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Influence of foot posture on immediate biomechanical responses during walking to variable-stiffness supported lateral wedge insole designs

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ABSTRACT

Background: Novel designs of lateral wedge insoles with arch support can alter walking biomechanics as a conservative treatment option for knee osteoarthritis. However, variations in foot posture may influence individual responses to insole intervention and these effects are not yet known.

Research question: How does foot posture influence biomechanical responses to novel designs of lateral wedge insoles with arch support?

Methods: This exploratory biomechanical investigation categorized forty healthy volunteers (age 23–34) into pronated (n = 16), neutral (n = 15), and supinated (n = 9) foot posture groups based on the Foot Posture Index. Three-dimensional gait analysis was conducted during walking with six orthotic insole conditions: flat control, lateral wedge, uniform-stiffness arch support, variable-stiffness arch support, and lateral wedge + each arch support. Frontal plane knee and ankle/subtalar joint kinetic and kinematic outcomes were compared among insole conditions and foot posture groups using a repeated measures analysis of variance.

Results: The lateral wedge alone and lateral wedge + variable-stiffness arch support were the only insole conditions effective at reducing the knee adduction moment. However, the lateral wedge + variable-stiffness arch support had a smaller increase in peak ankle/subtalar eversion moment than the lateral wedge alone. Supinated feet had smaller ankle/subtalar eversion excursion and moment impulse than neutral and pronated feet, across all insole conditions.

Significance: Supinated feet have less mobile ankle/subtalar joints than neutral and pronated feet and, as a result, may be less likely to respond to biomechanical intervention from orthotic insoles. Supported lateral wedge insoles incorporating an arch support design that is variable-stiffness may be better than uniform-stiffness since reductions in the knee adduction moment can be achieved while minimizing increases in the ankle/subtalar eversion moment.

1. Background

Lateral wedge insoles (LWI) are shoe-worn inserts that can alter walking biomechanics to conservatively manage knee osteoarthritis (OA). Specifically, LWI target reductions in the external knee adduction moment (KAM) – a surrogate measure of medial tibiofemoral compressive load [1]. Reducing the KAM is a primary goal of biomechanical interventions for knee OA, and a recent systematic review and meta-analysis reported that walking with LWI produces standardized mean differences between -0.20 and -0.27 (approximately 5–10 % reductions) across multiple components of the KAM [2]. However, approximately one third of patients with knee OA experience no change, or even increases in the KAM with LWI use [3–5]. Minimizing variability in the KAM response to LWI may enhance the clinical utility of these insoles for improving pain related to knee OA [6]. Investigation into biomechanical factors that influence the KAM response to LWI is warranted.

Differences in foot and ankle/subtalar posture and movement may be one source of variability in the KAM response to LWI. Foot posture describes the static position of the foot and ankle/subtalar joint during relaxed standing [7], and different foot postures demonstrate unique movement patterns from one another [8]. Ankle/subtalar eversion

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during gait has also been found to be a predictor of which patients with knee OA would likely experience a decrease in the KAM with LWI [5]. A previous investigation assessed healthy individuals with pronated, neutral, and supinated feet wearing LWI and found that only neutral feet exhibited a reduction in the KAM [9]. This study treated each limb of study participants as separate samples, which violates the assumption of independent samples and compromised any comparisons between foot posture groups. Changes in walking mechanics were also measured without footwear, which does not represent the conventional usage of orthotic insoles. Thus, research incorporating distinctly separated foot posture groups and standardized footwear may more clearly elucidate the possible link between foot posture and the biomechanical response to LWI.

The addition of medial arch support to LWI (supported-LWI) is a recent insole modification shown to reduce the KAM whilst mitigating external ankle/subtalar eversion changes in healthy adults [10,11] and patients with knee OA [2,12,13]. In a cohort of patients with knee OA and pronated feet, a supported-LWI also improved comfort compared to a flat insole, whereas the unsupported LWI did not [13]. Novel modifications to supported-LWI could involve variable-stiffness insole design. In footwear, midsoles incorporating a variable-stiffness design that is stiffer laterally than medially can significantly reduce the KAM during walking in patients with knee OA [14,15] and healthy adults [16]. However, supported-LWI with variable-stiffness designs have not yet been investigated, and examination of their basic biomechanical effects is necessary before they can be implemented into clinical research and clinical practice.

