Christopher Ferrigno[1]
Department of Anatomy and Cell Biology,
Rush University Medical Center,
1611 W. Harrison Street,
Suite 111,
Chicago, IL 60612
e-mail: christopher_ferrigno@rush.edu

Ina S. Stoller
Department of Orthopedic Surgery,
Rush University Medical Center,
1611 W. Harrison Street,
Suite 111,
Chicago, IL 60612
e-mail: ina.stoller@gmx.de

Najia Shakoor
Section of Rheumatology,
Rush University Medical Center,
1611 W. Harrison Street,
Suite 510,
Chicago, IL 60612
e-mail: najia_shakoor@rush.edu

Laura E. Thorp
Department of Anatomy and Cell Biology,
Rush University Medical Center,
600 S. Paulina,
Suite 507,
Chicago, IL 60612
e-mail: laura_thorp@rush.edu

Markus A. Wimmer
Department of Orthopedic Surgery,
Rush University Medical Center,
1611 W. Harrison Street,
Suite 205,
Chicago, IL 60612
e-mail: markus_a_wimmer@rush.edu

The Feasibility of Using Augmented Auditory Feedback From a Pressure Detecting Insole to Reduce the Knee Adduction Moment: A Proof of Concept Study

The objective of this work was to conduct a proof of concept study utilizing auditory feedback from a pressure-detecting shoe insole to shift plantar pressure medially in order to reduce the knee adduction moment (KAM). When compared with normal walking, 32 healthy subjects significantly reduced their peak KAM using feedback ($p < 0.001$). When compared with medial thrust gait, an established gait modification, walking with pressure-based feedback was equally effective at reducing the peak KAM, yet it successfully mitigated other potentially detrimental gait measures such as the peak knee flexion moment (KFM), knee internal rotation moment (KIrM), and a reduction in speed.
[DOI: 10.1115/1.4032123]

Introduction

Arthritis is the leading cause of disability among adults, and knee osteoarthritis (OA) is the most common form of arthritis affecting 12% of older adults [1]. The medial compartment of the knee is most often affected by arthritic changes [2] and is associated with higher biomechanical loads than the lateral compartment. The KAM is a surrogate marker of biomechanical load distribution across the tibiofemoral joint [3,4] and can be altered with gait modifications such as medial thrust gait, lateral trunk lean [5], toe-in gait [6], and toe-out gait [7].

To date, gait modifications employed to reduce the KAM focus either directly on knee position, such as medial thrust gait [8–11], or body positions proximal to the knee, such as hip "endorotation" [12] and lateral trunk lean [13]. Despite their names, toe-out gait and toe-in gait require a significant change in hip rotation to change the foot progression angle [14]. While such modifications elicit a KAM reduction, they may change other loading parameters at the knee, specifically the KFM [9–11,13], which increases both with medial thrust gait [10,11] and toe-in gait [15]. An increase in the KFM likely contributes to increased compressive loads across the knee joint [10,16] and potential decline in tibial cartilage quality [17]. Gait modifications can also generate inefficient movement patterns that may necessitate a reduction in gait speed [11]. Collectively, these factors make adopting such gait adaptations a less than ideal and potentially harmful as long-term treatment options [18].

A systematic review of the literature regarding gait modifications designed to alter medial joint loads suggests that medial thrust gait and lateral trunk lean each result in the greatest reductions in the KAM, specifically during the first half of the stance phase during gait [19]. A recently published side-by-side comparison of medial thrust gait and lateral trunk lean showed that both gait modifications significantly reduced the peak KAM [11]; however, medial thrust gait elicited a slightly greater peak KAM reduction with less overall variability in the response [11]. For this reason, and because a lateral trunk lean jeopardizes energy expenditure [5], medial thrust gait was chosen for this current proof of concept study to use as a comparison for another, less investigated gait modification using auditory feedback from a pressure-detecting shoe insole.

There has been little attention devoted to gait adaptations at the foot and ankle, where subtle changes may have a significant impact at more proximal joints. An increase in rearfoot eversion and a reduction in lateral tibia tilt are associated with a decreased KAM in subjects with knee OA [20], suggesting that increased foot pronation is associated with a decrease in the KAM. The reductions in the KAM seen with laterally wedged orthoses [21–23], variable-stiffness shoes [24–26], and flexible shoes [27,28] support the role of altering kinematics at the foot to change knee joint loading.

Shifting foot center of pressure (COP) has been suggested as a mechanism to lower the KAM [25,26]. A medial shift in barefoot COP has been correlated with a reduction in the KAM [29], and

[1]Corresponding author.
Manuscript received July 6, 2015; final manuscript received November 4, 2015; published online January 27, 2016. Editor: Beth A. Winkelstein.

wearing flexible shoes over 12 weeks medialized the foot COP while reducing the KAM [30]. Medializing foot pressure using augmented feedback from a simple "force" sensor under a shoe can successfully reduce the KAM [31]. Augmented feedback can facilitate skill acquisition by reinforcing the motor learning process in order to make the gait modification a permanent change in an individual's motor pattern [32]. Auditory [31], visual [12,13,33], and haptic [6,31,33,34] have been successfully used to augment gait modifications to lower the KAM. One of these studies used a single force sensor applied under the heel of the shoe to provide auditory cues to medialize foot pressure and, thus, lower the KAM. Further exploration into using a pressure-detecting shoe insole to provide auditory feedback to lower the KAM is warranted.

The current study tests the potential of using an in-shoe insole with more adaptability and practicality for training outside the laboratory setting. Because this is a proof of concept study, healthy young adults with relatively uncompromised gait were chosen to optimize the kinesthetic response to the pressure-based feedback. The primary hypothesis of this study was that subjects would demonstrate significant reductions in their KAM when they walked with auditory feedback from a pressure-based shoe insole and would be similar to those achieved with medial thrust gait. We further hypothesized that the KFM, speed, cadence, and stride would not be compromised with pressure-based feedback in contrast to the significant changes seen with medial thrust gait.

Methods

This single day cross-sectional study tested 32 healthy subjects (26.6 ± 3.6 yrs, 17M, 15F). The study was approved by Rush University's Institutional Review Board. Subjects were recruited by word of mouth from within the university student body, faculty, and staff and informed consent was obtained. Subjects were enrolled in the study if they had no recent history of lower extremity injury and self-reported as both healthy and pain free (<10 mm on a visual analog scale of 100 mm). Subject demographics are presented in Table 1.

