment with a subsequent increase in peak knee flexor/extensor moment may be detrimental for cartilage health.⁴⁰ For instance, studies investigating medial knee thrust gait have shown increases in peak knee flexor/extensor moment,^{28,62,63} and have suggested that an emphasis on increased internal hip rotation without a corresponding increase in knee flexion may mitigate an observed increase in peak knee flexor/extensor moment. These results suggest that KFM_{abs} should be considered when evaluating the effectiveness of any gait-modification intervention, since the frontal plane knee moment alone may not reflect the overall loading environment.^{40,62}

Internal versus external moments. The interpretation of the internal joint moment is different from that of the commonly reported external moment. However, they are

fundamentally equal with the internal moments resisting the actions of external moments. The relationship can be thought of as equal, but with opposing signs.³⁵ A large internal K_{abM} is needed to balance a large external K_{AM} , and will result in a large contact force.⁶⁴ For instance, increased external knee flexor moment is related to increased quadriceps activity, which contributes to increased internal knee joint loads.⁶⁵ This would correspond to an increased internal knee extensor moment.

Treatment Options

Numerous treatment and management options for TFJ OA have been recommended, including the use of non-pharmacologic, pharmacologic, and surgical interventions with the goal of reducing symptoms and medial compartment load.²⁰ Available treatment options include the use of land- and/or aquatic-based exercises that involve static and dynamic movements which have been reported to reduce pain and improve function in patients with TFJ OA.⁶⁶ Drug therapy is an effective treatment option, however such medications alleviate the symptoms but do not necessarily modify the damage to the joint structure.⁶⁶ Pharmacological options include the use of steroid injections such as cortisol and over-the-counter nonsteroidal antiinflammatory drugs such as aspirin.⁶⁷ Other treatment options include orthopaedic procedures such as knee replacement, osteotomy, and the use of external aids including lateral shoes wedges, knee braces, and walking poles. Current treatments have had limited impact on the prognosis of the disease, and with the forecasted 78 million adults projected to be diagnosed with OA by 2040, it is prudent to investigate potential options for treatment. Gait modification

is an emerging option with low cost, and early promising results for treating frontal plane knee moment.

Gait and balance training have shown positive outcomes in other pathologies (e.g., diabetes, stroke, Parkinson's, joint replacement).²²⁻²⁴ Improvement in motor and gross function, as well as dynamic and functional balance, have been reported, indicating greater success for gait retraining than for conventional physical therapy in various pathologies.^{22,24} These findings have been supported by recent studies reporting a similar effect of gait modification using RTB on peak frontal plane knee moment.¹⁷

Gait Retraining

Gait-modification strategies can be classified as single- or multi-parameter. Single-parameter strategies are directed at one kinematic or temporal spatial variable during training sessions, while multi-parameter strategies target 2 or more kinematic and/or temporal spatial variables. Gait-modification strategies reported in literature include trunk modification,^{21,29,32} medial knee thrust,²⁸ and altered foot progression angle.^{26,68,69} Medial weight shift of the foot during stance,^{70,71} and the use of self-selected kinematic adjustment to reduce frontal plane knee moment,^{72,73} have also been reported. Other gait-modification strategies reported in literature include reduced rate of loading through increased knee flexion and decreased vertical acceleration,⁷⁴ increased stride width,⁷⁵ gait retraining towards symmetrical and typical displacements of the trunk and pelvis,⁷⁶ and multi-parameter gait retraining through a combination of altered foot progression angle, increased trunk sway, medial knee thrust, and/or increased tibia angle.⁶⁹

Single parameter. Single-parameter gait-modification strategies have been associated with reductions in frontal plane knee moment ranging from 9 to 65%.^{21,28,29,71,77} Single-parameter strategies, such as lateral trunk lean,²¹ medial knee thrust,^{28,71} and medial weight shift,⁷¹ however have been reported to be less effective in reducing frontal plane knee moment compared to both self-selected⁷³ and multi-parameter.⁶⁹ These assessments were based primarily on the magnitude of the frontal plane knee moment reduction, and not on consideration of other factors such as changes in sagittal plane biomechanics or clinical practicality. Newer reports indicate that reductions in KAM/KabM with a concomitant increase in knee flexion moment result in no positive changes to medial compartment load.^{62,65,78}

Toe-in foot progression. Toe-in gait modification involves increasing the internal rotation of the foot with respect to the anterior posterior direction, and has the effect of shifting the center of pressure laterally as a result of the external rotation of the heel. This results in a reduction of the moment arm for the center of pressure to the knee joint center during the first double support period, which theoretically results in frontal plane knee moment reduction.⁷⁹

Toe-out foot progression. Toe-out gait modification involves increasing the external rotation of the foot with respect to the anterior posterior direction, and may reduce the frontal plane knee moment. The frontal plane knee moment is the product of the GRF vector and the perpendicular distance from the GRF vector to the knee joint center of rotation (moment arm). In theory, toeing-out during gait shifts the GRF vector

closer to the knee joint center and decreases the moment arm, thereby reducing the frontal plane knee moment.⁸⁰

Lateral trunk lean. Lateral trunk lean gait modification is defined as the frontal plane deviation of the line representing the trunk from the global vertical axis.²⁹ The lateral shift in the center of mass serves to move the GRF closer to the stance knee joint center, potentially decreasing the associated moment arm, thereby reducing the frontal plane knee moment.

Medial knee thrust. Medial knee thrust involves gait patterns that drive the targeted knee medially, causing the GRF vector to pass more laterally to the knee center than in the normal gait.⁶³ Increasing medial knee thrust reduces the knee varus angle, thereby decreasing the frontal plane moment arm.⁷⁹ The decrease in the moment arm of the GRF results in frontal plane knee moment reduction.

Stride width. Increased stride width lateralizes the center of pressure, allowing the ground reaction force to pass closer to the knee joint center.⁷⁹ This action results in decreasing the moment arm for the GRF vector, which theoretically will result in frontal plane knee moment reduction.

It has been suggested that implementing lateral trunk lean and medial knee thrust in symptomatic populations may present challenges potentially due to difficulty of adoption. In comparison, medial weight transfer is easier to adopt, as it requires only a subtle change in gait and is not associated with a concomitant increase in KFM reported with other gait-modification strategies. Nonetheless, reported reductions in the frontal plane knee moment of 9% to 14% when using medial weight transfer are only slightly

greater than those observed in orthotic interventions, reducing clinical impact compared to other modification strategies.^{81,82} Modified foot progression angle has also been reported to be relatively easier to implement as it requires less complex changes to gait but has shown smaller reductions in the frontal plane knee moment compared to medial knee thrust and lateral trunk lean strategies.^{26,68}

Multi-parameter. Multi-parameter gait modification is reported to result in greater reductions in the frontal plane knee moment compared to single-parameter. A recent study, however, reported secondary kinematic changes such as increased step width at an amplitude equal to 60% of the instructed modification when using a single parameter strategy, indicating that concomitant secondary kinematic gait changes do occur.⁸³ When participants combined 3 gait modifications (toe-in, increased step width, and increased trunk sway) a decrease in first peak frontal plane knee moment of approximately 49% was reported.⁸³ Multi-parameter strategies may represent an optimum approach to a natural concomitant relationship of the kinetic chain, whereas employing a single variable, especially when self-selected, might in addition result in unanticipated and unintended outcomes.

Self-selected gait modification. Individuals using a self-selected gait-modification strategy, without further instruction, have been observed to exhibit 35% of additional modifications such as: increased or decreased foot progression angle greater than 15°, increased stride width of more than 10-cm, increased knee flexion, hip abduction, and pelvic protraction.⁷² In general, gait modifications to modify frontal plane knee moment have been reported to result in kinematic, kinetic, and spatiotemporal

effects across the kinetic chain; however, long-term outcomes due to these changes remain poorly understood.¹⁷

Individualization. When implementing gait modification, specifically single-parameter strategies, individual responses should be considered. It is suggested that both the type of strategy employed and the dose of strategy should be individualized due to the variance in response observed in people undergoing gait retraining.^{65,83,84} Evidence suggests that reduction in the frontal plane knee moment per unit of gait modification is highly variable among participants, signifying that individual dose-response relationships exist.^{83,84} As an example, using the same protocol, the magnitude of frontal plane knee moment change varied from as little as 3% to more than 50% within the same study.⁷³ These results indicate that the optimal gait-modification strategy will differ between individuals and it is plausible to suggest that the intervention needs to be adaptable to each patient.

It can be inferred that adopting arbitrary gait-modification strategies and target ranges that are uniform across individuals can limit the effectiveness of the intervention. Utilizing individualized gait-modification strategies as well as individualized target ranges may lead to improved outcomes. This suggests that future studies should assess the effect of each modification on the individual before implementing a new gait strategy, demonstrating the importance of assessing each individual's biomechanics to identify the most appropriate intervention. Future studies should assess the effects of gait-modification strategies on the individual before implementation.

Biofeedback. Visual, haptic, auditory RTB, or a combination is often used to implement gait modification. The 2 most frequently used biofeedback techniques are visual^{28,69,73,76,85} and haptic.^{26,68,69,73} Some studies have combined both visual and haptic biofeedback in an effort to increase effectiveness.^{69,73,79} Concurrent visual feedback has been cited to be effective in rehabilitation of complex motor skills.^{81,86} Haptic biofeedback might, however, possess greater advantages both inside and outside the clinic due the miniature nature of haptic devices, and potential future advancements in technology.⁸⁷ Employing augmented haptic feedback provides added benefits to the sensory system due to the location and proximity of the haptic sensors to the site of intended modification.⁸⁸

Some studies have used the frontal plane knee moment as the biofeedback variable, although the majority of gait-modification studies use kinematic measures associated with estimated knee load reduction.^{21,26,28,68,69,71,76,85} Studies employing the frontal plane knee moment as the biofeedback variable have reported greater reductions, indicating a better response to biofeedback based on the target kinetic parameter, compared to a kinematic measure.^{72,73}

Direct and indirect feedback. The target of the biofeedback can either be a kinematic variable referred to as indirect, or a direct approach where frontal plane knee moment is the feedback variable. Direct feedback is associated with larger frontal plane knee moment reductions.⁷⁹ The use of kinematic measures such as trunk angle, knee angle, foot angle, and/or step width have been shown to result in effective reductions in the frontal plane knee moment. While both represent forms of augmented implicit

feedback on knowledge of performance, the indirect nature of the modifications results in varied response. For certain individuals change in the measured kinematic profile might not result in the anticipated frontal plane knee moment reduction; employing direct feedback overcomes this limitation.^{26,72,73}

The use of direct feedback presents issues with clinical applicability, and ecological validity. Physical therapy clinics and rehabilitation centers usually do not have access to instrumented treadmills or force plates, which are required to deliver direct feedback. Other benefits of using kinematic surrogates include the potential availability of customized haptic or visual devices used to reinforce gait modification acquired while outside the testing environment.

Gait Modification and Joint Biomechanics

It is important to consider the compartmental implications when implementing gait modification. Gait modification with the intention of reducing medial compartment load could be contraindicated for knees with both medial and lateral compartment OA. It is important to consider the biomechanical risk factors for OA in other compartments before implementing gait modification due to the prevalence of bi-compartmental knee OA.¹¹ For instance, gait-modification strategies employed to attenuate early stance KAM/KabM and KFM, which results in increased late stance KFM, would be contraindicated for individuals diagnosed with both TFJ OA and PFJ OA. Increased late stance peak KFM moment is associated with PFJ OA severity and progression.⁴¹

The first peak frontal plane knee moment or overall peak frontal plane knee moment during stance is usually the reported measure, and the target for reduction. The

first peak frontal plane knee moment is associated with the magnitude of joint load experienced during the first 50% of stance.⁵² Some studies have targeted the second peak frontal plane knee moment during gait modification.⁸⁰ Current evidence suggests that the first peak frontal plane knee moment is predictive of medial compartment OA severity and disease progression.^{49,52} The significance of second peak frontal plane knee moment reduction is not as apparent, since it is associated with terminal stance.

The Non-Modified Limb

Epidemiological reports indicate that 87% of patients who were candidates for knee replacement had radiographic knee OA with a severity greater than 2 on the Kellgren-Lawrence in their contralateral knee.⁸⁹ Asymmetry between limbs during gait is associated with pain in patients with unilateral symptomatic knee OA. This asymmetry was absent in patients with bilateral pain or in asymptomatic cohorts.⁹⁰ Gait asymmetry is believed to be a feature of knee OA.⁹⁰ The observed gait compensations for pain avoidance might accelerate onset of symptomatic OA in the pain-free knee.⁹⁰

Gait modification is usually implemented unilaterally. Despite the nature of gait modifications, and their propensity to increase axial loading along the kinetic chain⁹¹—particularly in the case of multi-parameter and self-selected gait strategies—their potential effects on the contralateral limb remain poorly understood. While it is important to understand the effectiveness and long-term benefit of gait modification with RTB, there is a concurrent need to better understand the potential effect of these modifications throughout the kinetic chain. When introducing gait modification unilaterally, it may be important to investigate load redistribution, specifically at lower extremity load-bearing

joints that have been indicated to be most susceptible to degenerative changes.^{20,89} To date however, the effects of gait modification on the non-modified side have yet to be explored.

Spinal Load

Trunk modification involves the frontal plane deviation of the trunk segment in respect to the global vertical axis.²⁹ The resulting displacement of the center of mass towards the implicated knee would theoretically move the GRF closer to the stance knee joint center. This is initiated to decrease the moment arm of the frontal plane knee moment and to redistribute medial compartment load.⁷⁷ Trunk modifications are associated with frontal plane knee moment reductions ranging from 9 to 65%.^{21,29,77} Two commonly implemented strategies are the trunk sway and lateral trunk lean. Trunk sway involves a medio-lateral shift during gait, typically using uncontrolled magnitude. Trunk sway gait modification has been credited with frontal plane knee moment reductions as high as 65%.²⁹ Lateral trunk lean involves a unilateral shift of the center of mass in the direction of the implicated limb and is associated with more modest frontal plane knee moment reductions.²¹ In contrast to trunk sway, trunk lean involves specified trunk modification magnitudes. Frontal plane knee moment reductions of 9-15% have been associated with this gait-modification strategy.²¹ Increased trunk motion is associated with changes to the structural load at the spine, however.³¹

Increased transverse plane trunk kinematics have been reported to contribute to lower back pain in individuals with transfemoral amputation.⁹² Transverse spinal instability accompanied with increased multi-planar trunk motions are believed to

contribute to increased spinal load.⁹² Additionally, asymmetrical trunk motion has been associated with detrimental spinal load and increased susceptibility to lower back pain.³³ Lower back pain is a common comorbidity for knee OA, and the presence of both is indicative of progressed disability.⁹³ Increased trunk motion is linked to increased trunk moment,^{55,79} which contributes to elevated spinal load³³ and muscle activation.³² Studies investigating the impact of trunk modification on trunk kinetics are lacking. A recent study reported that 20% frontal plane knee moment reduction during trunk sway corresponded with 34% increase in the lateral trunk moment.³² Increased magnitudes of trunk moment may exacerbate structural loading at the spine.³¹ Gravitational, inertial, and internal forces of the trunk segment are key contributors to spinal load.^{31,33} Adverse changes in spinal load are a reported proximate cause of low back pain,³³ and can be estimated biomechanically using trunk joint reaction force. Augmented internal joint reaction forces are indicative of increased demand on the tissues supporting the lower back, and are associated with elevated risk of lower back pain.^{31,33}

Conclusion

Gait-retraining interventions using RTB are conservative interventions associated with positive outcomes. Frequently studied gait modifications include medial knee thrust, medial weight shift, lateral trunk lean, altered foot progression, multi-parameter, and self-selected gait using either visual, haptic, or auditory RTB with prior reviews demonstrating positive effects on frontal plane knee moment with varying levels of effectiveness across all modifications and feedback modes. Despite these results, it

remains unclear as to which of these gait-modification strategies is most beneficial to reducing estimated knee joint loads.