In a sample population of healthy adults, the objectives of the current study were to explore: 1) the effect of foot posture on altering the immediate biomechanical responses to these supported-LWI designs, and 2) the biomechanical effects of novel supported-LWI with variable-stiffness design on knee and ankle gait biomechanics. It was hypothesized that LWI and supported-LWI would reduce the KAM compared to a flat control insole, but ankle eversion would be reduced only in the supported-LWI. It was also hypothesized that changes in knee and ankle gait mechanics with LWI and supported-LWI would differ between pronated, neutral, and supinated foot postures.

2. Methods

2.1. Participants and foot posture groups

Healthy adults were recruited from the university and surrounding community via electronic and print media, and word of mouth. Participants were screened for, and excluded from, participation if they had any history of neurological conditions that may impair gait. In the twelve months prior to participation, participants were also free of any musculoskeletal pain or injury, and did not use orthotic insoles during this time. The six-item foot posture index (FPI) assessment [7] was used to categorize participants into three foot posture groups: pronated (FPI $\geq$ 6), neutral (FPI = 0–5), supinated (FPI $\leq$ –1) [7]. This study received approval from the institutional Clinical Research Ethics Board. Study details were verbally explained to all participants and written informed consent was obtained prior to study enrolment.

2.2. Shoe insoles

Following confirmation of study eligibility, participants were referred to a Certified Canadian Pedorthist for volumetric casting of their feet, taken in a non-weightbearing subtalar neutral position. Four pairs of sulcus length orthotic insoles were custom-fabricated for each participant, and finished with an identical neoprene cover. Neutral 3 mm flat control (FLAT) and 5° lateral wedge (WEDG) insoles were made from ethyl-vinyl acetate foam (EVA) (Shore A stiffness 55). Next, two pairs of custom contoured arch supports were formed from the volumetric casts: variable-stiffness (V-ARCH) was made from plastazote foam laterally (Shore A stiffness 70) and EVA medially (Shore A stiffness 20); uniform-stiffness (U-ARCH) was made from EVA (Shore A stiffness 55). Each of the four fabricated insoles were tested individually, and two additional supported-LWI conditions were created by affixing each custom arch support on top of the WEDG: WEDG + V-ARCH and WEDG + U-ARCH. A total of six insole conditions were examined during gait testing.

Fig. 1. Standardized sandal setup showing orthotic insole and neoprene cover.

2.3. Gait analysis – data collection

Three-dimensional gait analysis was conducted while participants walked in each pair of orthotic insoles fitted into standardized sandal. The sandal had a neutral heel to toe drop and Velcro straps that secured the sandal to the foot while allowing for placement of retro-reflective markers on the forefoot and rearfoot (Fig. 1). Each participant was fitted with a sandal that appropriately matched the length and width of their foot. Prior to recording walking trials in each insole, participants were encouraged to walk freely in order to acclimate to the insole and resolve any abnormalities with the fit of the sandal or insole. The FLAT insole was tested first and the testing order of the remaining insoles was randomized for each participant. Participants were randomly assigned a study limb of interest.

Thirty-five retroreflective markers were affixed to the skin over anatomical landmarks on the pelvis and lower body, including: the sacrum, and bilaterally on anterior superior iliac spines (ASIS), lateral femoral epicondyles, lateral malleoli, posterior aspects of calcanei, and heads of the second metatarsals (toe). Additional tracking markers were placed bilaterally on the lateral thighs and shanks as rigid plates (four markers each), bilaterally on the anterior thighs and shanks, as well as on either side of the posterior calcanei markers forming a triad. Ten additional markers were affixed bilaterally during a static calibration trial, including: greater trochanters, medial femoral epicondyles, medial malleoli, and first and fifth metatarsal heads (Fig. 2). Retroreflective marker motion was measured by 14 optical motion capture cameras (Motion Analysis Corp., Santa Rosa, CA), sampling at 100 Hz. Ground reaction force data were measured simultaneously by a force platform (AMTI, Watertown, MA) embedded in a 10 m walkway, sampling at 2000 Hz.