The study protocol entailed that subjects undergo three sets of gait analyses. All subjects first walked with their normal gait pattern and subsequently with two randomly ordered gait modifications: medial thrust gait and gait with audible feedback from a pressure-detecting shoe insole programmed to limit lateral foot pressure. See Fig. 1 for study design.

All subjects first completed five walking trials at a self-selected normal speed with their normal gait pattern on a leveled 6-m walkway while wearing a standardized flexible shoe (FlexOA, Dr. Comfort, Mequon, WI) containing a pressure-detecting shoe insole (Pedar, Novel, Munich, Germany). After completing the five normal walking trials, subjects completed five trials each of the two gait modifications (Fig. 2) designed to reduce the KAM, specifically: (1) medial thrust gait and (2) gait with a pressure-detecting shoe insole providing auditory feedback designed to reduce pressure in two lateral foot regions (Fig. 3) by 25% compared to normal walking. The order in which the gait modifications were introduced was randomized: 16 subjects first walked with medial thrust gait and the other 16 subjects first walked while receiving pressure-based feedback from the shoe insole. All 32 subjects completed a total of 15 walking trials.

Table 1 Subject characteristics

Characteristics	Mean (SD)
N	32
Gender (M/F)	17/15
Age (yrs)	26.6 (3.6)
Height (m)	1.68 (0.08)
Mass (kg)	69.6 (17.4)
BMI (kg/m^2)	24.4 (5.1)

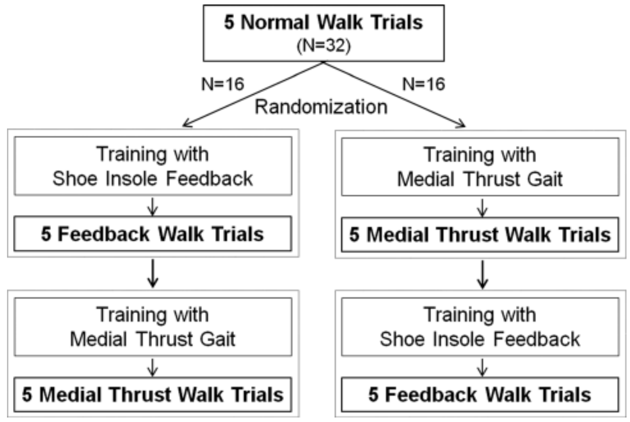

Fig. 1 Study design

Before subjects were gait tested with each gait modification, a training and practice session was performed under the supervision of an experienced and licensed physical therapist (CF) according to previously published methods [8,12,35,36]. Subjects were instructed to adduct and internally rotate the hip while slightly increasing their hip, knee, and ankle flexions. Subjects practiced medial thrust gait for a minimum of 5 min and until both the subjects were comfortable with the new gait strategy and the instructor observed a fluid gait pattern. Five minutes was an adequate amount of time for most of the subjects to become proficient with medial thrust gait while a few subjects required up to 10 min of practice.

During the shoe-insole training with pressure-based feedback, the physical therapist (CF) instructed the subjects to subtly alter their walking to prevent the generation of an audible tone from the pressure insole. When performing the modification, the therapist instructed the subjects to "walk as normal as possible so that a casual observer would not notice anything abnormal" in their gait

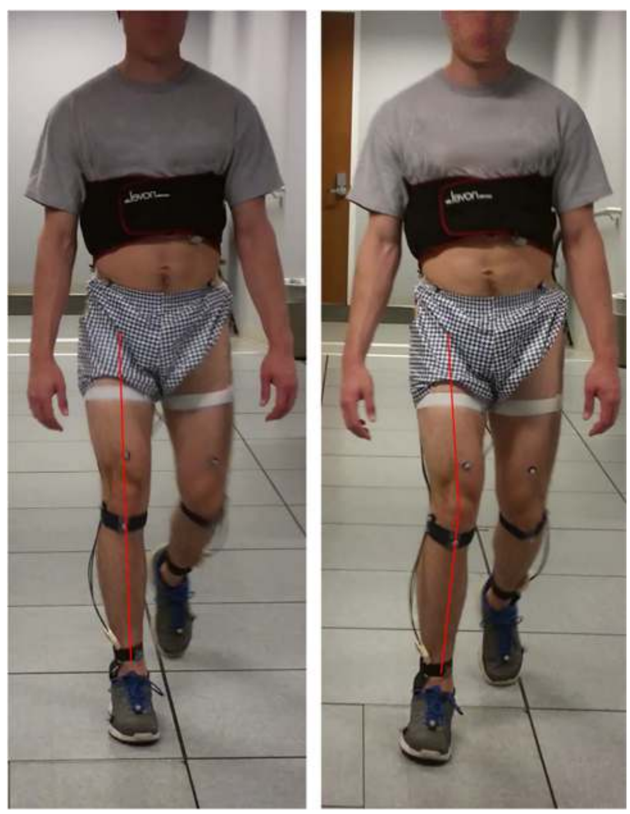

Fig. 2 Typical subject walking with pressure-based feedback (left) and medial thrust gait (right)