There is a need to consider inadvertent consequences of gait modification due to their intended purpose of frontal plane knee moment reduction. For instance, in the case of patients with bilateral OA, altered loading environment on the contralateral side could result in significant long-term health ramifications by accelerating the rate of disease progression. Research studies concurrently investigating the effectiveness of gait modification, and the biomechanical changes in the contralateral limb as a result of implementing gait modification, are needed. Furthermore, it is important to investigate potential acute and chronic adaptations throughout the kinetic chain as a result of gait retraining.

Literatures relevant to this dissertation were presented in this chapter in an effort to provide necessary background information on gait biomechanics and knee joint load. Additionally, the purpose of this chapter was to highlight the need for additional research to be conducted in the area of understanding the effects of gait modification on spine and lower extremity loads. Chapters 3 through 5 will describe research studies conducted to address this need.

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

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Current Status: Published: - **International Journal of Kinesiology & Sports Science (JKSS)**

Eddo O, Lindsey B, Caswell SV, Cortes N. Current Evidence of Gait Modification with Real-time Biofeedback to Alter Kinetic, Temporospacial, and Function-Related Outcomes: A Review. *IJKSS*. 2017;5(3):35–55.

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: (1) to assess if gait-retraining interventions using RTB are valuable to reduce KAM, pain, and improve function in individuals with knee osteoarthritis; (2) to evaluate the effectiveness of different gait modifications and modes of RTB in reducing KAM in healthy individuals; and (3) 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 5 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 11 distinctive gait modifications and 3 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 have positive effects to 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.

Keywords: Gait retraining, real-time biofeedback, osteoarthritis, knee adduction moment

Introduction

Osteoarthritis (OA) is one of the most common joint disorders in the U.S.¹⁻⁴ Over the past 20 years the incidence of symptomatic knee OA has risen dramatically,⁵ leading to \$128 billion in annual healthcare and economic costs.³ 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.⁴ The etiology of knee OA is multifactorial, with risk factors such as excessive bodyweight,⁶ aging, varus alignment, and altered joint mechanics.⁷ Knee OA most commonly occurs in the medial compartment,^{8,9} where articular surface damage narrows the medial joint space resulting in an increased knee adduction moment (KAM).¹⁰⁻¹² Increased KAM has been associated with OA severity,¹³ cartilage loss,^{14,15} and static malalignment,¹⁶ and has been shown to be a reliable indicator of medial knee joint load and alignment.¹⁷⁻¹⁹ Reducing KAM in individuals who have, or who are at elevated risk for knee OA may decrease pain,²⁰ reduce disease severity,¹⁸ and progression.¹⁷

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.²¹ Gait retraining using real-time biofeedback (RTB) is a conservative intervention that has shown positive outcomes in other pathologies (e.g., diabetes, stroke, Parkinson's, joint replacement).²² It has been suggested that gait modification with RTB results in modest to sizable short-term treatment outcomes when compared to conventional therapy.²³ Recent studies have demonstrated a similar effect of gait retraining and RTB on KAM.²⁴

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.²⁵ Reductions in peak KAM were also reported utilizing a medial knee thrust gait with visual RTB in healthy adults with varus malalignment,²⁶ while medial weight transfer of the foot resulted in reductions in peak KAM in healthy individuals with normal joint alignment.²⁷ Other gait strategies that have been successfully implemented include lateral trunk lean,²⁸ altered foot progression angle,²⁹ multi-parameter,^{25,30} and self-selected gait strategies.^{31,32} Similarly, a wide variety of biofeedback delivery, including visual,³¹ auditory,³³ and haptic,³⁰ 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.²⁴ 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.^{25,26} However, based on current evidence and the limited amount of retention testing, it cannot be determined if motor learning adaptations occur.²³

A recent systematic review and meta-analysis evaluating the effects of gait retraining with real-time biofeedback on KAM and pain-related outcome measures (PROMs) by Richards et al. 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.³⁴ 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.²⁴ 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^{35,36} and time under loading.³⁷ Additional variables such as stride speed³⁸ and length³⁹ that may also affect joint loading have also not been adequately considered in prior reviews.

Therefore, the purpose of this systematic review was threefold: (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; and (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,⁴⁰ or self-reported OA based on knee chronic joint pain.⁴¹ Gait-retraining studies employing any mode of RTB (e.g., video, auditory) 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.⁴²

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, 5 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 (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”).”

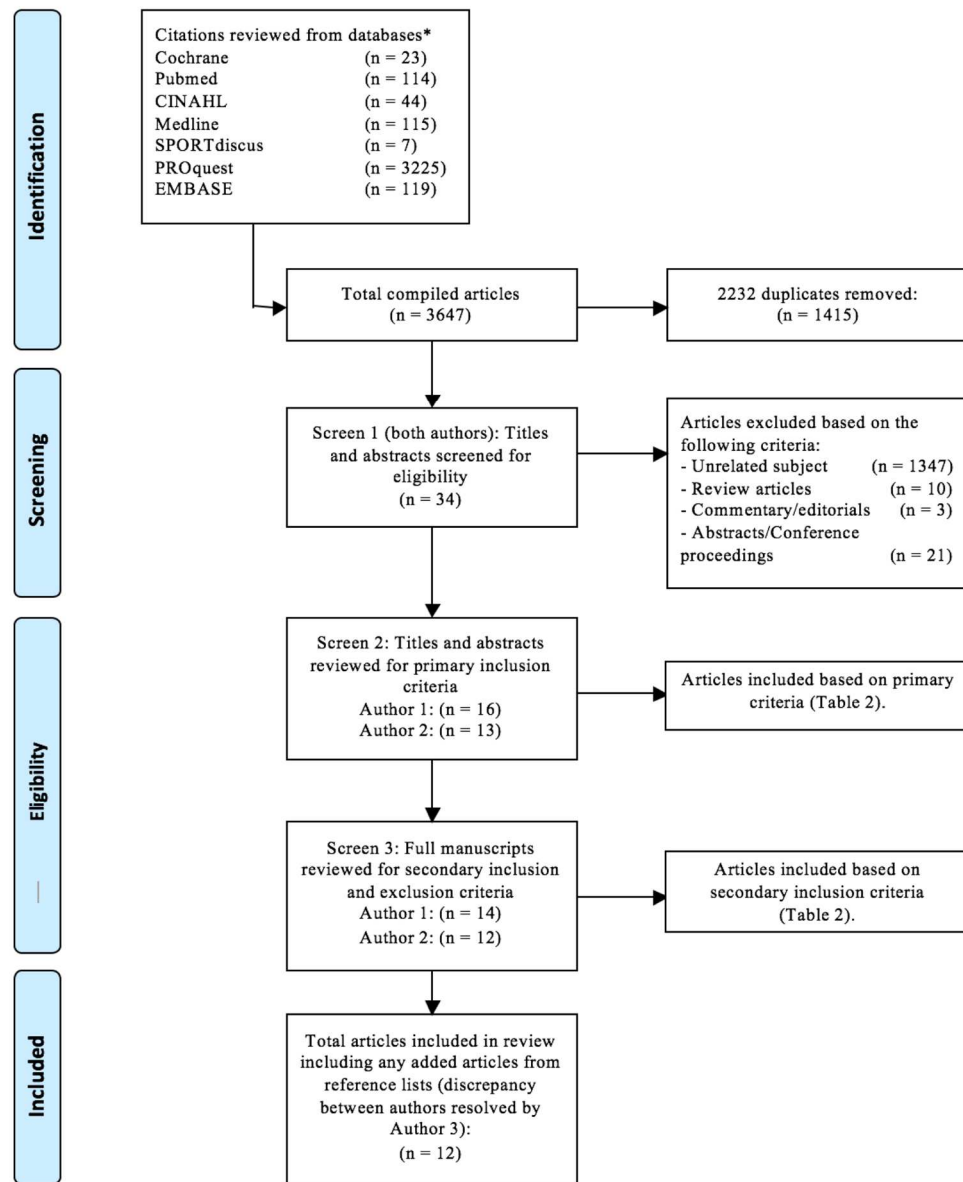


Figure 1. Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) Flow Diagram of Search Strategy

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 who 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).⁴³ 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 12 studies included were designed to test the effects of a gait-retraining intervention using RTB on measures of KAM, pain and/or function.^{25–33,44,45} 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.⁴⁶ Ten studies utilized a quasi-experimental within-subjects design,^{25–31,33,44,46} while 2 employed true experimental designs,^{32,45} including 1 randomized controlled trial.⁴⁵ Sample sizes ranged from 8 to 56 participants.

Four tested individuals with knee OA,^{25,28,29,45} the remaining 8 tested healthy individuals with the goal of developing and informing future studies to be conducted in symptomatic individuals.^{26,27,30–33,44,46} 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.^{25,29} A verbal confirmation of knee pain was an additional diagnostic criterion.^{25,28,45}

Nine studies employed a single-session design^{27–33,44,46} with 3 performing a single intervention trial.^{29,32,46} Six of these studies tested gait under multiple conditions to compare different types of gait strategies^{30,33} and feedback,^{27,31} as well as varying magnitudes.^{28,44} Only 3 studies were conducted over multiple sessions and included follow-up testing to assess retention.^{25,26,45}

Gait-retraining interventions. Eleven gait-modification strategies were identified across the 12 studies. Four studies evaluated the effects of modifying trunk position^{25,28,30,44} with 2 testing trunk sway,^{25,30} and 2 evaluating trunk lean.^{28,44} Three

studies investigated reduced foot progression angle,^{25,29,30} 2 studies utilized a weight shift to the medial side of the foot during the stance portion of gait,^{27,33} and 2 allowed participants to self-select the kinematic adjustment to reduce KAM.^{31,32}

Other gait-modification strategies included medial knee thrust²⁶; reduced rate of loading through increased knee flexion and decreased vertical acceleration⁴⁶; gait retraining towards symmetrical and typical displacements of the trunk and pelvis;⁴⁵ and multi-parameter gait retraining through a combination of altered foot progression angle, increased trunk sway, and increased tibia angle.³⁰

Biofeedback. Visual, haptic, and auditory real-time biofeedback or a combination was used to implement gait-modification strategies. The 2 most common biofeedback techniques were visual^{26,28,30–32,44,45} and haptic.^{25,27,29,30,32} Two studies employed auditory biofeedback.^{33,46}

Outcome assessment. Ten studies reported KAM as the primary outcome measure.^{25–33,44} Of these, 3 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).^{25,28,44} Seven studies reported additional kinetic and temporospatial variables including KFM,^{25,29,33,46} KAM impulse,^{28,31} stride speed,^{28,33,44,46} and stride length.^{28,33,46} Four studies using healthy participants reported numerical ratings (0-10) of awkwardness and difficulty in adopting gait modifications.^{26,31,32,44} Two studies did not report KAM as the primary outcome measure.^{45,46} 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.⁴⁶

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.⁴⁵ All 11 studies that reported KAM evaluated the overall or first peak during stance. Four studies also reported second peak KAM,^{28,29,33,44} and one study reported peak KAM at mid-stance in addition to first and second peak KAM.³¹

Quality and bias assessment. The mean (\pm 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, 8 studies scored a zero on random allocation (criterion 2), while 11 studies scored zeros on allocation concealment (criterion 3).

Table 1. PEDro Scores of Included Studies in Systematic Review⁴³

	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

Definition of criteria as in Fitzpatrick 2008:

1. Eligibility criteria were specified
2. Subjects were randomly allocated to groups (in a crossover 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 of the 4 studies conducted on OA patients reported smaller but still significant reductions in KAM compared to healthy individuals,^{25,28,29} ranging from 9.3%²⁸ to a maximum of 20%²⁵ (Table 2). Of these studies, self-selected gait retraining that allowed participants to choose between using both altered foot progression and trunk sway angle, or only altered foot or trunk sway angle, resulted in the greatest average reduction in KAM.²⁵ Increased trunk lean resulted in average KAM reductions between 9.3% and 14.9% depending on the magnitude of lean²⁸ while toe-in gait reduced KAM by 13%.²⁹ Two studies employed real-time visual feedback^{25,29} (Shull, Shultz, et al., 2013; Shull, Silder, et al., 2013) while the other 2 used real-time haptic feedback^{28,45} with participants responding equally well to both modes of feedback.

All 4 studies measured pain- and function-related outcome measures including WOMAC,²⁵ KOOS (Segal 2015), LLFDI,⁴⁵ and VAS scales (Table 3).^{25,28} Ratings of pain and function were significantly improved in all studies but one which was a single-

session design.²⁸ Improvements in WOMAC pain and function were retained at the 1-month 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^{25,29} that, when tested, was retained at the 1-month follow-up.²⁵ Lateral trunk lean reduced KAM impulse but did not significantly alter stride speed or length.²⁸

Effects of different gait modifications and modes of biofeedback on healthy individuals. Seven of the 8 studies conducted using healthy participants reported a significant reduction in KAM compared to baseline.^{26,27,30–33,44} KAM reduction ranged from 7%⁴⁴ to 55.8%³¹ with the magnitude of change differing based on gait modification used, biofeedback employed, and study design. Self-selected gait modification showed the greatest reductions in KAM in healthy individuals.^{31,32} Participants who were free to determine their own gait strategy without instruction reduced KAM by an average of 49%,³¹ while those who were instructed to select one or any combination of previously studied gait modifications decreased KAM 20.7%.³²

Multi-parameter gait retraining also resulted in a large average reduction in KAM of 36.6% in healthy participants.³⁰ 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.²⁶ Gait modifications involving the foot resulted in smaller but still significant reductions in KAM between 9.2%³³ and 14.2%.²⁷ An increase in first peak KAM of 12% after training with a feedback-based gait-monitoring knee brace was reported.⁴⁶

Of the 8 studies investigating healthy participants, 3 employed visual feedback,^{26,31,44} 2 used haptic,^{27,30} 2 used auditory,^{33,46} and 1 compared visual and haptic feedback between groups.³² Participants responded well to both visual and haptic feedback but displayed lesser reductions in KAM with auditory feedback (Table 2). Only 2 of the 8 studies used direct biofeedback, meaning feedback provided was the dependent variable of interest (KAM).^{31,32} The remaining studies employed indirect feedback whereby participants were provided feedback based on kinematic measures such as joint angle^{26,30,44,46} and foot pressure.^{27,33}

Half of the studies involving healthy participants also reported subjective ratings of gait modification using visual analogue scales (0/10) (Table 3).^{26,31,32,44} Three studies showed moderate ratings of difficulty and effort between 3-6.8/10 when adopting a modified gait^{26,31,44} with a third of healthy participants in one study reporting some form of pain or discomfort during the intervention.⁴⁴ Participants in 2 studies rated how awkward and or unnatural adopting a modified gait was with scores ranging from 5.25-7/10.^{26,32} 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.²⁶

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 ROL,⁴⁶ 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.³³ KAM impulse was reduced with both lateral trunk lean²⁸ and self-selected gait.³¹ Stride speed and length were minimally reduced, but not significantly changed^{44,46} except with medial knee thrust, which reduced gait speed by an average of 10.69%.³³

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 \pm SD KAM	Modified gait: mean \pm SD KAM	Calculated % KAM change	Primary Findings
Barrios et al. (2010)	Medial knee thrust	Knee adduction angle: $6.8 \pm 2.4^\circ$	Post-training: Natural: $6.2 \pm 2.2^\circ$ Modified: $5.0 \pm 2.1^\circ$ 1-month: Natural: $6.6 \pm 1.4^\circ$ Modified: $5.5 \pm 2.2^\circ$	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 KAM, however at 1-month natural gait remained unchanged although participants could replicate learned gait with similar reductions in KAM 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.
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, 3 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. While the change was overall positive, the magnitude of changed varied significantly.
Shull, Shultz et al. (2013)	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, Slider et al. (2013)	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.
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 KAM feedback: Early: 2.17 ± 0.25 Late: 2.10 ± 0.16 Mid: 1.91 ± 0.30	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.