Walking speed was monitored by photoelectric timing gates separated by a fixed distance along the walkway. Self-selected walking speed was determined during the FLAT walking trials and only walking trials within 5 % of this speed were analyzed for subsequent insole conditions. Successful walking trials required the entire foot of the study limb to contact the force platform within its boundaries. A minimum of five successful walking trials were collected for each insole condition.

Fig. 2. Marker set-up used during static calibration trial.

2.4. Gait analysis – data analysis and outcomes

Inverse dynamics calculations using synchronized retroreflective marker and force platform data were performed in Visual 3D (C-motion, Rockville, MD). Static trial marker positions defined the link-segment model for the following segments bilaterally: thigh, shank, and foot. Virtually defined landmarks include: hip joint centre (HJC) [17], midpoint between femoral epicondyles (EPI), midpoint between malleoli (MAL), midpoint between medial and lateral calcaneal markers (CAL), midpoint between first and fifth metatarsals heads (MET). The HJC (segment origin) and medial and lateral femoral epicondyles defined the thigh segment (superior-inferior axis: EPI to HJC; anterior-posterior axis: orthogonal to plane created by segment definition markers; medial-lateral axis: orthogonal to other axes). The femoral epicondyles (segment origin at EPI) and malleoli markers defined the shank segment (superior-inferior axis: MAL to EPI; anterior-posterior axis: orthogonal to plane created by segment definition markers; medial-lateral axis: orthogonal to other axes). Thigh and shank motions were each tracked by an anterior segment marker and plate-mounted markers. Two foot segments were defined for kinetic and kinematic outcomes. The MAL (segment origin), toe marker, and posterior calcaneus defined the kinetic foot (anterior-posterior axis: toe marker to MAL; medial-lateral axis: lateral malleolus marker to MAL; superior-inferior axis: orthogonal to other axes). The medial and lateral calcaneal markers (segment origin at CAL) and the first and fifth metatarsal markers defined the kinematic foot (anterior-posterior axis: MET to CAL; superior-inferior axis: orthogonal to plane created by metatarsal markers and CAL; medial-lateral axis: orthogonal to other axes). Both foot segments were tracked by the toe and calcaneal markers. Bilateral three-dimensional kinematic and kinetic gait outcomes were calculated for the knee and ankle/subtalar joints. All gait outcomes were time-normalized to percentage of stance (initial contact to toe-off).

The gait outcomes of interest included the overall peaks and impulses (area under the moment-time waveform during stance phase) of the KAM and ankle/subtalar eversion moments, the peak ankle/subtalar eversion angle during stance, and the frontal plane ankle/subtalar eversion excursion (angle at initial contact to maximum eversion angle during stance phase of gait). External joint moments (Nm/kg) and moment impulses (Nm/kg•sec) were calculated.

2.5. Sample size

Change in the KAM was our primary outcome of interest, and a recent systematic review and meta-analysis reported a small effect of LWI on reducing various magnitudes of the KAM (SMD = 0.20 – 0.27) [2]. Calculations determined that 39 participants were necessary to detect an effect size of 0.27 with 80 % power at $\alpha = 0.05$ for a repeated measures analysis of variance with three foot posture groups and six insole conditions.

2.6. Statistical analysis

Statistical analyses were computed using jamovi (jamovi project, Version 0.9 [computer software], Retrieved from https://www.jamovi.org). Normality was assessed via visual inspection of histograms of frequency distribution, and homogeneity of variance was assessed via Mauchly's test of sphericity. Repeated measures analysis of variance was used to test the effects of insole condition (within subject: 6 conditions) and foot posture group (between subject: 3 groups) on each gait outcome of interest. For any significant main effects or interactions, Tukey's post-hoc pairwise comparisons between insole conditions and/or foot posture groups were performed. Alpha level was $\alpha = 0.05$.

3. Results

Table 1 summarizes participant characteristics separated by foot posture groups, and Appendix 1 in Supplementary material summarizes frontal plane knee and ankle gait biomechanical outcomes.

3.1. Insole condition main effect

Compared to FLAT, the WEDG reduced the KAM peak (mean reduction = 0.01 Nm/kg [−3.4 %], $p < 0.05$) and impulse (mean reduction = 0.01 Nm/kg*sec [−5.3 %], $p < 0.05$), while the WEDG + V-ARCH reduced the KAM peak (mean reduction = 0.02 Nm/

Table 1
Participant characteristics by foot posture group. Values reported as mean ± standard deviation unless otherwise noted.