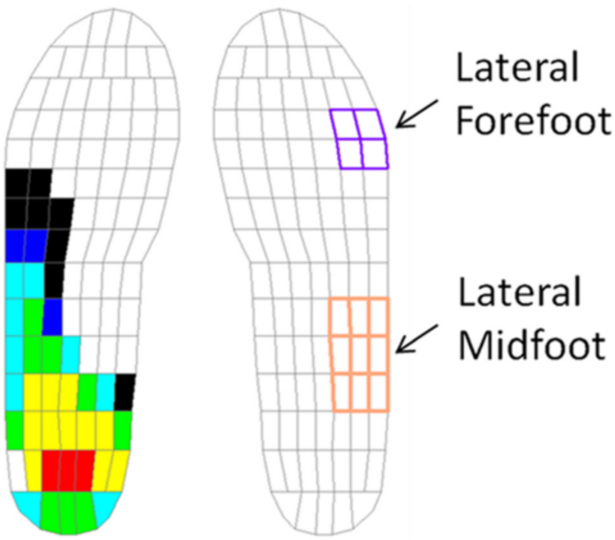

Fig. 3 Pressure-based feedback regions

pattern. Other than these two instructions, no further verbal instructions were given. Subjects practiced until they could successfully avoid the audible cues on several consecutive steps, typically requiring 2 to 5 min. During the latter portion of the practice session, subjects were instructed to hone their gait strategy until they occasionally elicited an audible tone. This additional practice time was designed to foster precision in reducing the plantar pressure close to the target of 25%. A 25% reduction ensured that the pressure was reduced more than one standard deviation from the average pressure readings during the normal walking trials. Preliminary laboratory testing suggested that a 25% reduction had potential to elicit consistent reductions in the KAM yet was comfortable to the subject and was easily accomplished. Subjects usually required less than one additional minute to successfully hone this skill but were asked to practice for a minimum of two additional minutes. After the feedback practice session, subjects completed five recorded walking trials while receiving the pressure-based, auditory feedback. A walking trial was deemed successful when no auditory feedback tones were generated during the stance phase of gait on the force plate; the lack of an audible tone confirmed that pressure was reduced by at least 25% in each of the two masked lateral areas.

Motion capture was performed using a ground embedded force plate (Bertec, Columbus, OH) to measure ground reaction forces and 12 optoelectric cameras (Qualysis, Gothenburg, Sweden) to capture lower extremity kinematics. Raw kinetic and kinematic data were processed in The Motion Monitor software (Innovative Sports Training, Chicago, IL). A 24-marker, modified Helen Hayes marker set was applied. The model combined the Helen Hayes [37] model with our existing six-marker link model [38], increasing the functionality of the model by viewing segments as 3D planes instead of 2D lines. Thigh and shank markers were moved off the long axis of the segment to create a segment plane. Markers on medial knee joint line and medial malleolus during a static collection defined respective joint centers of the knee and ankle. The ankle joint center was defined as the midpoint between the markers on the lateral and medial malleoli. The knee joint center was defined as the midpoint between the lateral and medial knee joint line markers. The hip joint center was defined as 2.5 cm distal to the midpoint of a line from the anterior–superior iliac spine to the pubic tubercle [39]. Knee moments were calculated with inverse dynamics [38]. Gait speed was calculated based on the average speed of the center of mass within the markered model.

Plantar pressure was detected between the foot and shoe using the Pedar pressure insole for all walking trials. The Pedar insole is commercially available and has been extensively validated for laboratory use. For example, McPoil et al. [40] determined measurement errors ranging from 16% to 0.8% for increasing pressures from 50 to 500 kPa. Also, good measurement repeatability has been reported [41]. For our test, the pressure insole was time-synced with force plate and cameras and data were acquired at 100 Hz. Out of the 99 capacitive sensors on every insole, two regions with four and nine sensors were grouped together into two pressure detecting units (Fig. 3). Region 1 included sensors under the anterior aspect of the lateral heel, an area lateral to the approximate location of the COP tracing that corresponds to the time-matched occurrence of the first peak KAM. Region 2 included sensors that typically register pressure from the head of the fifth metatarsal, an area lateral to the approximate location of COP tracing that corresponds to the time-matched occurrence of the second peak KAM. For each region, the maximum mean pressures for all five normal walking trials were averaged, reduced by 25%, and programmed into the insole software to provide real-time auditory feedback when the maximum mean pressure during the feedback walking trials was not reduced by at least 25% in either of the regions. Two audible tones, distinguished by pitch, could therefore be generated during each stance phase.

Statistical analyses were performed using IBM SPSS Statistics 22 (SPSS Inc. Chicago, IL). An alpha level of 0.05 was selected to determine significance. Descriptive statistics were calculated for all the variables of interest. One-way repeated measures ANOVAs and post hoc Bonferroni comparisons were used to evaluate the null hypothesis that there was no difference in participants' spatiotemporal parameters including speed, stride length, and cadence, and relevant peak moments, including overall peak KAM, the peak KAM during the first half of stance (KAM1), the peak KAM during the second half of stance (KAM2), and overall peak KFM for the three walking conditions. The peak values of the knee extension moment (KEM), knee abduction moment (KAbdM), KIrM, and knee external rotational moment (KErM) during the stance phase of gait were also examined. While moments other than the KAM and KFM have not been reported to contribute to medial knee OA pathology, the KEM has been observed to be lower in medial compartment knee OA and is linked with compensatory strategies associated with knee OA [42]. Substantial increases in any joint torque could theoretically contribute undesirably to joint loading and should be considered. A between-subject factor of gait modification order was applied to assess whether the order in which the gait modifications were performed played a role for each dependent variable.

Results

Means and SDs for kinetic and spatiotemporal variables of the three walking conditions are presented in Table 2. The differences from normal walking are demonstrated in Fig. 4. The order in which subjects performed the gait modifications had no effect on the knee moments and all spatiotemporal variables ($0.411 < p < 0.935$ for all variables).

Compared with normal walking, subjects significantly lowered their overall peak KAM by 12% (0.36%BW*Ht, $p < 0.001$) with both medial thrust gait and while walking with pressure-based feedback. Figure 5 provides graphical comparisons of the KAM and the KFM for each walking condition for the entire cohort of subjects. Twenty-three of the 32 subjects reduced their overall peak KAM executing medial thrust gait while pressure-based feedback resulted in 28 of 32 subjects reducing their overall peak KAM. The KAM1 was reduced 38.0% (0.66%BW*Ht, $p < 0.001$) with medial thrust gait (28 of 32 subjects) and 9.2% (0.18%BW*Ht, $p < 0.156$) with pressure-based feedback (31 of 32 subjects). The KAM2 was reduced by 11.7% (0.35%BW*Ht, $p < 0.001$) with medial thrust gait (24 of 32 subjects) and 12.0% (0.36%BW*Ht, $p < 0.001$) with pressure-based feedback (28 of 32 subjects). In contrast, the average KAbdM increased with medial thrust gait by 98% (0.47%BW*Ht, $p < 0.001$) compared with normal walking, but was unchanged with pressure-based

Table 2 Knee moments and spatiotemporal parameters for subjects walking in three conditions