								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 ± 0.32 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.

Legend:

- 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

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, Shultz et al. (2013)	1.48 ± 1.45	1.29 ± 1.39	-12.84%*	
	Shull, Slider et al. (2013)	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%*	

	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 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 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.

	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	Similar to ratings of difficulty/effort.
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. 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.
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%*	
WOMAC pain	Shull, Slider et al. (2013)	70.5†	Post-training: 85.0† One-month: 90.0†	20.57%* 27.66%*	
WOMAC function	Shull, Slider et al. (2013)	77.4†	Post-training: 91.7† One-month: 91.7†	18.48%* 18.48%*	
VAS (0/10)	Shull, Slider et al. (2013) 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%*	

Legend:

- 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
- \pm - standard deviation (if reported)
- * – calculated from data provided
- † – Author contacted for data

Discussion

The first aim of this review was to determine if gait retraining using real-time biofeedback is 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, with most studies employing a 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,^{25,28,29} 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.^{25,45} 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.⁴⁵ WOMAC pain and function scores showed similar improvements after a 6-week intervention also using visual RTB.²⁵ 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.^{47,48} As an example, individual reductions in KAM ranged from as little as 3% to more than 50% within the same gait-retraining protocol.³² 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.³⁶ Participants who 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.³¹ 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.²⁸

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.⁴⁷ When participants combined 3 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.⁴⁷ 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.^{25,26,30,44} 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.^{33,36,48} Nonetheless, reported reductions in KAM of 9% to 14% when using medial weight transfer are only slightly greater than those observed in orthotic interventions, reducing clinical impact compared to other modification strategies.^{49,50}

Visual biofeedback provided the greatest reduction in KAM in healthy individuals. Concurrent visual feedback has been effective in rehabilitation of complex motor skills.^{51,52} 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.^{53,54} 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 to 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.⁵⁵ We did not find any studies directly comparing visual, haptic, and auditory feedback, but prior motor learning research suggests concurrent visual feedback to be preferable for older adults attempting to learn a complex motor skill.⁵⁶ Surprisingly, only 2 studies used KAM as the biofeedback variable;^{31,32} the majority used kinematic measures.^{25,26,28–30,33,44,45} 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). KFM increases compressive loads at the knee joint,³⁶ and is a significant predictor of joint load even after accounting for variance attributed to

KAM.³⁵ Reductions in KFM were seen with self-selected²⁵ and toe-in gait²⁹ in OA participants and with medial weight shift in healthy individuals.³³ In contrast, walking with a feedback-monitoring knee brace designed to reduce ROL⁴⁶ and medial knee thrust³³ 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.⁴⁶ 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.³³ This supports the finding that KAM and KFM are not correlated,³⁵ 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.^{37,57} 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 defects⁵⁷ as well as knee pain.⁵⁸ Both increased lateral trunk lean in OA participants²⁸ and self-selected gait in healthy participants³¹ 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^{28,44,46} apart from medial knee thrust.³³ This can be attributed to the fact that gait speed was controlled to be within 5% of self-selected baseline speeds.^{28,44,46} 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.³⁸ However, study results do not consistently support this,²⁸ as others report that slower gait speeds increase KAM impulse.⁵⁹ 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.³⁹ 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 weaken 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.^{26,27,30–33,44,46} Participant follow-up was limited to 3 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%.²⁶ Participants reported completing 97%²⁵ and 92.4%⁴⁵ of prescribed at-home gait training in the other 2 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,⁴⁵ and of the 4 studies to employ random allocation in their study design, none concealed allocation to groups.^{27,32,33,45} 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.⁶⁰

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 a 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.

Acknowledgements

Publication of this article was funded in part by the George Mason University Libraries Open Access Publishing Fund.

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Chapter Four. Unintended Changes in Contralateral Limb as a Result of Acute Gait Modification

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Current status: Published – **Under review** in the *Journal of Applied Biomechanics*

Abstract

Gait modification using real-time biofeedback is a conservative intervention associated with positive joint load reductions. Results from systematic reviews corroborate the effectiveness of various strategies employing real-time biofeedback for reducing estimated knee joint load. The effects on the non-modified limb, however, remain unclear. Biomechanical changes to the non-modified limb were investigated during unilaterally implemented medial knee thrust, lateral trunk lean, and toe-in foot progression.

Nineteen healthy participants were recruited. Ten trials were completed for each gait condition including baseline. Assigned magnitude for each gait-modification strategy was individualized based on the mean and standard deviation of the gait parameter during baseline. Visual real-time biofeedback was provided.

During medial knee thrust, participants' non-modified limb presented with increased first peak medial knee contact force, internal first peak knee extensor moment, as well as knee and hip flexion angles at internal first peak knee extensor moment.

Observed biomechanical changes are elucidative of the body's attempt to attenuate increased external loads. These findings may carry significant implications for pathological populations. Load redistribution to the non-modified side may result in unfavorable long-term outcomes, particularly in patients with bilateral diagnosis. Future studies should explore acute and chronic changes in the non-modified limb of individuals with knee osteoarthritis.

Keywords: gait training, real-time biofeedback, knee extensor moment, medial knee contact force.

Word count: 3659

Introduction

Osteoarthritis (OA) is one of the most common joint disorders in the U.S., with total attributable cost ranging between \$303.5 and \$326.9 billion.¹ By 2040, an estimated 26% of the adult population are projected to be diagnosed with OA.² A common site of disease affliction is the knee, with projected lifetime risk of 40% in men and 47% in women.³ Data from an epidemiological study on candidates for knee replacement indicated that 87% of the patients had bilateral radiographic knee OA (knee OA ≥ 2 on the Kellgren and Lawrence).⁴ Additionally, between-limbs asymmetry was observed in patients with unilateral knee pain, and unilateral or bilateral structural knee OA.⁵ Risk factors are multifactorial and include: excessive bodyweight/obesity,³ aging,³ varus knee alignment,³ and altered joint mechanics.^{3,6}

The medial compartment of the knee is the predominantly affected site, where articular surface damage narrows the joint space, resulting in altered internal peak knee abductor moment (peak KabM).⁷ Altered peak KabM is associated with knee OA severity,⁸ cartilage degeneration/loss,⁹ and static malalignment,¹⁰ and has been shown to be a reliable indicator of medial compartment loads.¹¹ Results from a recent systematic review confirm the effectiveness of various gait-modification strategies with real-time biofeedback for reducing the magnitude of peak KabM.¹² A primary goal of gait modification is to reduce peak KabM by lateralizing the resultant vector of the ground reaction force on the targeted limb. Lateral trunk lean gait modification is defined as the frontal plane deviation of the line representing the trunk from the global vertical axis.¹³ The lateral shift in the center of mass serves to move the ground reaction force (GRF)

closer to the stance knee joint center, potentially decreasing the associated moment arm, thereby reducing KabM.¹⁴ Medial knee thrust modification involves gait patterns that drive the targeted knee medially, causing the GRF vector to pass laterally to the knee center.¹⁵ Increasing medial knee thrust reduces the knee varus angle, and is reported to decrease the frontal plane moment arm.¹⁶ Toe-in gait modification involves increasing the internal rotation of the foot with respect to the anterior posterior direction,¹⁷ and has the effect of shifting the center of pressure laterally as a result of the external rotation of the heel. This results in a reduction of the moment arm for the center of pressure to the knee joint center during stance.¹⁶ The reported reduction in peak KabM per unit of gait modification is highly variable among participants, signifying that individual dose-response relationships exist.¹⁸ These results indicate that the optimal gait-modification strategy and effective magnitude might differ between individuals.

Reduced peak KabM in individuals with knee OA is associated with decreased medial knee contact force,¹¹ which results in decreased pain, increased function, and improved quality of life. Medial knee contact force can be estimated using regression equations, which are strengthened by including both peak KabM and the absolute sagittal plane moment (KFM_{abs}).¹⁹ The absolute sagittal plane moment is defined as the larger of the internal peak knee extensor moment (peak KEM) and the internal peak knee flexor moment (peak KFM) during stance.^{18,19} Changes in the estimated medial knee contact force of the non-modified limb have yet to be investigated, and further research is needed to elucidate any existing relationship.

Charlton et al. investigated compensatory kinematic changes in the non-modified limb after implementing toe-in foot progression unilaterally, however, they only assessed changes mirroring those of the modified limb.²⁰ Research investigating consequential changes in joint kinetics of the non-modified hip and knee remains limited. While it is important to understand the effectiveness and long-term benefits of gait modification, there is a concurrent need to investigate potential detrimental effects in the kinetic chain. Chronic adaptations to reported gait asymmetries have been reported in patients with unilateral symptomatic knee OA, which may be responsible for observed contralateral knee joint degeneration.⁵ This is evidenced by the prevalence of bilateral structural knee OA in patients with unilateral end stage knee OA.⁴ When introducing gait modification unilaterally, it may be important to investigate load redistribution, specifically at lower extremity load-bearing joints that have been indicated to be most susceptible to degenerative changes.^{4,21}

To date however, the effects of gait modification on both the kinematic and kinetic parameters of the non-modified side have yet to be explored. The purpose of this study was to investigate the acute changes in the biomechanical parameters of the non-modified side in participants undergoing dose-specific medial knee thrust, lateral trunk lean, and toe-in foot progression gait modification. It was hypothesized that implementing these gait-modification strategies would increase the joint moments at the non-modified knee and hip as a result of the introduced asymmetry.

Methods

Participants. A within-group repeated measures study design was employed for this study. Nineteen healthy individuals (age 26.7 ± 4.8 years; height 1.69 ± 0.17 m; mass 72.3 ± 11.8 kg) participated after giving informed consent that was approved by the University Human Subjects Review Board. Participants had no history of lower limb or back surgery, and did not report any knee, hip, ankle, or lower back pain that required treatment within 6 months preceding testing. Furthermore, no participant had any neurological, musculoskeletal, or cognitive impairment that would affect gait or inhibit motor learning. Gait modifications were implemented unilaterally on the dominant limb, which was defined as the preferred swing leg in a kicking task.²² The non-modified limb was designated as the experimental leg for the purpose of this study.

Instrumentation. Eight high-speed motion analysis cameras (Vicon, Oxford, England) sampling at 200 Hz, and 4 floor-embedded force plates (Bertec, Columbus, OH) sampling at 1000 Hz were used to track marker trajectory and record ground reaction forces concurrently. The force plates were located along a 6-meter walkway and aligned with the direction of walking; z rotation was vertical, y was anterior-posterior, and x was medio-lateral. Fifty-three retroreflective markers were attached to the trunk, and bilaterally to the lower extremity of participants. Tracking clusters were placed on the lower back, thigh, shank, and foot segments. In addition, tracking markers were attached to the jugular notch, seventh cervical vertebrae, 10th thoracic vertebrae, right scapula, and bilaterally to the acromion, lateral iliac crest, posterior superior iliac crest, and the tibial tuberosity. Calibration markers were attached to lateral/medial malleoli,

lateral/medial knee joint lines, and greater trochanters. Participants were instructed to assume a T-pose with feet aligned with the anterior posterior axis of the biomechanics lab. A static calibration trial was collected to define the segment coordinate systems and joint axes. Knee and ankle joint centers were defined as the point on each joint axis that was equidistant from the respective medial and lateral calibration markers. Following static calibration, participants were instructed to complete 3 hula-hoop motions to aid in estimating hip joint center.²³ Calibration markers were removed prior to walking trials.

Baseline trials. Participants were instructed to walk along the laboratory walkway using a self-selected gait speed. Timing gates (Brower Timing Systems, Draper UT, USA) positioned 2.4 meters apart, and covering the length of the force plate area, were used to measure average walking speed per trial. Participants completed 10 baseline-walking trials. For a trial to be valid, one full contact with a force plate by both the modified and non-modified limbs was required.

Initial overground analysis. Upon completing the baseline trials, data were exported to Visual 3D software (C-Motion, Germantown MD, USA) for processing. From the static calibration a kinematic model was created for each participant which included the trunk, pelvis, both thighs, shank, and foot segments using a least-square optimization.²⁴ A cardan angle sequence was used to calculate joint angles relative to static trial using joint conventions previously reported in literature.²⁵ Segmental inertial characteristics were estimated for each participant based on Dempsters method,²⁶ and internal joint moments were estimated using standard inverse dynamics analysis.²⁷ Joint kinematics were filtered at 8 Hz and joint angles were measured in degrees. Mean and

standard deviation (SD) for gait speed, trunk, knee, and foot angles during stance were calculated.

Lateral trunk lean. Trunk lean was calculated as the frontal plane deviation of the trunk segment from the vertical laboratory axis. Markers located on the seventh cervical vertebrae, right scapula, 10th thoracic vertebrae, and lower back cluster were used to define the trunk segment. Lateral trunk lean to the right was quantified as positive and a lean to the left was negative. Ten trials were completed using real-time biofeedback with joint angle targets of 1-3 SD greater than baseline mean trunk angle for the first 5 trials, and 3-5 SD greater than baseline mean for the last 5 trials.

Medial knee thrust. Medial knee thrust was determined as the knee valgus angle, and was quantified as negative. Ten trials were completed using real-time biofeedback with joint angle targets of 1-3 SD less than baseline knee valgus mean for the first 5 trials, and 3-5 SD less than baseline knee valgus mean for the last 5 trials.

Toe-in foot progression. Toe-in foot progression angle was found as the offset between the lines formed by the posterior calcaneus and second metatarsal phalangeal joint markers, and the anterior posterior laboratory axis.¹⁷ Toe-in foot progression angle was quantified as positive. Ten trials were completed using real-time biofeedback with joint angle targets of 1-3 SD greater than baseline mean foot angle for the first 5 trials, and 3-5 SD greater than baseline mean foot angle for the last 5 trials.

Gait modification. The 1-3 SD range was designated as the small modification, whereas the 3-5 SD range was referred to as the large modification. Real-time biofeedback was delivered visually using the built-in real-time function on Visual 3D by

projecting a line graph displaying real-time joint angle during stance. The target modification range was represented visually using a highlighted bandwidth on the line graph. Participants were instructed to walk so that the line representing their targeted gait parameter fell within the range. After completing the first 5 trials of each modification, the target range was adjusted from the small to the large magnitude of gait modification. Feedback was projected to a large screen (4.9 x 3.4 m) located 7.6 m from the center of the walkway, and was visible to the participants during the gait-modification trials.

Standardized verbal instructions were provided to participants before implementing each gait strategy. Participants were allowed to complete as many practice trials as needed while maintaining a walking speed $\pm 5\%$ of the baseline average. Additional verbal feedback was provided to participants during practice trials to ensure that the intended strategy was achieved. Trials were deemed valid if the participant contacted the force plates with both the dominant limb and non-modified limb.