	Pronated (n = 16)	Neutral (n = 15)	Supinated (n = 9)	All Participants (n = 40)
Age (years)	26.0 ± 2.2	26.7 ± 2.8	27.3 ± 4.1	26.6 ± 2.9
Sex (F:M)	9:7	9:6	5:4	23:17
Height (cm)	172.5 ± 8.4	174.6 ± 8.8	173.8 ± 9.3	173 ± 8.6
Mass (kg)	68.8 ± 10.3	73.8 ± 11.7	71.4 ± 17.9	71.2 ± 12.7
BMI (kg/m^2)	23.0 ± 2.4	24.1 ± 2.4	23.3 ± 3.8	23.5 ± 2.8
Foot Posture[a]	9 (9, 10)	4 (3, 5)	−2 (-3, -1)	5 (2, 9)
Frontal Plane Knee Angle[b]	−2.7 ± 2.4*	−0.3 ± 3.1	−0.0 ± 1.8	−1.2 ± 2.8

[a] Reported using the foot posture index (FPI) scale as the median score (25th, 75th percentile value).
[b] Mean angle during 25–50 % of stance phase of walking trials using FLAT insole condition (negative values indicate knee varus).
* Indicates a significant difference between foot posture groups.

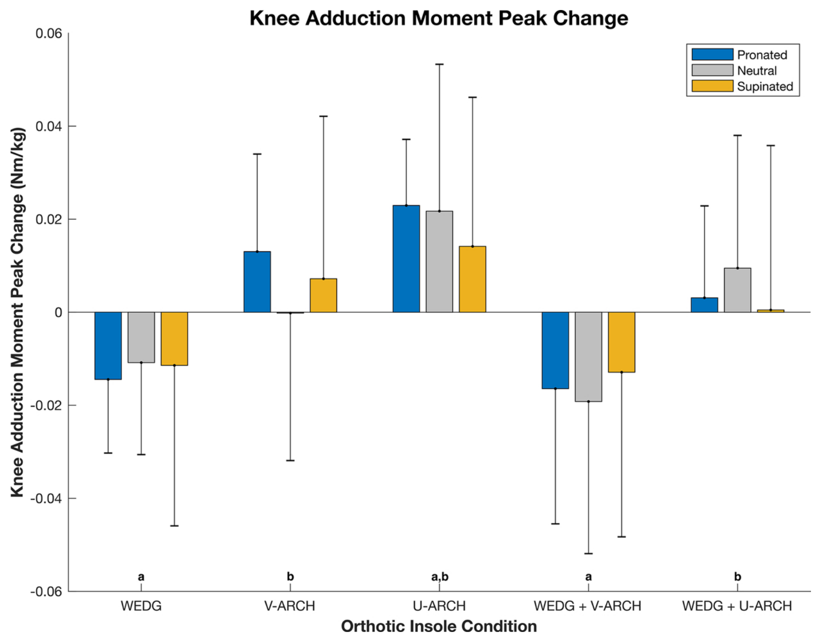

Fig. 3. Change in knee adduction moment peak compared to FLAT. **a** and **b** along the x-axis denotes a significant difference between the insole condition and FLAT and WEDG, respectively ($p < 0.05$).

kg [−4.6 %], $p < 0.05$) (Fig. 3). U-ARCH significantly increased KAM peak (mean increase = 0.02 Nm/kg [5.7 %], $p < 0.05$) and impulse (mean increase = 0.01 Nm/kg*sec [10.7 %], $p < 0.05$), while V-ARCH increased the KAM impulse (mean increase = 0.01 Nm/kg*sec [6.2 %], $p < 0.05$) relative to FLAT. WEDG + U-ARCH was not significantly different from FLAT for KAM peak or impulse ($p > 0.91$).