	Descriptive statistics							
	Normal walking		Medial thrust walking			Walking with pressure-based feedback		
	Mean	SD	Mean	SD	Probability[a]	Mean	SD	Probability[a]
Spatiatemporal parameters								
Speed (m/s)	1.31	0.13	1.17	0.15	<0.001	1.26[b]	0.15	0.066
Stride (m)	1.37	0.12	1.32	0.12	0.003	1.35	0.12	0.321
Cadence (steps/min)	55.3	3.4	51.3	4.4	<0.001	54.0[b]	4.5	0.064
Loading parameters, *s*(%BW*Ht)								
KErM	0.49	0.29	0.81	0.55	0.001	0.49[b]	0.31	1.000
KIrM	1.38	0.41	1.33	0.43	0.535	1.28	0.41	0.027
KEM	2.77	0.81	2.55	0.84	0.162	2.59	0.87	0.239
KFM	3.01	1.50	4.02	1.98	0.004	2.79[b]	1.25	0.532
KAbdM	0.48	0.21	0.95	0.70	0.002	0.49[b]	0.23	1.00
KAM	3.03	0.86	2.66	0.95	<0.001	2.66	0.85	<0.001
KAM1	1.74	0.76	1.08	0.72	<0.001	1.58[b]	0.72	0.156
KAM2	2.99	0.88	2.64	0.98	<0.001	2.63	0.87	<0.001

Note: m/s, meters per second; m, meters; min, minute; %BW*Ht, percent body weight times height; KErM, knee external rotation moment; KIrM, knee internal rotation moment; KEM, knee extension moment; KFM, knee flexion moment; KAbdM, knee abduction moment; KImpulse, knee angular impulse; KAM, knee adduction moment.

[a]Comparing the gait modification with normal walking.

[b]Denotes significance ($p < 0.01$) comparing walking with pressure-based feedback with medial thrust gait.

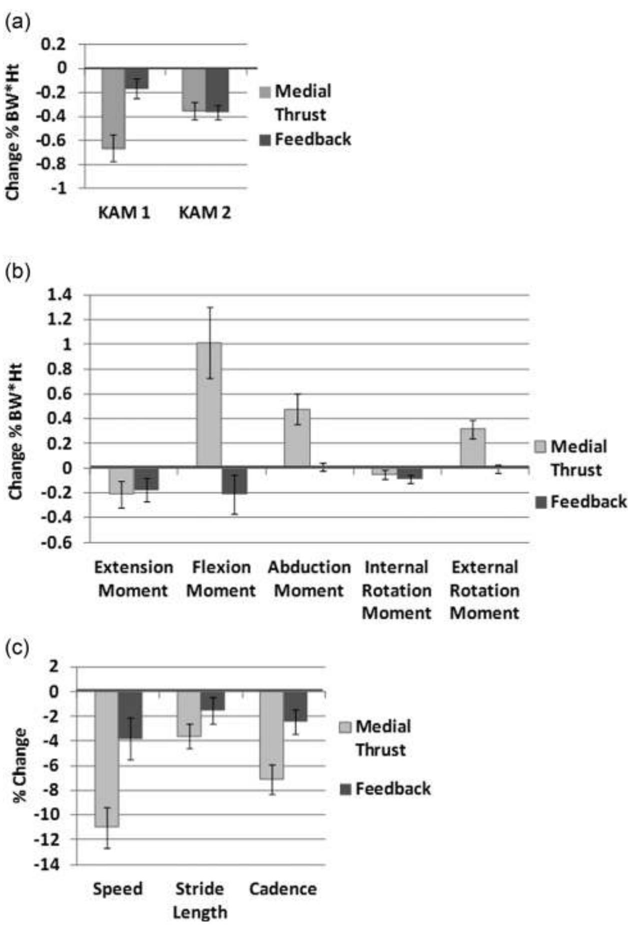

Fig. 4 The average amount of change, compared with normal walking, when subjects walked with medial thrust gait and pressure-based feedback in the (*a*) external KAM during early stance (KAM1) and late stance (KAM2), (*b*) in the other five external knee moments, and (*c*) the percent change in walking speed, stride length, and cadence

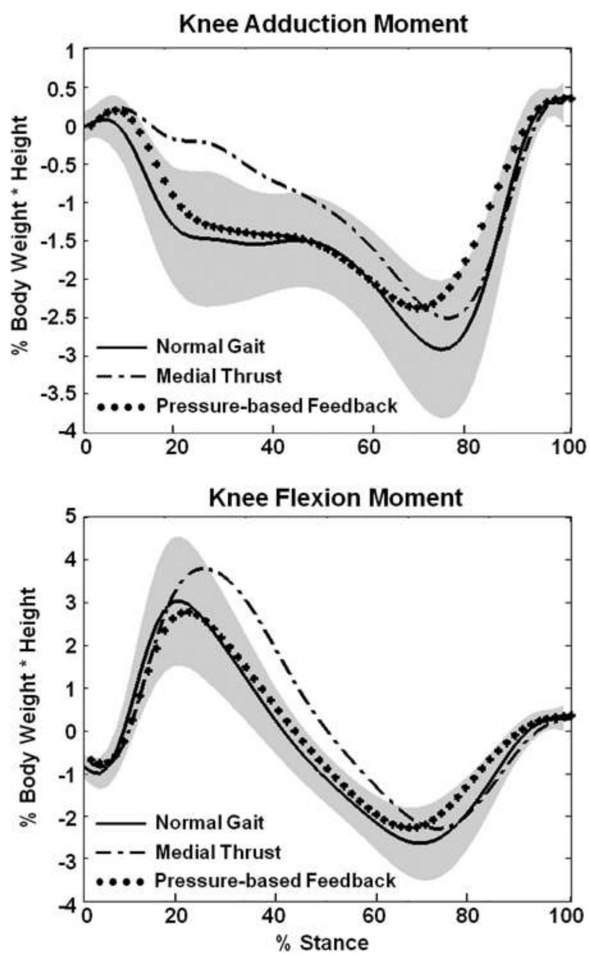

Fig. 5 The average KAM and KFM waveform for all three walking conditions. The shaded region represents one standard deviation of the normal walking condition only.

feedback. Similarly, when compared to normal gait, the KFM increased 33.6% (1.01%BW*Ht, $p = 0.004$) when subjects walked with a medial thrust gait, but the KFM was not significantly altered (0.22% BW*Ht decrease, $p = 0.532$) while walking with pressure-based feedback. The KEM did not significantly change with either gait modification. The KErM increased with medial thrust gait 65% (0.32%BW*Ht, $p = 0.001$) but was unaffected pressure-based feedback ($p = 1.000$) while the KIrM was unaffected with medial thrust gait ($p = 0.535$) but decreased with pressure-based feedback 7.2% (0.10%BW*Ht, $p = 0.027$).