Non-modified limb analysis. Joint kinematics and kinetics were filtered at 8 Hz based on residual analysis.²⁷ Joint moments were normalized to mass and height (Nm/Kgm),²⁸ and ground reaction force was normalized to body weight. Joint moments were resolved using the proximal coordinate system, and reported as internal moments. Gait trials were normalized to 100% of stance, which was defined during the time when the vertical ground reaction force was greater than 20 Newtons. Peak hip abductor moment, peak KabM, peak KFM, and peak KEM, as well as hip and knee angles at these peaks, were calculated for the first (0-50%) and second half (50-100%) of non-modified limb stance¹⁸ using Visual 3D. KFM_{abs} was calculated for the non-modified limb during

both halves of stance, due to its association with medial knee loads.^{19,29} Mean values for non-modified limb peak K_{abM} and KFM_{abs} were streamed into MATLAB R2017b (MathsWork Corporation, Natick, MA, USA) to estimate medial knee contact force.

To assess medial knee contact force, a linear regression equation was used¹⁹:

Equation 1

$$MCF \approx 0.38 * K_{abM} + 0.13 * KFM_{abs} + 0.50 \quad (1)$$

Coefficients were obtained from a prior study that quantified medial knee contact force directly using a force-measuring knee implant.¹⁹ Peak K_{abM} and KFM_{abs} from the present study were used for estimation of medial knee contact force. Medial knee contact force was normalized to body weight.

Statistical analyses. All statistical analyses were performed using SPSS (IBM, Chicago, IL). Descriptive statistics and normality tests were conducted. Data distribution was assessed using a Shapiro-Wilk's test ($p < 0.05$),³⁰ skewness and kurtosis values, and visual investigation of histograms, normal Q-Q plots, and box plots. Differences between baseline and gait-modification strategies (medial knee thrust small, medial knee thrust large, lateral trunk lean small, lateral trunk lean large, toe-in foot progression small, toe-in foot progression large) were examined using one-factor-repeated-measures analysis of variance (ANOVA). When significant main effects were identified, pairwise comparisons with Bonferroni corrections were conducted. A Friedman test with Wilcoxon signed-ranked test and Bonferroni-adjusted significance level was conducted in the case where the assumption of normality was violated. All analyses were conducted using a significance level of $p < 0.05$.

Results

Results showed that all dependent variables except for peak KabM and medial knee contact force were normally distributed. Results of task performance relative to prescribed magnitude are presented in Table 4. Descriptive statistics on kinematic, kinetic, and temporal spatial parameters for non-modified limb are presented in Table 5.

There was an overall significant difference between conditions $\lambda = .063$, $F_{150, 464.7} = 1.867$, $p < .001$. Non-modified limb hip flexion at first peak KEM was significantly different from baseline during gait-modification conditions (Table 5; $F_{6, 102} = 10.729$, $p < .001$). Post hoc analysis showed that participants had greater hip flexion angles at first peak KEM during small toe-in foot progression and medial knee thrust, as well as during the large medial knee thrust and lateral trunk lean modifications compared to baseline ($d = .56$, 95% CI [12.2, 16.8], $d = .87$, 95% CI [13.5, 18.5], $d = 1.04$, 95% CI [14.2, 19.1], and $d = .43$, 95% CI [11.7, 16.4] respectively) (Figure 2). At the non-modified knee, participants presented greater knee flexion angles at first peak KEM (Table 5; $F_{2.004, 34.062} = 11.715$, $p < .001$). Post hoc analysis revealed that participants had greater knee flexion angles at first peak KEM when using both small and large medial knee thrust magnitudes compared to baseline ($d = .73$, 95% CI [-18.1, -13.0] and $d = .98$, 95% CI [-19.0, -14.2] respectively) (Figure 2).

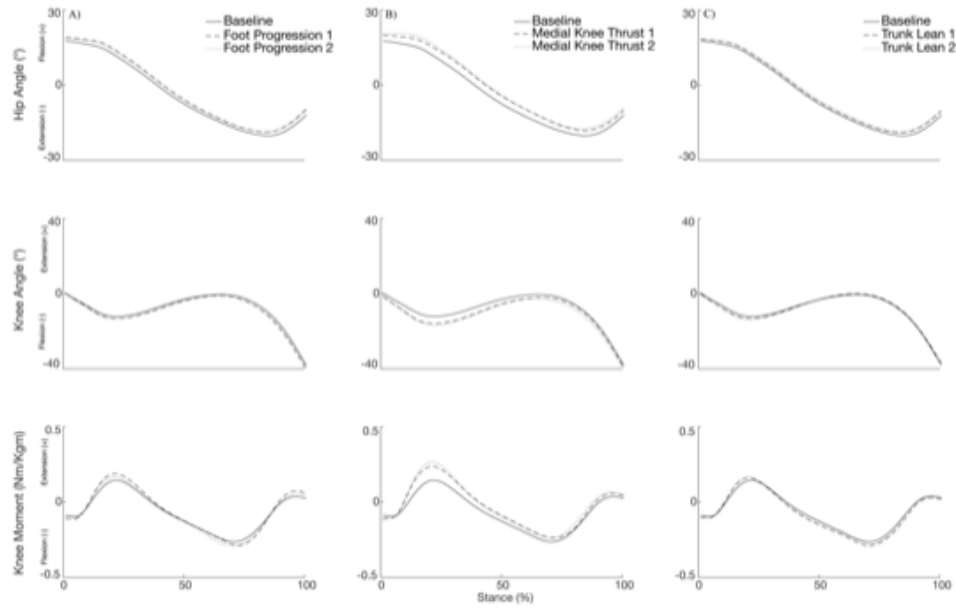


Figure 2. Hip Angle, Knee Angle and Internal Knee Extensor Moment From All Participants During Stance: (A) Toe-In Foot Progression, (B) Medial Knee Thrust, and (C) Lateral Trunk Lean

The non-modified knee first peak KEM was significantly different from baseline to gait-modification conditions (Table 5; $F_{3,972, 108} = 9.934, p < .001$). Participants' non-modified knee first peak KEM increased by 43% during the small ($d = .52$), and 60% during the large ($d = .62$) medial knee thrust modifications compared to baseline (Figure 2).

The non-modified limb first peak medial knee contact force increased significantly during gait modifications ($\chi^2(6) = 30.5, p < .001$). Post hoc analysis using Wilcoxon signed rank test and a Bonferroni adjusted p value showed that during large medial knee thrust modification the medial knee contact force significantly increased compared to baseline ($p = 0.004, d = .42, 95\% \text{ CI } [.61, .65]$).

There was no statistically significant change in non-modified limb peak KabM ($\chi^2(6) = 13.4, p = 0.037$), considering a Bonferroni adjusted p value of 0.008. Post hoc analysis using Wilcoxon signed rank test revealed that there was no statistically significant change in Peak KabM during gait-modification trials compared to baseline (Table 5). No other statistically significant differences were observed ($p < .05$).

Discussion

This study investigated potential changes in both kinematic and kinetic parameters of the non-modified limb as a result of gait modification. It was hypothesized that implementing gait modification unilaterally would result in acute changes to the biomechanics of the non-modified limb. The results from assessing 19 healthy individuals support the hypothesis. There were significant increases in non-modified limb sagittal plane hip and knee angles, as well as sagittal plane knee moment, when controlling for gait speed. There was also an increase in the estimated first peak medial knee contact force for the non-modified knee. These changes mostly occurred during the medial knee thrust gait-modification strategy. These results provide evidence that implementing medial knee thrust gait modification could result in detrimental compensatory gait changes in the non-modified limb.

Increased peak KabM is an established predictor of changes to knee compartmental loading.⁹ Emerging evidence suggests that the KFM_{abs} also significantly influences medial compartment knee loads.¹⁹ Increased KFM_{abs} is associated with increased joint compression, which in turn results in increased medial knee contact force.¹⁹ In particular, increased peak KEM is a suggested surrogate for net muscle

contraction and has been reported to be a significant predictor of medial to lateral cartilage thickness change over 5 years for patients with medial compartment knee OA.⁹ In the current study, although there were no significant changes in non-modified limb peak KabM (Table 5), a large internal moment is required to balance against large external moments, which would result in increased contact force. This was evidenced by the observed increase in both peak KEM and estimated medial knee contact force of the non-modified limb during early stance in large medial knee thrust modification trials.

An increase of 43% and 60% in the internal first peak KEM were observed in the non-modified limb during the small and large medial knee thrust modifications respectively (Table 5). Increased peak KEM is related to increased quadriceps activity leading to increased knee joint loads.¹⁸ The observed concurrent increase in hip and knee angles at first peak KEM may be evidence of gait asymmetry contributing to the increased joint loads experienced during early stance. These changes are most likely due to the nature of the medial knee thrust strategy compared to the other strategies. Toe-in foot progression involves modifying the foot relative to the line of forward progression,¹⁷ and is targeted at the most distal segment. Lateral trunk lean involves modifying the trunk relative to the global vertical axis.¹³ Although directed proximally, the effect on lower extremity asymmetry may be minimal, and trunk sway is a naturally occurring gait compensation.³¹ Contrarily, medial knee thrust involves a medial change to both hip and knee joint angles with the intent to redistribute the load between the knee compartments. During the small toe-in foot progression and large lateral trunk lean modifications there was an increase in the hip flexion angle at first peak KEM, however these changes did

not result in load redistribution to the non-modified limb. This was evidenced by the lack of significant change to the first peak KEM during both the small toe-in foot progression and large lateral trunk lean modifications. These findings carry significant implications for pathological populations. An increase in sagittal plane moment is associated with increased joint compression.¹⁹ Previous studies have reported that increased sagittal plane moments during gait modification mitigate expected reductions in medial compartment load as a result of peak KabM reduction,¹⁹ which illustrates the relationship between frontal plane moments, sagittal plane moments, and medial knee contact force. In the current study, although increase in first peak KabM for the non-modified limb across gait conditions was not significant, there was a 9% increase on average during medial knee thrust compared to baseline (Table 5). These findings along with the reported increase in non-modified limb first peak KEM and medial knee contact force suggest altered joint loads at the non-modified knee, particularly during large medial knee thrust gait modification.

The altered loading environment is likely explained by a medialization of the force vector from the non-modified limb as a result of unilateral gait modification. Changes to the non-modified limb's medial knee contact force were influenced by the magnitude of gait modification. It is noteworthy that a small medial knee thrust gait modification also increased estimated knee load; however, this increase did not reach statistical significance. As a result of the repetitive nature of gait, even a small increase in first peak KEM and/or first peak medial knee contact force over each step may result in a large increase in the joint load experienced over time. Changes in the gait mechanics of

the non-modified limb could be attributed to gait asymmetry inherent to unilateral gait modification.

It is possible that the reported biomechanical changes in the non-modified limb are due to expected natural learning errors as a result of implementing gait modification. Such errors may be attributable to the acquisition phase, and may disappear over multiple training sessions. During the gait-modification trials, participants were able to successfully achieve kinematic target on average 22% of the time while exceeding the upper-level of the recommended target 61.5% of time (Table 4). These findings could be attributed to the physiological challenge of maintaining the prescribed 2 standard deviation bandwidths compared to the range of motion naturally present during stance, and suggests that wider bandwidths and modification magnitudes may be more effective.

A significant limitation of the current study was the use of a healthy cohort. The order in which the gait-modification strategies were completed was not randomized. The impact of order effect on non-modified limb biomechanics is possibly minimal since the purpose of the current study was not to compare the effectiveness of gait-modification strategies. An additional limitation was the use of a regression equation obtained from a study that assessed medial knee contact force in a patient with a knee-instrumented device. Caution should be exercised when interpreting the estimated medial knee contact force due to potential dissimilarities between the 2 populations. Nevertheless, reported findings demonstrate the importance of considering potential detrimental changes across the kinetic chain as a result of implementing gait modification. Individuals with radiographic and/or symptomatic OA in the non-modified knee could be contraindicated

for the medial knee thrust gait-modification strategy. Attempts to reduce joint load in the gait-modification targeted limb could compromise the loading environment on the non-modified side. These acute changes, if reinforced through practice, would become part of the newly acquired gait pattern. Chronic adaptations in the non-modified limb could result in undesired long-term effects.

Mechanical loading plays an important role in the onset and progression of knee OA. In the current study, the effect of gait modification on non-modified limb joint load was measured. It is recommended that when considering choice of gait modification, strategies such as lateral trunk lean and toe-in foot progression may be biomechanically superior options due to their limited impact on lower extremity gait symmetry. The results of this study add to current knowledge regarding the secondary biomechanical changes as a result of implementing gait-modification strategies.

Acknowledgements

None.

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Tables

Table 4. Mean Difference Between Target and Achieved Kinematic Change, Success Rate, and Performance Relative to Target Bandwidth for Modified Limb During Gait Modification: Toe-In Foot Progression, Medial Knee Thrust Modification, and Lateral Trunk Lean

Gait Modification	Mean difference (°)	Success rate (%)	Above minimum threshold (%)	Above target
<i>TFP small</i>	2.85	22.0	92.0	70.0
<i>TFP large</i>	2.97	28.0	95.0	67.0
<i>MKT small</i>	0.31	17.0	66.0	49.0
<i>MKT large</i>	0.33	23.0	74.0	51.0
<i>LTL small</i>	1.79	26.0	87.0	61.0
<i>LTL large</i>	1.83	17.0	88.0	71.0

Abbreviations: TFP small, Toe-in foot progression small modification; TFP large, toe-in foot progression large modification; MKT small, medial knee thrust small modification; MKT large, medial knee thrust large modification; LTL small, lateral trunk lean small modification; LTL large, lateral trunk lean large modification.

Table 5. Mean and Standard Deviation for Non-Modified Limb Gait Parameters

Parameter	Baseline	TFP small	TFP large	MKT small	MKT large	LTL small	LTL large
Gait speed (m/s)	1.33±.18	1.34±.19	1.34±.19	1.32±.18	1.33±.18	1.33±.19	1.34±.19
Stride length (m)	1.41±.17	1.41±.19	1.40±.17	1.42±.19	1.43±.17	1.41±.17	1.41±.14
Stride width (m)	0.13±.03	0.13±.03	0.13±.03	0.14±.03	0.13±.03	0.14±.03	0.14±.03
Hip flexion at 1 st PKEM (°)	11.8±3.7	14.2±4.7 ^a	13.9±4.1	15.8±5.3 ^c	16.5±5.1 ^d	13.4±4.4	13.6±4.5 ^f
Knee flexion at 1 st PKEM (°)	-11.6±5.1	-12.8±6.1	-12.3±5.7	-15.5±5.4 ^c	-16.7±5.2 ^d	-12.3±4.9	-12.9±4.8
1 st Peak KEM (N m/kgm)	0.18±0.1	0.21±0.2	0.20±0.2	0.26±0.1 ^c	0.29±0.2 ^d	0.19±0.2	0.19±0.2
1 st Peak KabM (N m/kgm)	-0.26±0.1	-0.27±0.1	-0.26±0.1	-0.28±0.1	-0.28±0.1	-0.23±0.1	-0.24±0.1

Abbreviations: TFP small, Toe-in foot progression small modification; TFP large, toe-in foot progression large modification; MKT small, medial knee thrust small modification; MKT large, medial knee thrust large modification; LTL small, lateral trunk lean small modification; LTL large, lateral trunk lean large modification; Peak KEM, Internal peak knee extensor moment; Peak KabM, Internal peak knee abductor moment.