At the ankle/subtalar joint, eversion moment peak increased with WEDG (mean increase = 0.04 Nm/kg [24.4 %], $p < 0.05$) and WEDG + V-ARCH (mean increase = 0.02 Nm/kg [11.9 %], $p < 0.05$) compared to FLAT (Fig. 4). Similarly ankle/subtalar eversion moment impulse significantly increased with WEDG (mean increase = 0.02 Nm/kg•sec [45.2 %], $p < 0.05$) and WEDG + V-ARCH (mean increase = 0.02 Nm/kg•sec [45.2 %], $p < 0.05$) compared to FLAT. However, the peak ankle/subtalar eversion moment was significantly lower in WEDG + V-ARCH than WEDG (mean decrease = 0.02 Nm/kg [−10.0 %], $p < 0.05$).

Ankle/subtalar eversion angle peak was increased with WEDG (mean increase = 1.5°, $p < 0.05$) and WEDG + V-ARCH (mean increase = 2.5°, $p < 0.05$) compared to FLAT. Ankle/subtalar eversion excursion was not significantly different between FLAT and any unsupported or supported-LWI conditions ($p > 0.52$). Values of ankle/subtalar eversion moment peak and eversion angle peak and excursion were not significantly different between the WEDG + U-ARCH and FLAT conditions ($p > 0.84$).

3.2. Foot posture group main effect

A main effect of foot posture group was only present for ankle/subtalar eversion moment impulse and eversion excursion (Appendix 1 in Supplementary material). Supinated feet had lower ankle/subtalar

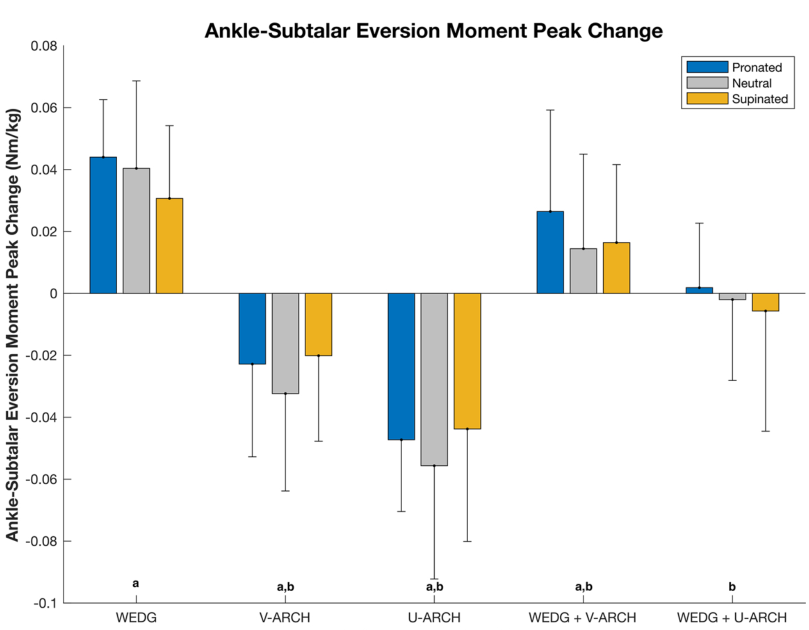

Fig. 4. Change in peak ankle/subtalar eversion moment compared to FLAT. **a** and **b** along the x-axis denotes a significant difference between the insole condition and FLAT and WEDG, respectively ($p < 0.05$). Please note that since calculated negative values for ankle/subtalar frontal plane moments refer to the eversion direction (see Appendix 1), more negative values (higher eversion moments) for a given condition are depicted as positive amounts in this eversion moment change graph.