When examining changes in spatiotemporal parameters, subjects walked significantly slower than normal when walking with medial thrust gait (−11.5% or −0.14 m/s, $p < 0.001$) but did not significantly reduce their walking speed with pressure-based feedback (−3.8% or −0.05 m/s, $p = 0.066$). Stride length shortened 4.5% or 0.05 m with medial thrust gait ($p = 0.003$); however, no significant change in stride length was observed with pressure-based feedback ($p = 0.337$). Cadence was reduced 7.2% or 4.0 steps/min with medial thrust gait ($p < 0.001$) but not significantly with pressure-based feedback ($p = 0.64$).

Discussion

This proof of concept study was designed to test the feasibility of using a shoe insole providing pressure-based audible feedback to reduce the KAM. Changes in gait parameters were compared to the changes observed with a medial thrust gait modification, which is known to reduce the KAM but negatively impacts other gait parameters. This study supports the hypothesis that walking with auditory feedback from a pressure-detecting insole reduces the overall KAM by a similar magnitude as medial thrust gait without increasing other surrogate markers of knee load or causing major alterations in kinematic gait parameters.

During normal walking, the average KAM1 (1.74%BW*Ht) was considerably lower than KAM2 (average 2.99%BW*Ht). Despite the relatively low baseline KAM1 values, subjects significantly reduced their KAM1 with both gait modifications. Medial thrust gait; however, elicited a far greater reduction on the KAM1 than pressure-based feedback. The reduction in speed may have contributed to this reduction in KAM1; however, debate exists regarding the role of speed in affecting the KAM [43,44]. Slower speed has been associated with reductions in the KAM [43] but others have observed minimal effects in those with knee OA and no effects in healthy subjects [44,45].

This significant KAM1 reduction may outwardly appear to be advantageous, but a closer examination of the KAM1 with medial thrust gait shows that many subjects elicited a moment reversal where there was little to no KAM during the first half of stance but rather a substantial increase in the KAbdM. The KAbdM nearly doubled with medial thrust gait but was unaffected with pressure-based feedback. Interpreting this moment reversal with medial thrust gait is difficult as little is known about the effects of KAbdM on knee loading as related to medial or lateral knee OA. However, the KAbdM has been implicated in other conditions of knee injury including patellofemoral pain [46] and anterior cruciate ligament tears during jumping [47] suggesting that increases in the KAbdM could potentially strain other soft tissue structures in the knee, especially with prolonged use.

The 9.2% reduction of KAM1 with pressure-based feedback in this study is greater than the 6% reductions with 5 deg lateral wedges [22] and the 7.2% reductions with combined variable stiffness sole and laterally wedged shoes [48]. Pressure-based feedback elicited significant reductions for both KAM1 and KAM2, a finding not always observed with other gait modifications. While medial thrust gait typically elicits reductions in both KAM1 and KAM2, toeing in reduces the KAM1 but not the KAM2 [6,15,49] and toeing out has been reported to reduce the KAM2 but not the KAM1 [49–51]. Historically, the KAM1 has been the target for biomechanical interventions; more recent evidence has shown that significant changes in only the KAM2 results in clinical improvements such as a decrease in pain for subjects with knee OA [51]. While these KAM reductions were realized with a simple, binary cue, subsequent investigations of pressure-based feedback could benefit from more sophisticated auditory feedback on a longitudinal scale allowing subjects to fine-tune their skills. Also, a dose–response study allowing subjects to gradually adjust to the final threshold of 25%, or more, might be beneficial.

The subjects in this study realized a large increase in the KFM during medial thrust gait. This finding is not unique to the current work and has been previously reported in other studies [10,11]. The large increase in the KFM during medial thrust gait may affect tibial cartilage [17] and contribute to the potential deleterious effect of an increased KAbdM while negating some of the potential benefits from the reduction in KAM1 due to a general increase in knee loading [10,16]. Medial thrust gait also increased the KErM. Given the small direct muscular support in the transverse plane, biomechanical principles suggest that an increase in this rotational moment can stress secondary restraints of the knee such as the menisci. Conversely, pressure-based feedback resulted in a small decrease in the KFM and a significant decrease in the KIrM, suggesting additional unloading of the knee joint.

Gait speed, stride length, and cadence were adversely affected with medial thrust gait and were somewhat affected, although not significantly, with pressure-based feedback. Since loss of speed is a defining characteristic for frailty with strong associations to loss of functional mobility [52–54], and reduced stride length can increase energy expenditure [55], gait efficiency is an important consideration in order for the gait modification to be efficacious in the long term. A longitudinal study should therefore assess whether these spatiotemporal parameters would normalize over time as individuals become accustomed to the modification.

This study has several limitations. Similar to other studies investigating gait modifications [33,34,56], the current study trained and tested young healthy subjects in a single visit. We acknowledge that pressure-based feedback is ultimately intended for older individuals with medial knee OA who are potentially less kinesthetically capable. For this proof of concept study, we felt it was important to first test the training algorithm in a cohort of subjects without pain and joint disease. Given the ease of the adaptation in this study, combined with studies where those with knee OA quickly learned a gait modification in a single visit [6,13,14,57], we see the potential benefit of using pressure-based feedback in a population with knee OA.

Subjects performed these two gait modifications back to back in a single test session, and the first gait modification could theoretically influence the other. However, we are confident that the order in which the subjects learned the gait modification did not impact the results of this work since our study design randomized the modification order and our statistical analysis yielded very high probability values when the modification order was included as a between-subjects factor. In addition, the fact that order did not play a role suggests a different underlying mechanism for the KAM reduction between medial thrust gait and pressure-based feedback.

The mechanism behind the loading differences between the three walking conditions remains unclear. Further investigation is warranted to elucidate how such subtle changes during gait using pressure-based feedback lowers the KAM without adversely affecting other knee moments. We hypothesize that several small changes add up to induce significant alterations in frontal plane loading. For instance, both a small medial change in the knee position and a slight ipsilateral shift in the center of mass may be sufficient to substantially alter knee load distribution.