^aSignificant difference between TFP small and baseline; ^bSignificant difference between TFP large and baseline;

^cSignificant difference between MKT small and baseline; ^dSignificant difference between MKT large and baseline;

^eSignificant difference between TL small and baseline; ^fSignificant difference between TL large and baseline ($p < 0.05$)

Chapter Five. Increased Trunk Kinetics Observed During Subject-Specific Trunk Lean Gait Modification

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Current status: Published – In **preparation to be submitted**

Abstract

Gait modification using real-time biofeedback (RTB) has been reported to decrease the knee abductor moment (KabM). Trunk modifications are associated with KabM reductions ranging from 9 to 65%. Lateral trunk lean is a commonly implemented gait-modification strategy that involves a unilateral shift of the center of mass to the implicated side, which serves to move the ground reaction force (GRF) closer to the stance knee joint center, and resulting in reduced KabM. Structural loads at the spine have been implicated in the etiology of low back pain and can be estimated via trunk kinetics. The purpose of this study was to investigate changes in trunk kinetics during subject-specific lateral trunk lean in healthy participants.

Nineteen healthy individuals were recruited. Participants completed 10 baseline walking trials followed by 10 trials of lateral trunk lean strategy. Trunk modification magnitudes were determined based on average baseline trial trunk angle. Five trials of small and large gait modification magnitude were completed. Visual RTB was projected as a line graph displaying the trunk angle during stance and a highlighted bandwidth designated the target angle range. Trunk angles, peak axial and frontal trunk moment, axial and frontal trunk angular impulse, and peak trunk joint reaction forces were calculated during both ipsilateral and contralateral stance.

Results showed that lateral trunk lean angle at peak frontal plane moment increased significantly during ipsilateral stance for both gait modification magnitudes. There was a significant increase in both the frontal plane trunk moment and frontal plane trunk impulse during ipsilateral stance. Peak lateral joint reaction force during ipsilateral

stance for both magnitudes of trunk lean and for large modification during contralateral stance were increased compared to baseline.

Results from the current study demonstrate that measures of trunk kinetics are susceptible to significant increase even during conservative increases in trunk angle. Increased peak lateral joint reaction force serves as further confirmation of a compromised loading environment at the spine during lateral trunk lean strategies. Implementing lateral trunk lean might result in unintended secondary changes along the kinetic chain, but further investigation is required.

Keywords: gait training, spinal load, trunk moment, trunk modification, gait modification.

Introduction

Gait retraining is an emerging, inexpensive alternative treatment option for patients with various pathologies.¹ It has been reported that gait retraining using kinematic feedback can improve mobility, balance, strength, flexibility, and efficiency in patients diagnosed with Parkinson's disease² or post stroke.² Gait modification using real-time biofeedback (RTB) has been reported to decrease the knee abductor moment (KabM).¹ Increased KabM is a consequence of the ground reaction force (GRF) passing medially to the knee joint center, which results in uneven load distribution at the joint surface.^{3,4} An increase in first peak KabM is an established biomechanical risk factor of knee osteoarthritis severity,⁵ cartilage degeneration,⁶ and joint misalignment.⁷ Gait-modification strategies reported to reduce KabM include increased step width,⁸ medial knee thrust,⁹ modified foot progressions,¹⁰ and trunk modification.^{4,11}

Trunk modification involves the frontal plane deviation of the line representing the trunk from the global vertical axis.⁴ The shift of the center of mass to the implicated side serves to move the GRF closer to the stance knee joint center, potentially decreasing the associated moment arm, thereby reducing KabM.¹¹ Trunk modifications are associated with KabM reductions ranging from 9 to 65%.^{4,11-13} Two commonly implemented strategies are the trunk sway and lateral trunk lean. Trunk sway involves a medio-lateral shift during gait typically using uncontrolled magnitude. The timing of sway is critical due to a potential increase in KabM if performed incorrectly.¹² Trunk sway gait-modification strategy has been credited with KabM reductions as high as 65%.⁴ Lateral trunk lean involves a unilateral shift of the center of mass in the direction of the

implicated side and is associated with more modest KabM reductions.¹³ In contrast to trunk sway, trunk lean involves specified trunk modification magnitudes. KabM reductions of 9-15% have been reported as a result of implementing unilateral lateral trunk lean.¹³

Nüesch et al. investigated changes to KabM as a consequence of implementing trunk sway gait modification.¹² Their results indicated that 20% KabM reduction in healthy individuals was associated with a concurrent 34% increase in lateral trunk moment.¹² Increased trunk kinematics contribute to lower back pain level in individuals with transfemoral amputation.¹⁴ Asymmetrical trunk motion is associated with increased susceptibility to lower back pain.^{15,16} Lower back pain is a common comorbidity for knee OA, and the presence of both is indicative of progressed disability.¹⁷ Recent reports suggests that increased trunk motion is associated with increased trunk moment,¹⁵ which is associated with increased spinal load¹⁶ and muscle activation.¹² Gravitational, inertial, and internal forces of the trunk segment are key contributors to spinal load.^{15,16} Increased spinal load is a reported proximate cause of low back pain,¹⁶ and can be estimated biomechanically using trunk kinetics.

To date, research on changes in spinal load and trunk moment as a result of unilateral trunk lean is limited. Therefore, the purpose of this study was to investigate the effect of subject-specific lateral trunk lean gait modification on trunk kinetics during both ipsilateral and contralateral stance phases in healthy participants. It was hypothesized that implementing subject-specific lateral trunk lean would result in non-significant increases

in trunk kinetics due to the conservative increase in trunk angle associated with this strategy.

Methods

Participants. Nineteen healthy individuals (age 26.7 ± 4.8 years; height 1.69 ± 0.17 m; mass 72.3 ± 11.8 kg) qualified for inclusion in the within-group repeated measures study. Participants completed an informed consent form, which was approved by the University Human Subjects Review Board prior to the study. Exclusion criteria included recent lower back, hip, knee, or ankle pain requiring treatment within 6 months of testing or a history of lower back or lower extremity surgery. In addition, none of the participants had musculoskeletal, neurological, or cognitive impairments affecting motor learning or gait. The dominant limb was determined as the preferred swing leg in a kicking task,¹⁸ and was designated as the experimental leg for the purpose of this study.

Instrumentation. Marker trajectory sampled at 200 Hz was acquired using 8 high-speed motion analysis cameras (Vicon, Oxford, England) sampling at 200 Hz. GRF was acquired using 4 floor-embedded force plates (Bertec, Columbus, OH) located along a 6-meter walkway and sampled at 1000Hz. Marker trajectory and GRF were acquired concurrently. Force plates were aligned with the direction of walking; z rotation was vertical, y was anterior-posterior, and x was medio-lateral. Fifty-three retroflective markers were attached to the trunk, and bilaterally to the lower extremity of participants. Tracking clusters were placed on the lower back, thigh, shank, and foot segments. Tracking markers were also attached to the jugular notch, seventh cervical vertebrae, 10th thoracic vertebrae, right scapula, and bilaterally to the acromion, lateral iliac crest,

posterior superior iliac crest, and the tibial tuberosity. Calibration markers were attached to the lateral/medial malleoli, lateral/medial knee joint lines, and greater trochanters. Participants stood in a T-pose with feet aligned with the anterior posterior axis of the lab. A static calibration trial was taken to define the segment coordinate system and joint axes. The point on each joint axis equidistant from the respective medial and lateral calibration markers defined the knee and ankle joint centers. A dynamic calibration was captured as participants completed hula-hoop motions to aid in estimating hip joint center.¹⁹ Calibration markers were removed prior to walking trials.

Baseline trials. Participants completed 10 successful baseline walking trials at a self-selected speed along the laboratory walkway. For a trial to be valid, full contact with force plates by both the modified and contralateral leg was required. Timing gates (Brower Timing Systems, Draper UT, USA) positioned 2.4 meters apart, covering the length of the force plate area, measured the average walking speed.

Initial overground analysis. After the baseline trials, data were exported to Visual 3D software (C-Motion, Germantown MD, USA) for processing. A kinematic model was created for each participant based on the static calibration. This kinematic model included the trunk, pelvis, both thighs, shank, and foot segments using a least-square optimization.²⁰ Joint angles were calculated relative to static trial by a cardan angle sequence using joint conventions previously reported in literature.²¹ Segmental inertial characteristics were estimated for each participant based on Dempsters method,²² and internal joint moments were estimated using standard inverse dynamics analysis.²³

Joint kinematics were filtered at 8 Hz. Mean and standard deviation (SD) for gait speed and trunk angle during stance were calculated.

Gait modification. Lateral trunk lean was determined as the frontal plane deviation of the trunk segment from the vertical axis. Markers located on the seventh cervical vertebrae, right scapula, 10th thoracic vertebrae, and lower back cluster were used to define the trunk segment. Lateral trunk lean to the right was quantified as positive and lean to the left was negative. Participants completed 10 trials of subject-specific lateral trunk lean strategy. The first 5 trials targeted a small modification defined as 1-3 SD greater than the baseline mean. The second 5 trials aimed for a large modification defined as 3-5 SD greater than the baseline mean. Visual RTB was provided via the Visual 3D built-in real-time function by projecting a line graph with real-time joint angle during stance. Feedback was shown on a large screen (4.9 x 3.4 m) positioned 7.6 m from the walkway. A highlighted bandwidth on the line graph displayed the designated target angle range. Participants were asked to walk so that the line representing their trunk angle fell within the goal gait-modification range. Standardized verbal instructions and practice trials were provided before implementing gait modification. Trials were valid if gait speed was within $\pm 5\%$ of the baseline average speed and if participants contacted the force plates with both the modified and contralateral leg.

Data analysis. Based on residual analysis the joint kinematics and kinetics were filtered at 8 Hz.²³ Internal joint moments were normalized to mass and height (Nm/Kgm),²⁴ GRF was normalized to body weight, and joint reaction force was normalized to body mass. Joint moments, reported as internal, were resolved to the

proximal coordinate system. Gait trials were normalized to 100% of stance. This was determined as the time when the vertical GRF was greater than 20 Newtons. Peak frontal plane trunk moment, peak axial plane trunk moment, frontal plane trunk angular impulse, axial plane trunk angular impulse, and peak joint reaction forces as well as trunk angle at these peaks were calculated during stance using Visual 3D. First peak KabM was calculated for the first (0-50%) half of stance.²⁵

Statistical analysis. Using SPSS (IBM, Chicago IL), descriptive and normality tests were conducted. A Shapiro-Wilk's test ($p < 0.05$),²⁶ skewness and kurtosis values, visual investigation of the histograms, normal Q-Q plots, and box plots were used to assess the data distribution. A one-factor-repeated-measures analysis of variance (ANOVA) was performed comparing the effects between baseline and gait-modification strategies (lateral trunk lean small and lateral trunk lean large). Pairwise comparisons with Bonferroni corrections were conducted in identified significant main effects. In situations where the assumption of normality was violated, a Friedman test with Wilcoxon signed-ranked test and Bonferroni-adjusted significant level was performed. All analyses were conducted using a significance level of $p < 0.05$.

Results

Results from descriptive analysis showed that the lateral joint reaction force during both ipsilateral and contralateral stance, first peak KabM, and trunk angular impulse during ipsilateral stance were not normally distributed. Results of task performance relative to prescribed magnitude are presented in Table 6. Descriptive statistics on kinematic, kinetic, and temporal spatial parameters are presented in Table 7.

Lateral trunk angle during ipsilateral stance at peak frontal plane trunk moment was significantly different from baseline during gait-modification conditions (Table 8; $F_{2, 36} = 15.224, p < .001$). Post hoc analysis showed that participants had greater lateral trunk angle at peak trunk moment compared to baseline during both the small and large lateral trunk lean modifications ($d = .66$ and $d = .90$, respectively) (Figure 3). Lateral trunk angle during stance of the contralateral limb at peak frontal plane trunk moment was significantly different from baseline during gait modification (Table 8; $F_{2, 36} = 6.782, p = .003$). Post hoc analysis showed that participants had greater lateral trunk angle at peak trunk moment compared to baseline during the large lateral trunk lean modification ($d = .70$) (Figure 3). During ipsilateral stance, trunk angle at heel contact was significantly increased compared to baseline (Table 8; $F_{1.1, 26.8} = 34.048, p < .001, d = .85$ and $d = 1.3$, small and large lateral trunk lean modifications respectively). Trunk angle at first peak KabM during ipsilateral stance significantly increased compared to baseline (Table 8; $F_{1.3, 23.6} = 47.246, p < .001, d = 1.4$ and $d = 2.0$, small and large lateral trunk lean modifications respectively).

Peak frontal plane trunk moment during ipsilateral stance was significantly different from baseline to gait-modification conditions (Table 9; $F_{2, 36} = 9.787, p < .001$). Post hoc analysis showed that participants had greater peak trunk moment during the small ($d = .28$), and large ($d = .34$) lateral trunk lean modifications compared to baseline (Figure 4). Frontal plane trunk angular impulse during ipsilateral stance was significantly different from baseline to gait-modification conditions (Table 9; $\chi^2 (2) = 30.6, p < .001$). Post hoc analysis using a Wilcoxon signed rank test and a Bonferroni adjusted p value

showed increased trunk angular impulse during the small ($d = 1.1$) and large ($d = 1.3$) lateral trunk lean modifications compared to baseline. When using lateral trunk lean modification, frontal (Table 9; $F_{2, 36} = 10.448$, $p < .001$, $d = .37$ and $d = .44$, small and large lateral trunk lean modifications respectively) and axial (Table 9; $F_{2, 36} = 7.609$, $p = .002$, $d = .58$, large lateral trunk lean modification) trunk moments at heel contact during ipsilateral stance were significantly increased compared to baseline. Frontal plane trunk moment at peak KabM during ipsilateral stance significantly increased compared to baseline (Table 9; $F_{1.3, 23.6} = 37.132$, $p < .001$, $d = 1.1$ and $d = 1.5$, small and large lateral trunk lean modifications respectively).

Peak lateral joint reaction force during ipsilateral stance was significantly different from baseline to gait-modification conditions (Table 10; $\chi^2 (2) = 32.9$, $p < .001$). Post hoc analysis using a Wilcoxon signed rank test and a Bonferroni adjusted p value showed increased lateral joint reaction force during the small ($d = 1.5$) and large ($d = 1.7$) lateral trunk lean modifications compared to baseline (Figure 5). Peak lateral joint reaction force during contralateral stance was significantly different from baseline to gait-modification conditions (Table 10; $\chi^2 (2) = 30.7$, $p < .001$). Post hoc analysis using a Wilcoxon signed rank test and a Bonferroni adjusted p value showed increased lateral joint reaction force during the small ($d = 1.6$), and large ($d = 1.7$) lateral trunk lean modifications compared to baseline (Figure 5).

There was no statistically significant change in ipsilateral first peak KabM (Table 2; $\chi^2 (2) = 2.84$, $p = 0.241$), considering a Bonferroni adjusted p value of 0.025. Post hoc analysis using Wilcoxon signed rank test revealed that there was no statistically

significant change in peak KabM during gait-modification trials compared to baseline.

No other statistically significant differences were observed ($p < .05$).

Discussion

This study investigated the effect of subject-specific lateral trunk lean gait modification on trunk kinetics during ipsilateral and contralateral stance phases. It was hypothesized that implementing lateral trunk lean would not result in significant increases in measures of trunk kinetics. The results from assessing 19 healthy individuals did not support the hypothesis. There were increases in peak frontal plane trunk moment, frontal plane trunk angular impulse, and lateral joint reaction force when controlling for gait speed. These changes occurred during both ipsilateral and contralateral stance phases. These results provide evidence that implementing lateral trunk lean could result in detrimental compensatory changes along the kinetic chain.

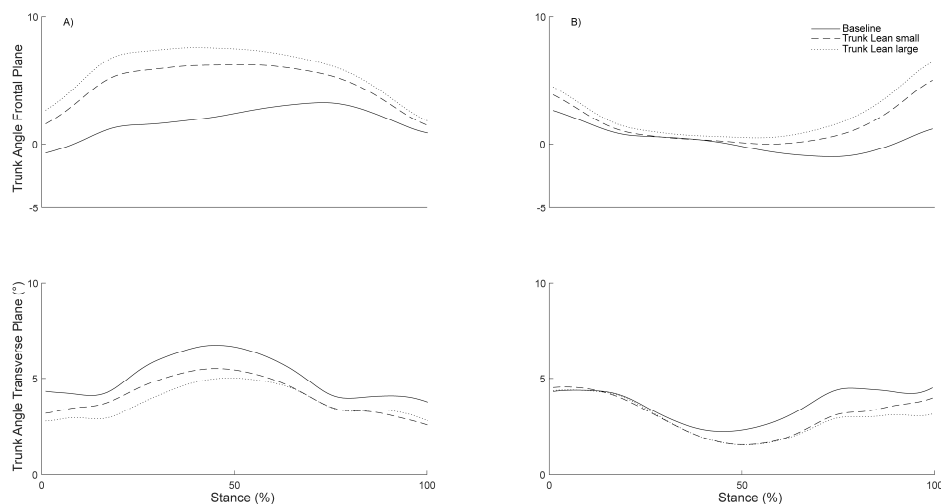


Figure 3. Trunk Angle in (°) From All Participants During Stance: (A) Trunk Angle During Ipsilateral Stance, and (B) Trunk Angle During Contralateral Stance

Trunk kinematics. During lateral trunk lean the mean increases in trunk angle compared to baseline were 1.79 and 1.83 degrees for the small and large modification respectively (Table 6). A statistically significant increase in trunk angle was observed during ipsilateral stance at peak frontal plane trunk moment for both the small and large modification (Table 8). Similarly, a significant increase in trunk angle was observed during contralateral stance at peak frontal plane trunk moment but only for the large modification (Table 8). These findings suggest that at increased trunk lean angles, unilaterally implemented trunk modifications could result in bilateral manifestations. During contralateral stance trunk lean to the targeted side persisted, indicating continued asymmetric trunk motion (Figure 3). Trunk angle at heel contact and at first peak KabM during ipsilateral stance were significantly increased for both the small and large lateral trunk lean modifications compared to baseline. The goal of trunk modification is to attain the desired changes in trunk angle during early stance, and through first peak KabM. The results from kinematic analysis confirm that these objectives were met.

There were no statistically significant changes to the transverse plane trunk kinematics during the small or large lateral trunk lean compared to baseline. Increase in the transverse trunk rotation has been previously reported to contribute to lower back pain.¹⁴

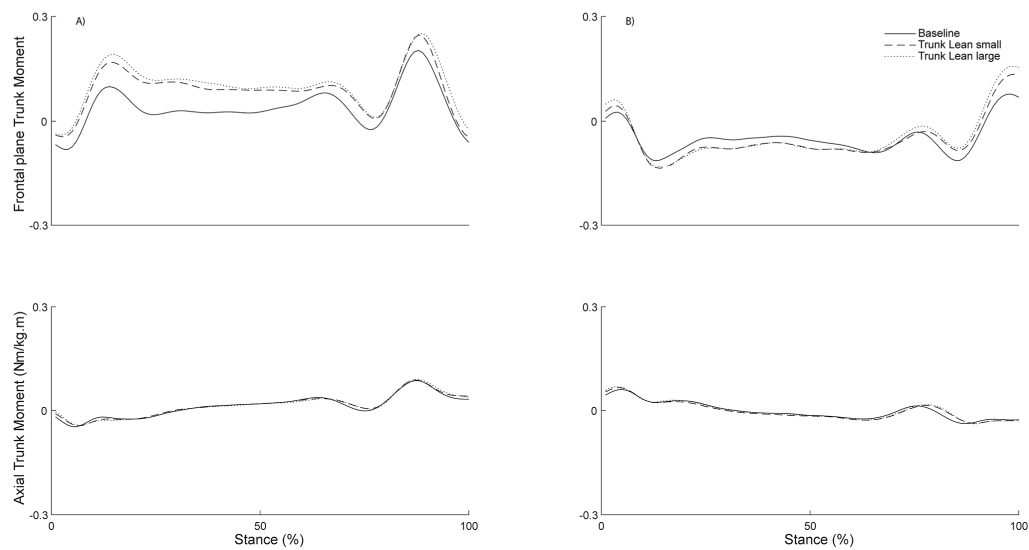


Figure 4. Trunk Moment in (Nm/Kg.M) From All Participants During Stance: (A) Trunk Moment During Ipsilateral Stance, and (B) Trunk Moment During Contralateral Stance

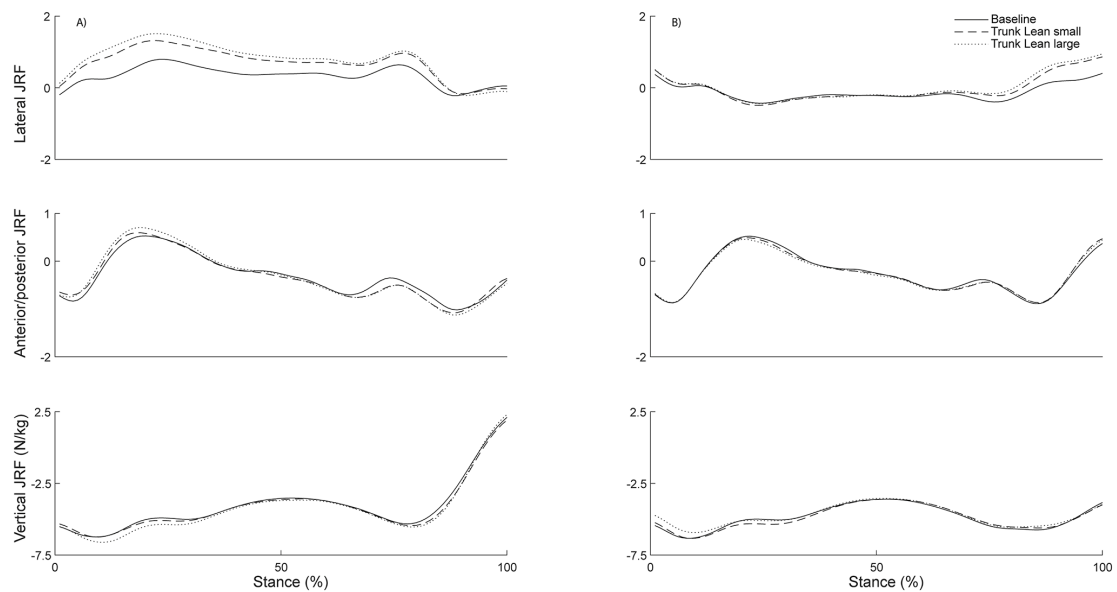


Figure 5. Trunk Joint Reaction Force in (N/Kg) From All Participants During Stance: (A) Trunk Joint Reaction Force During Ipsilateral Stance, and (B) Lateral Trunk Joint Reaction Force During Contralateral Stance

Trunk kinetics. Increase in lateral trunk motion has been previously associated with elevated lateral trunk moment during trunk sway gait modification.¹² Results from the current study demonstrate that lateral trunk moment is susceptible to significant changes even during conservative increases in trunk angle (Figure 4). An increase of 21.7% and 26.1% in trunk moment were observed during the small and large lateral trunk lean modifications respectively (Table 9). Higher magnitudes of trunk moment are reported to contribute to structural loading at the spine.¹⁵ Augmented external load, which is quantified as trunk moment, is mitigated internally by the action of the trunk muscles.^{15,16} This augmented trunk moment is reported to correspond to elevated muscle activity resulting in a compromised spinal loading environment.¹⁵ The observed changes in frontal plane trunk angular impulse during ipsilateral stance serve as further evidence of altered structural loading at the spine. Additionally, the reported changes in trunk moment during ipsilateral stance were observed at both heel contact and first peak KabM. At heel contact, there was a concurrent increase in twisting moment during ipsilateral stance.

Analysis of the trunk joint reaction force provided further confirmation of a compromised loading environment at the spine during gait modification. An increase of 50% in lateral joint reaction force during dynamic movement had been previously associated with lateral spinal flexion.¹⁵ Changes in trunk dynamics corresponded to elevated spinal loads. During both ipsilateral and contralateral stance there was an increase in the lateral joint reaction force for both magnitudes of modification (Table 10).

During contralateral stance, lateral joint reaction force to the targeted side persisted, indicating continued asymmetric trunk load (Figure 5). Augmented internal joint reaction force is indicative of increased demand on the tissues supporting the lower back, and is associated with elevated risk of lower back pain.^{15,16} These changes to the lateral joint reaction force, which were present during both stance phases of the gait cycle, suggest an extended period of increased spinal load (Figure 5). The concurrent increase in the lateral joint reaction force and lateral trunk moment when employing conservative magnitudes of trunk modification suggest that trunk modification may be contraindicated for a segment of the population. Longitudinal inquiry into changes to the structural loading of the spine during trunk modification is required. Over prolonged periods, exposure to increased trunk loads could result in unfavorable long-term consequences.

Knee abductor moment. In the current study there was no statistically significant change to the first peak KabM. On average, implementing subject-specific lateral trunk lean decreased KabM magnitude by 8.9%. However, contrary to the reports from other papers,^{4,12,13} small or large magnitudes of trunk modification did not result in significant KabM reduction.

During the gait-modification trials, participants on average successfully achieved the lateral trunk lean target 21.5% of the time while exceeding the recommended target 66% of time (Table 6). These findings, along with the previously reported mean increase in trunk angle during lateral trunk lean trials (Table 6), suggests that wider bandwidths and modification magnitudes may be more effective.

A limitation of the study was the use of a young healthy cohort. The results are not generalizable to older populations, or to individuals with medial compartment knee osteoarthritis. An additional limitation was that the trunk was modeled as a rigid single segment attached distally to the pelvis, which was defined by markers placed on the left and right anterior superior and posterior superior iliac spine. No additional markers were placed at the L5/S1 joint.

Considering the low magnitude of trunk lean implemented in the current study, and the associated increase in spinal load, our findings suggest that lateral trunk lean could result in detrimental adaptations along the kinetic chain, especially considering that higher magnitudes of modification have been reported in the literature.^{4,12,13} Implementing lateral trunk lean resulted in asymmetrical spinal loads, which has been implicated in the pathogenesis of lower back pain. Further research is required to investigate the chronic nature of these adaptations.

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Tables

Table 6. Mean Difference Between Target and Achieved Kinematic Change, Success Rate, and Performance Relative to Target Bandwidth for Modified Limb During Gait Modification: Lateral Trunk Lean

Gait Modification	Mean difference	Success rate (%)	Above minimum threshold (%)	Above target
<i>LTL small</i>	1.79	26.0	87.	61.0
<i>LTL large</i>	1.83	17.0	88. 0	71.0

Abbreviations: LTL small, lateral trunk lean small modification; LTL large, lateral trunk lean large modification.

Table 7. Mean and Standard Deviation for Gait Parameters

	Ipsilateral stance			Contralateral stance		
	Baseline	Trunk lean small	Trunk lean large	Baseline	Trunk lean small	Trunk lean large
Gait speed (m/s)	1.33±0.18	1.34±0.19	1.34±0.19	--	--	--
Stride length (m)	1.41±0.17	1.41±0.19	1.40±0.17	--	--	--
Stride width (m)	0.13±0.03	0.13±0.03	0.13±0.03	--	--	--
Peak KabM (Nm/kg.m)	-0.28±0.09	-0.25±0.08	-0.26±0.10	--	--	--

Abbreviations: Peak KabM, peak knee abductor moment.

*Significant difference between trunk lean and baseline

Table 8. Mean and Standard Deviation for Trunk Angle in Degrees (°) at Gait Events

	Ipsilateral stance			Contralateral stance		
	Baseline	Trunk lean small	Trunk lean large	Baseline	Trunk lean small	Trunk lean large
<i>Lateral</i>						
@ Heel strike	-0.71±2.87	1.62± 2.58*	2.65±2.17*	--	--	--
@ First peak KabM	1.50±3.11	5.58±2.81*	6.99±2.32*	--	--	--
@ Peak lateral trunk moment	1.73±2.31	3.59±3.22*	4.09±2.91*	0.47±2.07	1.51±3.01	2.18±2.82*
<i>Axial</i>						
@ Heel strike	4.31±4.09	3.15±4.82	2.77±4.77	--	--	--
@ First peak KabM	5.02±3.67	4.00±4.45	3.28±4.82	--	--	--
@ Peak lateral trunk moment	4.27±4.33	3.46±4.67	2.96±4.55	3.64±3.60	3.17±3.78	3.16±4.42

Abbreviations: Peak KabM, peak knee abductor moment.

*Significant difference between trunk lean and baseline

Table 9. Mean and Standard Deviation for Trunk Moment and Trunk Angular Impulse at Gait Events

	Ipsilateral stance			Contralateral stance		
	Baseline	Trunk lean small	Trunk lean large	Baseline	Trunk lean small	Trunk lean large
<i>Lateral moment</i>						
@ Peak moment (Nm/kg.m)	0.23±0.16	0.28±0.20*	0.29±0.18*	-0.17±0.13	-0.17±0.20	-0.17±0.20
@ Heel strike (Nm/kg.m)	-0.06±0.06	-0.04±0.05*	-0.04±0.06*	--	--	--
@ First peak KabM (Nm/kg.m)	0.01±0.06	0.10±0.08*	0.12±0.08*	--	--	--
<i>Axial moment</i>						
@ Peak moment (Nm/kg.m)	0.09±0.07	0.09±0.08	0.09±0.08	-0.05±0.04	-0.05±0.05	-0.05±0.05
@ Heel strike (Nm/kg.m)	-0.02±0.03	-0.02±0.03	-0.004±0.03*	--	--	--
@ First peak KabM (Nm/kg.m)	-0.02±0.02	-0.02±0.03	-0.02±0.03	--	--	--
<i>Trunk impulse</i>						
Lateral (Nms/kg.m)	0.03±0.02	0.06±0.03*	0.07±0.04*	-0.03±0.04	-0.03±0.04	-0.03±0.04
Axial (Nms/kg.m)	0.01±0.01	0.01±0.01	0.01±0.01	-0.001±0.01	-0.001±0.01	-0.001±0.01

Abbreviaions: Peak KabM, peak knee abductor moment.