The cross-sectional design didn't allow for the assessment of motor learning; rather, it assessed motor performance [32]. Motor learning research suggests that in addition to frequent accurate practice and verbal feedback, augmented feedback plays a critical role in integrating a new motor pattern [58]. Long-term success of a gait modification relies on complete integration of the new movement pattern, which is a defining principle of motor learning [59]. With the observation that unloading the lateral foot can reduce the KAM without changing other loading or spatiotemporal parameters, plantar pressure-based feedback is potentially a formidable tool for treating knee OA. With the advent of integrated insoles with feedback capabilities, it is feasible for a subject to initiate feedback training in a clinic and transition to home with a progressive, daily training regimen. This would allow frequent practice of the gait modification with the certainty that lateral foot unloading occurred with only minimal and intermittent clinician oversight. A longitudinal study examining the efficacy of a longer training regimen and motor learning is necessary.

In conclusion, this proof of concept study demonstrates that pressure-based feedback is equally as effective as medial thrust gait in lowering the KAM in healthy subjects without the unwanted and potentially deleterious effects of other gait modifications. These findings suggest that walking with feedback designed to alter foot pressure was feasible in nearly all of the healthy individuals tested to reduce knee joint loading while they maintained their speed, stride length, and cadence. This study supports the need for future investigations into the short-term and long-term efficacy of augmented pressure-based feedback designed to subtly unload the lateral foot as a treatment modality for medial compartment knee OA.

Acknowledgment

The authors acknowledge the data acquisition contributions of Renee Kawecki, BS and the time and efforts of our volunteer study subjects.

References

[1] Brault, M. W., Hootman, J. M., Helmick, C. G., Theis, K. A., and Armour, B. S., 2009, "Prevalence and Most Common Causes of Disability Among Adults—United States, 2005," Morb. Mortal. Wkly. Rep., **58**, pp. 421–426.

[2] Ahlbäck, S., 1968, "Osteoarthrosis of the Knee. A Radiographic Investigation," Acta Radiol. Diagn. (Stockh), **277**(Suppl.), pp. 7–72.

[3] Schipplein, O. D., and Andriacchi, T. P., 1991, "Interaction Between Active and Passive Knee Stabilizers During Level Walking," J. Orthop. Res., **9**(1), pp. 113–119.

[4] Kutzner, I., Trepczynski, A., Heller, M. O., and Bergmann, G., 2013, "Knee Adduction Moment and Medial Contact Force—Facts About Their Correlation During Gait," PLoS ONE, **8**(12), p. e81036.

[5] Mündermann, A., Asay, J. L., Mündermann, L., and Andriacchi, T. P., 2008, "Implications of Increased Medio-Lateral Trunk Sway for Ambulatory Mechanics," J. Biomech., **41**(1), pp. 165–170.

[6] Shull, P. B., Silder, A., Shultz, R., Dragoo, J. L., Besier, T. F., Delp, S. L., and Cutkosky, M. R., 2013, "Six-Week Gait Retraining Program Reduces Knee Adduction Moment, Reduces Pain, and Improves Function for Individuals With Medial Compartment Knee Osteoarthritis," J. Orthop. Res., **31**(7), pp. 1020–1025.

[7] Chang, A., Hurwitz, D., Dunlop, D., Song, J., Cahue, S., Hayes, K., and Sharma, L., 2007, "The Relationship Between Toe-Out Angle During Gait and Progression of Medial Tibiofemoral Osteoarthritis," Ann. Rheum. Dis., **66**(10), pp. 1271–1275.

[8] Fregly, B. J., Reinbolt, J. A., Rooney, K. L., Mitchell, K. H., and Chmielewski, T. L., 2007, "Design of Patient-Specific Gait Modifications for Knee Osteoarthritis Rehabilitation," IEEE Trans. Biomed. Eng., **54**(9), pp. 1687–1695.

[9] Schache, A. G., Fregly, B. J., Crossley, K. M., Hinman, R. S., and Pandy, M. G., 2008, "The Effect of Gait Modification on the External Knee Adduction Moment is Reference Frame Dependent," Clin. Biomech., **23**(5), pp. 601–608.

[10] Walter, J. P., D'Lima, D. D., Colwell, C. W., Jr., and Fregly, B. J., 2010, "Decreased Knee Adduction Moment Does Not Guarantee Decreased Medial Contact Force During Gait," J. Orthop. Res., **28**(10), pp. 1348–1354.

[11] Gerbrands, T. A., Pisters, M. F., and Vanwanseele, B., 2014, "Individual Selection of Gait Retraining Strategies is Essential to Optimally Reduce Medial Knee Load During Gait," Clin. Biomech., **29**(7), pp. 828–834.

[12] Barrios, J. A., Crossley, K. M., and Davis, I. S., 2010, "Gait Retraining to Reduce the Knee Adduction Moment Through Real-Time Visual Feedback of Dynamic Knee Alignment," J. Biomech., **43**(11), pp. 2208–2213.

[13] Simic, M., Hunt, M. A., Bennell, K. L., Hinman, R. S., and Wrigley, T. V., 2012, "Trunk Lean Gait Modification and Knee Joint Load in People With Medial Knee Osteoarthritis: The Effect of Varying Trunk Lean Angles," Arthritis Care Res., **64**(10), pp. 1545–1553.

[14] Cochrane, C. K., Takacs, J., and Hunt, M. A., 2014, "Biomechanical Mechanisms of Toe-Out Gait Performance in People With and Without Knee Osteoarthritis," Clin. Biomech., **29**(1), pp. 83–86.

[15] Simic, M., Wrigley, T. V., Hinman, R. S., Hunt, M. A., and Bennell, K. L., 2013, "Altering Foot Progression Angle in People With Medial Knee Osteoarthritis: The Effects of Varying Toe-In and Toe-Out Angles are Mediated by Pain and Malalignment," Osteoarthritis Cartilage, **21**(9), pp. 1272–1280.

[16] Manal, K., Gardinier, E., Buchanan, T. S., and Snyder-Mackler, L., 2015, "A More Informed Evaluation of Medial Compartment Loading: The Combined Use of the Knee Adduction and Flexor Moments," Osteoarthritis Cartilage, **23**(7), pp. 1107–1111.