*Significant difference between trunk lean and baseline

Table 10. Mean and Standard Deviation for Trunk Joint Reaction Force

	Ipsilateral stance			Contralateral stance		
	Baseline	Trunk lean small	Trunk lean large	Baseline	Trunk lean small	Trunk lean large
Anterior/ Posterior (N/kg)	0.80±0.29	0.91±0.44	0.95±0.55	0.81±0.31	0.87±0.45	0.88±0.49
Lateral (N/kg)	0.94±0.26	1.50±0.45*	1.64±0.51*	0.69±0.19	1.25±0.46*	1.35±0.52*
Vertical (N/kg)	-1.98±1.20	-2.10±1.43	-2.08±1.73	-4.37±1.32	-4.30±1.45	-4.02±1.61

*Significant difference between trunk lean and baseline

Chapter Six. General Discussion

Discussion

This PhD dissertation was conducted to assess the efficacy of gait modification using real-time biofeedback for reducing lower extremity mechanical loads. In addition, acute changes in the biomechanical parameters of the trunk and non-modified side in participants undergoing unilaterally implemented gait modification were studied. The current chapter is divided into 3 sections. The first section provides a comprehensive overview of the main findings according the research questions of the 3 scientific studies completed for this PhD. Limitations are discussed in the second section, and suggestions for future research are presented in the third and final section.

Main findings. A primary purpose of the dissertation was to assess beneficial load reductions associated with gait modification. In addition, various strategies and modes of feedback were compared to rank effectiveness. Limitations due to the level of evidence constrain generalizability and clinical utility. Research into the effectiveness of gait retraining using RTB within a symptomatic population is lacking. Differences in methodological approach such as strategy implemented, training methods, and evaluation of skill acquisition exist. Currently, there is no clear consensus regarding the most effective gait strategy, magnitude of modification, or mode of feedback.¹⁷

In addition, gait asymmetry is believed to adversely alter lower extremity joint load during gait.⁹⁰ This inspired additional investigations into the biomechanical loading environment of the contralateral limb and spine during unilaterally implemented gait modification. Asymmetry introduced during gait modification could result in unfavorable load redistribution in the non-modified limb. Increased trunk motion is associated with increased trunk moment,³¹ which is associated with increased spinal load³³ and muscle activation.³² Increased spinal load is a contributing factor to lower back pain.³³ Gait modification introduced unilaterally may induce undesired load redistribution. Investigating unintended changes as a result of unilaterally implemented gait modification, specifically at lower extremity load-bearing joints most susceptible to degenerative changes^{20,89} and at the spine, is necessary.

Study 1. Results revealed that the current quality of evidence is low, with most studies employing quasi-experimental designs. There was a prevalence of studies using healthy individuals, and heterogeneous designs with only a few experimental designs studying symptomatic populations. Nonetheless, all studies that measured frontal plane knee moment in OA participants reported significant reductions post-training, suggesting that gait retraining can be effective in reducing frontal plane knee moment in patients with knee OA.^{21,26,68} Self-selected gait modification resulted in the greatest frontal plane knee moment reduction in healthy individuals. In general, direct biofeedback resulted in the greatest reductions in frontal plane knee moment. This suggests a better response to biofeedback based on the target kinetic parameter, compared to using a kinematic measure.^{72,73} Evidence from the systematic review corroborates reports that frontal plane

knee moment reduction per unit of gait modification is highly variable among individuals, indicating that individual dose-response relationships exist.^{83,84}

Results from the systematic review did not produce a consensus related to the efficacy of gait modification using RTB for reducing pain, or improving function in individuals with knee OA.^{68,76} Visual delivery of biofeedback was associated with the largest frontal plane knee moment reductions in healthy individuals. Concurrent visual feedback has been reported to be effective in rehabilitation of complex motor skills.^{81,86} Older adults who are more susceptible to knee OA have been reported to benefit from receiving concurrent visual feedback, as they remain in an attention-demanding phase of learning longer than their younger counterparts.⁹⁴ Results from the literature search did not identify any studies directly comparing visual, haptic, and auditory feedback.

Increased KFM_{abs} is associated with increased joint compression, which in turn results in increased medial knee contact force.⁶² Results from Study 1 showed that multi-parameter,⁶⁸ toe-in foot progression,²⁶ and medial weight shift⁷¹ gait modifications resulted in reduced peak sagittal plane knee moment. Walking with a feedback-monitoring knee brace designed to reduce ROL⁷⁴ and medial knee thrust⁷¹ resulted in increased KFM. It is important that gait-retraining interventions do not offset the benefits of reduced frontal plane knee moment with equal or greater increases in KFM. Future research should identify which strategies are most beneficial in terms of both frontal plane knee moment and KFM.

Study 2. Acute changes in the biomechanical parameters of the non-modified limb during unilaterally implemented gait modification were investigated. Although there

were no significant changes in the non-modified limb peak frontal plane knee moment, there were significant increases in both the KFM_{abs} and the estimated MCF during early stance in medial knee thrust modification trials. Increased MCF in the non-modified limb appeared to be related to the magnitude of the modification. During the small medial knee thrust modification, there was increased MCF, however it was not statistically significant. Changes in hip and knee angles reported during the medial knee thrust modification provide evidence of gait asymmetry, possibly contributing to the reported changes in joint load during early stance. These changes are most likely due to the nature of the gait-modification strategy. Medial knee thrust, unlike lateral trunk lean and the toe-in foot progression, involves a medial change to both hip and knee joint angles with the intent to redistribute the load between the knee compartments.

Study 3. Increased trunk motion has been previously associated with elevated trunk moment during trunk sway gait modification.³² Results from Study 3 demonstrate the susceptibility of trunk moment to significant changes even during conservative trunk modifications. Increases in frontal plane trunk moment as high as 26% were observed during unilateral trunk lean modification. Elevated magnitudes of trunk moment are associated with increased spinal structural load.³¹ The increased frontal plane trunk angular impulse and lateral joint reaction force during ipsilateral stance served as further confirmation of an altered loading environment at the spine. Changes to the trunk lateral joint reaction force persisted into contralateral stance. This can be observed in Figure 10 by the increase in the lateral joint reaction force during contralateral stance in the direction of the modified side. The concurrent increase in both the lateral joint reaction

force and trunk moment during dose-specific trunk lean suggests that trunk modification may be contraindicated for individuals predisposed to lower back pain/injury.

Limitations. Most of the studies included in the systematic review were of low quality evidence due to methodological decisions related to study design and sample size. In Studies 2 and 3, healthy cohorts were investigated. It is possible the reported results might not manifest similarly in pathological populations. It is important to also consider that symptomatic individuals may be more sensitive to changes in their lower extremity load. Response may also be dependent on disease severity, pain, and disability level.

The magnitudes of the modifications used in Studies 2 and 3 were made subject specific. A bandwidth the size of 2 SD was used to provide a target magnitude. This most likely contributed to the observed low success rate reported during gait modification. During both magnitudes of the lateral trunk lean gait modification, participants exceeded recommended magnitudes 66% of the time, and were successful in 22% of the trials. This observed “over-modification” may contribute to the significant increase in trunk kinetics, which was contrary to the research hypothesis.

MCF was estimated using regression equations obtained from a study that assessed medial knee contact force in a patient with a knee-instrumented device. Caution should be exercised when interpreting the estimated medial knee contact force due to potential dissimilarities between the 2 populations. It is also possible that the reported biomechanical changes in the non-modified limb are due to expected natural learning errors as a result of implementing gait modification. Such errors may be attributable to the acquisition phase, and may disappear over multiple training sessions. Finally, the

trunk was modeled as a rigid single segment attached distally to the pelvis, and defined by markers placed on the left and right anterior superior and posterior superior iliac spine. No additional markers were placed at the L5/S1 joint, which resulted in our model differing slightly from validated models reported in literature.³³

Recommendations for future research. Research studies investigating acute and chronic changes to the mechanical load experienced at the non-modified limb and at the spine during unilateral implemented medial knee thrust and lateral trunk lean are needed. Experimental studies employing randomized controlled study designs are needed to compare the effects of different gait-modification strategies and biofeedback modes—specifically in patients with knee OA—while including additional outcome measures that may affect clinical outcomes. In addition, these experimental studies should consider concurrently investigating unintended changes throughout the kinetic chain as a result of unilaterally implemented gait modification. Longitudinal inquiry into changes to the structural loading of the spine during trunk modification is required. Over prolonged periods, exposure to increased loads could result in unfavorable long-term consequences.

Chapter Seven. Conclusion

Research is a recursive process. The objective of this PhD dissertation is to contribute to the available scientific knowledge relating to the use of gait modification to favorably alter biomechanical risk factors for knee OA. While the preponderance of available research on gait retraining is focused on beneficial changes to the knee joint loading environment, investigating both acute and chronic potentially detrimental adaptations should hold equal priority. Based on the findings from this PhD dissertation, it is suggested that future experimental studies implementing gait-modification strategies using individuals with knee OA are needed. Additionally, these studies should concurrently consider changes throughout the kinetic chain as a result of load redistribution. Unintended changes—mainly in weight-bearing joints such as the spine, ipsilateral/contralateral hip and ankle, as well as the contralateral knee—should be investigated.

Appendix A

PEDro scale

PEDro scale

1. eligibility criteria were specified	no <input type="checkbox"/> yes <input type="checkbox"/> where:
2. subjects were randomly allocated to groups (in a crossover study, subjects were randomly allocated an order in which treatments were received)	no <input type="checkbox"/> yes <input type="checkbox"/> where:
3. allocation was concealed	no <input type="checkbox"/> yes <input type="checkbox"/> where:
4. the groups were similar at baseline regarding the most important prognostic indicators	no <input type="checkbox"/> yes <input type="checkbox"/> where:
5. there was blinding of all subjects	no <input type="checkbox"/> yes <input type="checkbox"/> where:
6. there was blinding of all therapists who administered the therapy	no <input type="checkbox"/> yes <input type="checkbox"/> where:
7. there was blinding of all assessors who measured at least one key outcome	no <input type="checkbox"/> yes <input type="checkbox"/> where:
8. measures of at least one key outcome were obtained from more than 85% of the subjects initially allocated to groups	no <input type="checkbox"/> yes <input type="checkbox"/> where:
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 analysed by "intention to treat"	no <input type="checkbox"/> yes <input type="checkbox"/> where:
10. the results of between-group statistical comparisons are reported for at least one key outcome	no <input type="checkbox"/> yes <input type="checkbox"/> where:
11. the study provides both point measures and measures of variability for at least one key outcome	no <input type="checkbox"/> yes <input type="checkbox"/> where:

The PEDro scale is based on the Delphi list developed by Verhagen and colleagues at the Department of Epidemiology, University of Maastricht (Verhagen AP *et al* (1998). *The Delphi list: a criteria list for quality assessment of randomised clinical trials for conducting systematic reviews developed by Delphi consensus. Journal of Clinical Epidemiology*, 51(12):1235-41). The list is based on "expert consensus" not, for the most part, on empirical data. Two additional items not on the Delphi list (PEDro scale items 8 and 10) have been included in the PEDro scale. As more empirical data comes to hand it may become possible to "weight" scale items so that the PEDro score reflects the importance of individual scale items.

The purpose of the PEDro scale is to help the users of the PEDro database rapidly identify which of the known or suspected randomised clinical trials (ie RCTs or CCTs) archived on the PEDro database are likely to be internally valid (criteria 2-9), and could have sufficient statistical information to make their results interpretable (criteria 10-11). An additional criterion (criterion 1) that relates to the external validity (or "generalisability" or "applicability" of the trial) has been retained so that the Delphi list is complete, but this criterion will not be used to calculate the PEDro score reported on the PEDro web site.

The PEDro scale should not be used as a measure of the "validity" of a study's conclusions. In particular, we caution users of the PEDro scale that studies which show significant treatment effects and which score highly on the PEDro scale do not necessarily provide evidence that the treatment is clinically useful. Additional considerations include whether the treatment effect was big enough to be clinically worthwhile, whether the positive effects of the treatment outweigh its negative effects, and the cost-effectiveness of the treatment. The scale should not be used to compare the "quality" of trials performed in different areas of therapy, primarily because it is not possible to satisfy all scale items in some areas of physiotherapy practice.

Last amended June 21st, 1999

Notes on administration of the PEDro scale:

All criteria	Points are only awarded when a criterion is clearly satisfied. If on a literal reading of the trial report it is possible that a criterion was not satisfied, a point should not be awarded for that criterion.
Criterion 1	This criterion is satisfied if the report describes the source of subjects and a list of criteria used to determine who was eligible to participate in the study.
Criterion 2	A study is considered to have used random allocation if the report states that allocation was random. The precise method of randomisation need not be specified. Procedures such as coin-tossing and dice-rolling should be considered random. Quasi-randomisation allocation procedures such as allocation by hospital record number or birth date, or alternation, do not satisfy this criterion.
Criterion 3	<i>Concealed allocation</i> means that the person who determined if a subject was eligible for inclusion in the trial was unaware, when this decision was made, of which group the subject would be allocated to. A point is awarded for this criteria, even if it is not stated that allocation was concealed, when the report states that allocation was by sealed opaque envelopes or that allocation involved contacting the holder of the allocation schedule who was "off-site".
Criterion 4	At a minimum, in studies of therapeutic interventions, the report must describe at least one measure of the severity of the condition being treated and at least one (different) key outcome measure at baseline. The rater must be satisfied that the groups' outcomes would not be expected to differ, on the basis of baseline differences in prognostic variables alone, by a clinically significant amount. This criterion is satisfied even if only baseline data of study completers are presented.
Criteria 4, 7-11	<i>Key outcomes</i> are those outcomes which provide the primary measure of the effectiveness (or lack of effectiveness) of the therapy. In most studies, more than one variable is used as an outcome measure.
Criterion 5-7	<i>Blinding</i> means the person in question (subject, therapist or assessor) did not know which group the subject had been allocated to. In addition, subjects and therapists are only considered to be "blind" if it could be expected that they would have been unable to distinguish between the treatments applied to different groups. In trials in which key outcomes are self-reported (eg, visual analogue scale, pain diary), the assessor is considered to be blind if the subject was blind.
Criterion 8	This criterion is only satisfied if the report explicitly states <i>both</i> the number of subjects initially allocated to groups <i>and</i> the number of subjects from whom key outcome measures were obtained. In trials in which outcomes are measured at several points in time, a key outcome must have been measured in more than 85% of subjects at one of those points in time.
Criterion 9	An <i>intention to treat</i> analysis means that, where subjects did not receive treatment (or the control condition) as allocated, and where measures of outcomes were available, the analysis was performed as if subjects received the treatment (or control condition) they were allocated to. This criterion is satisfied, even if there is no mention of analysis by intention to treat, if the report explicitly states that all subjects received treatment or control conditions as allocated.
Criterion 10	A <i>between-group</i> statistical comparison involves statistical comparison of one group with another. Depending on the design of the study, this may involve comparison of two or more treatments, or comparison of treatment with a control condition. The analysis may be a simple comparison of outcomes measured after the treatment was administered, or a comparison of the change in one group with the change in another (when a factorial analysis of variance has been used to analyse the data, the latter is often reported as a group \times time interaction). The comparison may be in the form hypothesis testing (which provides a "p" value, describing the probability that the groups differed only by chance) or in the form of an estimate (for example, the mean or median difference, or a difference in proportions, or number needed to treat, or a relative risk or hazard ratio) and its confidence interval.
Criterion 11	A <i>point measure</i> is a measure of the size of the treatment effect. The treatment effect may be described as a difference in group outcomes, or as the outcome in (each of) all groups. <i>Measures of variability</i> include standard deviations, standard errors, confidence intervals, interquartile ranges (or other quantile ranges), and ranges. Point measures and/or measures of variability may be provided graphically (for example, SDs may be given as error bars in a Figure) as long as it is clear what is being graphed (for example, as long as it is clear whether error bars represent SDs or SEs). Where outcomes are categorical, this criterion is considered to have been met if the number of subjects in each category is given for each group.

Appendix B

Study 1 (Published Manuscript)



International Journal of Kinesiology & Sports Science

ISSN: 2202-946X
www.ijkss.aiac.org.au



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

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ARTICLE INFO

Article history

Received: May 22, 2017

Accepted: July 08, 2017

Published: July 31, 2017

Volume: 5 Issue: 3

Conflicts of interest: None

Funding: None

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, & Vanwanselle, 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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<http://dx.doi.org/10.7575/aiac.ijkss.v.5n.3p.35>

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, non-randomized 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

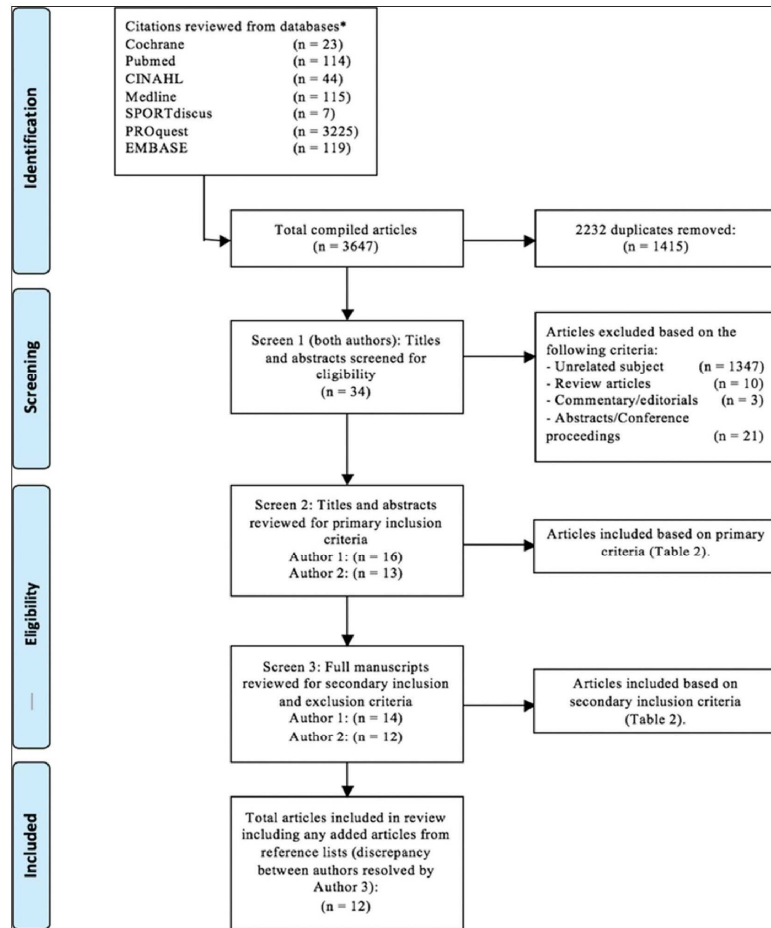


Figure 1. Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) Flow Diagram of search strategy

(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 proprio-

ceptive 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 (\pm 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, et al., 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: 6.2±2.2° Natural: 6.0±2.1° 1-month: 6.6±1.4° Modified: 5.5±2.2°	Nm/kg*Ht	Visual; knee angle	KAM	0.43±0.07	Post-training: 0.42±0.05 Natural: 0.34±0.07 1-month: 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. A slight weight bearing shift to the medial side of the foot during gait using real-time haptic biofeedback reduced first peak KAM.
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	-14.2	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.
Ferrigno et al. (2016)	Medial thrust 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: 2.66±0.95 KAM 1: 1.08±0.72 KAM 2: 2.64±0.98	-8.3 -12 -38 -11.7	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	Pressure based feedback: 2.66±0.85 KAM 1: 1.58±0.72 KAM 2: 2.63±0.87	-12 -9.2 -12	Average peak KAM: 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.

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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
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 gait 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.

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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
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*	While the change was overall positive, the magnitude of changed varied significantly. 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°	Foot progression angle: Post-training: -5.1±5.1° 1-month follow-up: -6.0±4.7°	%BW*Ht	Haptic; trunk and foot progression angles	trunk 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.
	Trunk sway:	Trunk sway angle: 1.0±2.1°	Trunk sway angle: 0.7±1.6° 1-month follow-up: 0.7±1.5°							

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Table 2. (Continued)

Author (year)	Gait modification	Natural Gait: Mean value of target parameter	Modified gait: value of target parameter	Mean 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: 6.1° 6° lean: 8.7° 12° lean: 11.1° Early Stance: 5.1° 6° lean: 7.6° 9° lean: 9.3° Late Stance: 3.0° 6° lean: 4.4° 9° lean: 5.6° 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: value of target parameter	Mean KAM measure	Unit of measure	Biofeedback variable	KAM outcome reported	Natural gait: mean±SD KAM	Modified gait: mean±SD KAM	Calculated % KAM change	Primary Findings										
Wheeler et al. (2011)	Self-selected	NR	NR	%BW*Ht	Visual and haptic; KAM	Visual and haptic; KAM	KAM 1	All participants: 3.19 ± 0.93 Visual: 3.98±0.90 Haptic: 4.07±0.89	All participants: 3.19 ± 0.93 Visual: 3.29±0.98 Haptic: 3.90±0.94	-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										
												Bar Early: 1.17±0.25 Bar Late: 0.94±0.39 Bar Mid: 0.94±0.30	KAM feedback: KAM Early: 2.17±0.25 Late: 2.10±0.16 Mid: 1.91±0.30	KAM feedback: KAM Early: 1.17±0.25 Bar Early: -46.08% Bar Late: 0.94±0.39 Bar Late: -55.21% Bar Mid: 0.94±0.30 Bar Mid: -50.80%	KAM feedback: KAM Early: 0.96±0.26 Polar Late: 0.94±0.34 Polar Mid: 0.94±0.32	KAM feedback: KAM Early: -55.84 Polar Late: -55.00 Polar Mid: -50.57					
																	Color Early: 1.20±0.27 Color Late: 0.98±0.36 Color Mid: 0.98±0.33	KAM feedback: KAM Early: -44.72 Color Late: -53.40 Color Mid: -48.82			
																			Graph Early: 1.10±0.26 Graph Late: 1.23±0.30 Graph Mid: 1.23±0.32	KAM feedback: KAM Early: -49.48 Graph Late: -41.40 Graph Mid: -35.63	
												All participants: 3.19 ± 0.93 Visual: 3.29±0.98 Haptic: 3.90±0.94	All participants: 3.19 ± 0.93 Visual: 3.29±0.98 Haptic: 3.90±0.94								
														Visual and haptic; KAM	Visual and haptic; KAM	KAM 1	All participants: 3.19 ± 0.93 Visual: 3.29±0.98 Haptic: 3.90±0.94	All participants: 3.19 ± 0.93 Visual: 3.29±0.98 Haptic: 3.90±0.94			
																			Visual and haptic; KAM	Visual and haptic; KAM	KAM 1
												Visual and haptic; KAM	Visual and haptic; KAM								
														Visual and haptic; KAM	Visual and haptic; KAM	KAM 1	All participants: 3.19 ± 0.93 Visual: 3.29±0.98 Haptic: 3.90±0.94	All participants: 3.19 ± 0.93 Visual: 3.29±0.98 Haptic: 3.90±0.94			
																			Visual and haptic; KAM	Visual and haptic; KAM	KAM 1
												Visual and haptic; KAM	Visual and haptic; KAM								
														Visual and haptic; KAM	Visual and haptic; KAM	KAM 1	All participants: 3.19 ± 0.93 Visual: 3.29±0.98 Haptic: 3.90±0.94	All participants: 3.19 ± 0.93 Visual: 3.29±0.98 Haptic: 3.90±0.94			

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Table 2. (Continued)

Author (year)	Gait modification	Natural Gait: Mean value of target parameter	Modified Gait: Modified gait: value of target parameter	Mean KAM unit of measure of target parameter	Biofeedback variable	KAM outcome reported	Natural gait: mean±SD KAM	Modified gait: mean±SD KAM	Calculated % KAM change	Primary Findings
										<ul style="list-style-type: none"> • 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).

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*	
	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 (Nm.s/%BW*Ht)	Van den Noort et al. (2014)	KAM feedback: 1.21±0.17	KAM feedback: Bar: 0.63±0.17 Polar: 0.47±0.18 Color: 0.67±0.19 Graph: 0.62±0.18	-48.17 -61.02 -44.81 -49.24	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.
		HIR feedback: 1.17±0.13	HIR feedback: Bar: 0.98±0.15 Polar: 0.90±0.15 Color: 1.10±0.16 Graph: 1.17±0.15	-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
Stride length (m)	Riskowski (2010)	1.28±0.05	Training gait (with brace): 1.26±0.04	1.56*	Stride length was minimally reduced but not significantly altered across all gait modifications studied.
	Simic et al. (2012)	1.24	Post-training (no brace): 1.27±0.03 6° lean: 1.25 9° lean: 1.24 12° lean: 1.23	-0.78* 0.81* -0* -0.81*	
	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*	
	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)	Session 1: 6.63±1.83† 0 – “Effortless” 10 – “Max effort”	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)	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)	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	
	1 – “Very difficult” 10 – “Very easy”				

Table 3. (Continued)

Outcome measure	Author (year)	Natural gait: Mean value of target variable	Modified gait: Mean value of target variable	Calculated % change	Findings
Awkwardness/ Intuitive (0/10)	Barrios et al. (2010) 0 – “Natural” 10 – “Maximally unnatural”	Session 1: 7.06±0.78†	HIR feedback: Bar: 6.0±1.7 Polar: 6.1±2.5 Color: 5.9±2.4 Graph: 6.4±1.8 Last session: 3.88±1.64†	N/A N/A N/A N/A -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.
PROM: KOOS pain	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	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)	62.7±10.8	3-month: 70.9 6-month: 68.1 12-month: 72.8	13.07* 8.61* 16.12*	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.
LLFDI	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*	
WOMAC pain	Shull et al. (2013b)	70.5†	3-month: 69.1 6-month: 68.9 12-month: 69.7	5.02* 4.71* 5.93*	
WOMAC function	Shull et al. (2013b)	77.4†	Post-training: 85.0† One-month: 90.0†	20.57* 27.66*	

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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 McMaster 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 protrusion (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 strat-

egies. 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; Stülzenbrück & 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.

ACKNOWLEDGEMENTS

Publication of this article was funded in part by the George Mason University Libraries Open Access Publishing Fund.

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Appendix C

Consent Form

Osteoarthritis in the ACL reconstructed: A multifactorial approach

INFORMED CONSENT FORM

RESEARCH PROCEDURES

This research is being done to evaluate the mechanisms for osteoarthritis development in individuals that have a history of anterior cruciate ligament (ACL) reconstruction. If you agree to participate, you will be asked to perform a number of tests to determine your muscle strength, muscle characteristics, muscle activity, and movement patterns while jumping, walking, and running. We will measure your height, and weight, and you will fill a questionnaire with questions pertaining to your injury history, and quality of life.

- We will then measure your muscle size using ultrasound imaging. For this you will sit on a table, relax your legs, and we will place a cold water base gel on your legs to then place the ultrasound probe. We will be able to visualize your muscles.
- Your muscle strength will be measure with a dynamometer. We will ask you to sit on a chair and resist a static object. At the same time we will be measure the amount of force you are applying to resist the object.

After those measures are obtained, we will ask you to jump, walk and run at different times for us to assess your movement patterns:

- We will then collect your muscle activity using surface electrodes. These non-invasive surface electrodes will attached over your thigh and calf muscles and over the flat part of the shinbone. We will prepare the skin above these areas by it shaving and wiping with alcohol swabs. The surface electrodes will be connected to wires that lead to a computer that measures muscle activity. These methods are commonly used for collecting muscle activity data.
- You will have a 10-minute warm-up period that will consist of running and stretching. Thereafter, forty (40) reflective markers will be placed on specific areas on your body. A measurement tape will be used to measure your leg length. The measurement will be taken from your hip to your ankle.
- You will then have time to familiarize yourself with the jumping, walking and running tasks.
- After you familiarize yourself with the tasks, we will ask you to jump from a box, placed at different heights (26, 30, and 40 cm). After, we will ask you to walk across a path and/or on a treadmill at your preferred speed. Lastly, we will ask you to run on that same path (or treadmill) at your preferred speed. While you perform these tasks we will be measuring your muscle activity, muscle contraction velocities, and movement patterns.

All tasks will be videotaped; this will allow us to evaluate differences between jumping, walking, and running. If you say YES, then your participation will last for approximately 90 minutes at the SMART Lab, Room 215, in the Freedom Aquatic Center.

Approximately 20 females and 20 males with knee osteoarthritis will be participating in this study, as well as 40 healthy individuals.

RISKS

There are no known risks of using ultrasound imaging, EMG, and strength devices that will be used during this protocol. You may feel increased pain on the knee with osteoarthritis when performing the dynamic tasks, and minimally increase cartilage degeneration in that same knee. You may experience increased instability in the knee with osteoarthritis. The foreseeable risks or discomforts include ankle sprain, knee injury, muscle pain, and muscle soreness. The researcher has tried to reduce these risks by providing clear directions on how to jump from a box, and walk and run. You could also experience muscle injury, inappropriate changes in blood pressure or heart rhythm, a heart attack, stroke or death during the exercise tests. The risk of these events is very low in individuals who are physically active and apparently healthy. The risk is likely no greater than what you experience during walking, walk downstairs or step down on a sidewalk. There is also a risk of too much exposure to x-rays, since you will need to have a radiograph done prior to participate if you are in the injured group. If you experience knee pain while performing our protocol, we request that you inform any of the researchers immediately. Finally, as with any research, there is some possibility that you may be subject to risks that have not yet been identified. In case of injury, the investigators or George Mason University are not liable for an injury and cannot cover any expenses related to treatment of an injury. In case of that rare event, you should seek medical help.

BENEFITS

There are no benefits to you as a participant other than to further research in lower extremity injury prevention.

CONFIDENTIALITY

All data in this study will be confidential. The researchers will take reasonable steps to ensure confidentiality is upheld. The researchers will store all questionnaires, videotapes, and laboratory findings in a locked file cabinet prior to processing. The results of this study may be used in reports, presentations and publications, but the researcher will not identify you.

PARTICIPATION

Your participation is voluntary, and you may withdraw from the study at any time and for any reason. The age range for participation is 21 to 46 years old. If you decide not to participate or if you withdraw from the study, there is no penalty or loss of benefits to which you are otherwise entitled. There are no costs to you or any other party.

CONTACT

This research is being conducted by Dr. Nelson Cortes, and Dr. Siddhartha Sikdar from the SMART Laboratory at George Mason University. They may be reached at 703-993-9257 for questions or to report a research-related problem. You may contact the George Mason University

Office of Research Subject Protections at 703-993-4121 if you have questions or comments regarding your rights as a participant in the research.

This research has been reviewed according to George Mason University procedures governing your participation in this research.

CONSENT

I have read this form and agree to participate in this study.

_____ I agree to audio (video) taping.

_____ I do not agree to audio (video) taping

Name

Date of Signature

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Biography

Oladipo Eddo received his Bachelor of Science from George Mason University in 2012. He was employed as a fitness consultant with Sports Club LA in Washington, DC, for 3 years and received his Master of Science in Exercise Fitness and Health Promotion from George Mason University in 2014.