[17] Chehab, E. F., Favre, J., Erhart-Hledik, J. C., and Andriacchi, T. P., 2014, "Baseline Knee Adduction and Flexion Moments During Walking are Both Associated With 5 Year Cartilage Changes in Patients With Medial Knee Osteoarthritis," Osteoarthritis Cartilage, **22**(11), pp. 1833–1839.

[18] Studenski, S., Perera, S., Patel, K., Rosano, C., Faulkner, K., Inzitari, M., Brach, J., Chandler, J., Cawthon, P., Connor, E. B., Nevitt, M., Visser, M., Kritchevsky, S., Badinelli, S., Harris, T., Newman, A. B., Cauley, J., Ferrucci, L., and Guralnik, J., 2011, "Gait Speed and Survival in Older Adults," J. Am. Med. Assoc., **305**(1), pp. 50–58.

[19] Simic, M., Hinman, R. S., Wrigley, T. V., Bennell, K. L., and Hunt, M. A., 2011, "Gait Modification Strategies for Altering Medial Knee Joint Load: A Systematic Review," Arthritis Care Res., **63**, pp. 405–426.

[20] Levinger, P., Menz, H. B., Morrow, A. D., Bartlett, J. R., Feller, J. A., and Bergman, N. R., 2013, "Relationship Between Foot Function and Medial Knee Joint Loading in People With Medial Compartment Knee Osteoarthritis," J. Foot Ankle Res., **6**(1), p. 33.

[21] Kerrigan, D. C., Lelas, J. L., Goggins, J., Merriman, G. J., Kaplan, R. J., and Felson, D. T., 2002, "Effectiveness of a Lateral-Wedge Insole on Knee Varus Torque in Patients With Knee Osteoarthritis," Arch. Phys. Med. Rehabil., **83**(7), pp. 889–893.

[22] Hinman, R. S., Bowles, K. A., Payne, C., and Bennell, K. L., 2008, "Effect of Length on Laterally-Wedged Insoles in Knee Osteoarthritis," Arthritis Care Res., **59**(1), pp. 144–147.

[23] Hinman, R. S., Bowles, K. A., Metcalf, B. B., Wrigley, T. V., and Bennell, K. L., 2012, "Lateral Wedge Insoles for Medial Knee Osteoarthritis: Effects on Lower Limb Frontal Plane Biomechanics," Clin. Biomech., **27**(1), pp. 27–33.

[24] Erhart, J. C., Mündermann, A., Elspas, B., Giori, N. J., and Andriacchi, T. P., 2010, "Changes in Knee Adduction Moment, Pain, and Functionality With a Variable-Stiffness Walking Shoe After 6 Months," J. Orthop. Res., **28**(7), pp. 873–879.

[25] Jenkyn, T. R., Erhart, J. C., and Andriacchi, T. P., 2011, "An Analysis of the Mechanisms for Reducing the Knee Adduction Moment During Walking Using a Variable Stiffness Shoe in Subjects With Knee Osteoarthritis," J. Biomech., **44**(7), pp. 1271–1276.

[26] Boyer, K. A., Federolf, P., Lin, C., Nigg, B. M., and Andriacchi, T. P., 2012, "Kinematic Adaptations to a Variable Stiffness Shoe: Mechanisms for Reducing Joint Loading," J. Biomech., **45**(9), pp. 1619–1624.

[27] Shakoor, N., Lidtke, R. H., Sengupta, M., Fogg, L. F., and Block, J. A., 2008, "Effects of Specialized Footwear on Joint Loads in Osteoarthritis of the Knee," Arthritis Rheum., **59**(9), pp. 1214–1220.

[28] Shakoor, N., Lidtke, R. H., Wimmer, M. A., Mikolaitis, R. A., Foucher, K. C., Thorp, L. E., Fogg, L. F., and Block, J. A., 2013, "Improvement in Knee Loading After Use of Specialized Footwear for Knee Osteoarthritis," Arthritis Rheum., **65**(5), pp. 1282–1289.

[29] Ferrigno, C., Thorp, L. E., Shakoor, N., and Wimmer, M. A., 2014, "Center of Plantar Pressure Can Predict Changes in Tibiofemoral Contact Load," Osteoarthritis Cartilage, **22**(Suppl.), pp. S92–S93.

[30] Ferrigno, C., Wimmer, M. A., Thorp, L. E., Block, J. A., Lidtke, R. H., and Shakoor, N., 2015, "Medializing Foot Center of Pressure With Flexible Shoes is Associated With a Medial Knee Load Reduction in Knee Osteoarthritis," Osteoarthritis Cartilage, **23**(Suppl. 2), pp. A98–A99.

[31] Dowling, A. V., Fisher, D. S., and Andriacchi, T. P., 2010, "Gait Modification Via Verbal Instruction and an Active Feedback System to Reduce Peak Knee Adduction Moment," ASME J. Biomech. Eng., **132**(7), p. 071007.

[32] Schmidt, R. A., and Lee, T., 2011, *Motor Control and Learning: A Behavioral Emphasis*, Human Kinetics, Champaign, IL.

[33] Wheeler, J. W., Shull, P. B., and Besier, T. F., 2011, "Real-Time Knee Adduction Moment Feedback for Gait Retraining Through Visual and Tactile Displays," ASME J. Biomech. Eng., **133**(4), p. 041007.

[34] Shull, P. B., Lurie, K. L., Cutkosky, M. R., and Besier, T. F., 2011, "Training Multi-Parameter Gaits to Reduce the Knee Adduction Moment With Data-Driven Models and Haptic Feedback," J. Biomech., **44**(8), pp. 1605–1609.

[35] Fregly, B. J., D'Lima, D. D., and Colwell, C. W., Jr., 2009, "Effective Gait Patterns for Offloading the Medial Compartment of the Knee," J. Orthop. Res., **27**(8), pp. 1016–1021.

[36] Fregly, B. J., Rooney, K. L., and Reinbolt, J. A., 2005, "Predicted Gait Modifications to Reduce the Peak Knee Adduction Torque," ISB XXth Congress—ASB 29th Annual Meeting, Cleveland, OH, July 30–Aug. 5, p. 283.

[37] Kadaba, M. P., Ramakrishnan, H. K., and Wootten, M. E., 1990, "Measurement of Lower Extremity Kinematics During Level Walking," J. Orthop. Res., **8**(3), pp. 383–392.

[38] Andriacchi, T., Natarajan, R., and Hurwitz, D., 2005, *Musculo-Skeletal Dynamic Locomotion and Clinical Applications*, Lippincott, Philadelphia, PA.

[39] Andriacchi, T., and Strickland, A., 1985, "Gait Analysis as a Tool to Assess Joint Kinetics," *Biomechanics of Normal and Pathological Human Articulating Joints*, E. Berme, A. Engin, and K. M., Correia da Silva, Eds. Martiuns Nijhoff, Doordrecht, p. 83.

[40] McPoil, T. G., Cornwall, M. W., and Yamada, W., 1995, "A Comparison of Two In-Shoe Plantar Pressure Measurement Systems," Lower Extremity, **2**, pp. 95–103.

[41] Putti, A. B., Arnold, G. P., Cochrane, L., and Abboud, R. J., 2007, "The Pedar® In-Shoe System: Repeatability and Normal Pressure Values," Gait Posture, **25**(3), pp. 401–405.
[42] Favre, J., Erhart-Hledik, J. C., and Andriacchi, T. P., 2014, "Age-Related Differences in Sagittal-Plane Knee Function at Heel-Strike of Walking are Increased in Osteoarthritic Patients," Osteoarthritis Cartilage, **22**(3), pp. 464–471.
[43] Robbins, S. M. K., and Maly, M. R., 2009, "The Effect of Gait Speed on the Knee Adduction Moment Depends on Waveform Summary Measures," Gait Posture, **30**(4), pp. 543–546.
[44] Mündermann, A., Dyrby, C. O., Hurwitz, D. E., Sharma, L., and Andriacchi, T. P., 2004, "Potential Strategies to Reduce Medial Compartment Loading in Patients With Knee Osteoarthritis of Varying Severity: Reduced Walking Speed," Arthritis Rheum., **50**(4), pp. 1172–1178.
[45] Zeni, J. A., Jr., and Higginson, J. S., 2009, "Differences in Gait Parameters Between Healthy Subjects and Persons With Moderate and Severe Knee Osteoarthritis: A Result of Altered Walking Speed?" Clin. Biomech., **24**(4), pp. 372–378.
[46] Myer, G. D., Ford, K. R., Barber, K. D., Foss, Goodman, A., Ceasar, A., Rauh, M. J., Divine, J. G., and Hewett, T. E., 2010, "The Incidence and Potential Pathomechanics of Patellofemoral Pain in Female Athletes," Clin. Biomech., **25**(7), pp. 700–707.
[47] Hewett, T. E., Myer, G. D., Ford, K. R., Heidt, R. S., Jr., Colosimo, A. J., McLean, S. G., Van Den Bogert, A. J., Paterno, M. V., and Succop, P., 2005, "Biomechanical Measures of Neuromuscular Control and Valgus Loading of the Knee Predict Anterior Cruciate Ligament Injury Risk in Female Athletes: A Prospective Study," Am. J. Sports Med., **33**(4), pp. 492–501.
[48] Kean, C. O., Bennell, K. L., Wrigley, T. V., and Hinman, R. S., 2013, "Modified Walking Shoes for Knee Osteoarthritis: Mechanisms for Reductions in the Knee Adduction Moment," J. Biomech., **46**(12), pp. 2060–2066.
[49] Lynn, S. K., Kajaks, T., and Costigan, P. A., 2008, "The Effect of Internal and External Foot Rotation on the Adduction Moment and Lateral–Medial Shear Force at the Knee During Gait," J. Sci. Med. Sport, **11**(5), pp. 444–451.
[50] Guo, M., Axe, M. J., and Manal, K., 2007, "The Influence of Foot Progression Angle on the Knee Adduction Moment During Walking and Stair Climbing in Pain Free Individuals With Knee Osteoarthritis," Gait Posture, **26**(3), pp. 436–441.
[51] Hunt, M. A., and Takacs, J., 2014, "Effects of a 10-Week Toe-Out Gait Modification Intervention in People With Medial Knee Osteoarthritis: A Pilot, Feasibility Study," Osteoarthritis Cartilage, **22**(7), pp. 904–911.
[52] Rothman, M. D., Leo-Summers, L., and Gill, T. M., 2008, "Prognostic Significance of Potential Frailty Criteria," J. Am. Geriatr. Soc., **56**(12), pp. 2211–2216.
[53] Vermeulen, J., Neyens, J. C., Van Rossum, E., Spreeuwenberg, M. D., and De Witte, L. P., 2011, "Predicting ADL Disability in Community-Dwelling Elderly People Using Physical Frailty Indicators: A Systematic Review," BMC Geriatr., **11**(1), p. 33.
[54] Fried, L. P., Tangen, C. M., Walston, J., Newman, A. B., Hirsch, C., Gottdiener, J., Seeman, T., Tracy, R., Kop, W. J., Burke, G., and McBurnie, M. A., 2001, "Frailty in Older Adults: Evidence for a Phenotype," J. Gerontol. Ser. A Biol. Sci. Med. Sci., **56**(3), pp. M146–M156.
[55] Russell, E. M., Braun, B., and Hamill, J., 2010, "Does Stride Length Influence Metabolic Cost and Biomechanical Risk Factors for Knee Osteoarthritis in Obese Women?" Clin. Biomech., **25**(5), pp. 438–443.
[56] Caldwell, L. K., Laubach, L. L., and Barrios, J. A., 2013, "Effect of Specific Gait Modifications on Medial Knee Loading, Metabolic Cost and Perception of Task Difficulty," Clin. Biomech., **28**(6), pp. 649–654.
[57] Shull, P. B., Shultz, R., Silder, A., Dragoo, J. L., Besier, T. F., Cutkosky, M. R., and Delp, S. L., 2013, "Toe-in Gait Reduces the First Peak Knee Adduction Moment in Patients With Medial Compartment Knee Osteoarthritis," J. Biomech., **46**(1), pp. 122–128.
[58] Winstein, C. J., 1991, "Knowledge of Results and Motor Learning—Implications for Physical Therapy," Phys. Ther., **71**, pp. 140–149.
[59] Haibach, P., Reid, G., and Collier, D., 2011, *Motor Learning and Development*, Human Kinetics, Champaign, IL.