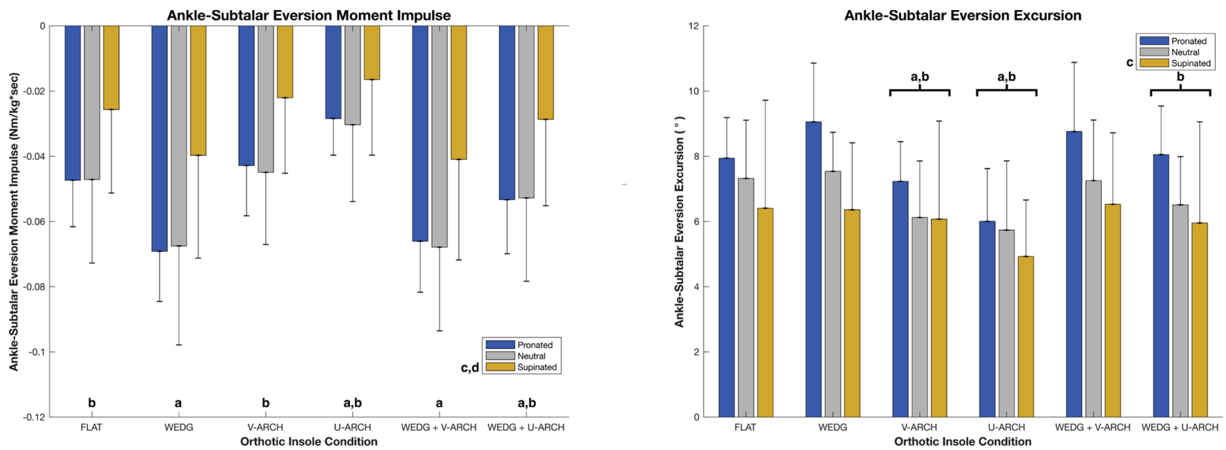

Fig. 5. Ankle/subtalar eversion moment impulse and eversion excursion in each orthotic insole condition, separated by foot posture group. **a** and **b** denotes a significant difference between the insole condition and FLAT and WEDG, respectively ($p < 0.05$). **c** and **d** denotes a significant difference between the adjacent foot posture group and the Supinated foot posture group ($p < 0.05$).

eversion moment impulse than neutral (mean decrease = 0.02 Nm/kg•sec [−42.6 %], $p < 0.05$) and pronated feet (mean decrease = 0.02 Nm/kg•sec [−41.5 %], $p < 0.05$) (Fig. 5). Supinated feet also had less eversion excursion than pronated feet (mean decrease = 1.8°, $p < 0.05$).

3.3. Insole condition and foot posture group interaction

There was a significant interaction for ankle/subtalar eversion moment impulse. Post-hoc pairwise comparisons did not reveal any results that were different than what was summarized by the main effects of insole condition and foot posture group (Fig. 5). Specifically, ankle/subtalar eversion moment impulse was smaller with FLAT than all insoles involving a WEDG and smallest in the supinated foot posture group. No other significant interactions were found for any other gait outcomes of interest.

4. Discussion

The current investigation explored novel designs of LWI and whether different foot postures would exhibit different biomechanical responses to these insoles. Five orthotic insole conditions – three of which included a LWI – were compared against a flat control insole. A reduction in the KAM was found only with the standalone LWI and one of the supported-LWI (WEDG + V-ARCH). The supported-LWI (WEDG + V-ARCH), however, minimized the increase in ankle/subtalar eversion moment compared to the LWI alone and may be the better option of the two. Supinated foot postures exhibited smaller eversion excursion and eversion moment at the ankle/subtalar joint than the remaining foot posture groups. This suggests that ankle/subtalar joints of supinated feet may be less mobile and not as responsive to orthotic insole interventions than neutral and pronated foot types. Consequently, supinated feet may be less likely to receive a biomechanical benefit from any LWI design.

Systematic reviews and meta-analyses report consistent average reductions in the KAM with LWI in patients with knee OA [2,18], which our results support. KAM reduction remains a primary goal of biomechanical intervention with insoles. Preservation of ankle/subtalar mechanics, however, is also important in LWI interventions since greater angulations of LWI are linked to larger ankle/subtalar eversion moments [19] and reduced comfort [20]. Our investigation found that both supported-LWI designs mitigated increases in peak ankle/subtalar eversion moment compared to LWI alone, which is consistent with previous literature [2,10]. At the knee, we found the variable-stiffness supported-LWI (WEDG + V-ARCH) reduced the KAM peak compared to FLAT, whereas the uniform-stiffness supported-LWI (WEDG + U-ARCH) did not. Considering the KAM was reduced with a smaller increase in ankle/subtalar eversion moment than the standalone LWI, supported-LWI designs using variable-stiffness arch support may be more appropriate than designs with uniform-stiffness arch support for biomechanical intervention with orthotic insoles.

Our examination of foot posture found that supinated foot types exhibited changes at the ankle/subtalar joint that were distinct from neutral or pronated feet. Of the foot types compared, supinated feet had the smallest ankle/subtalar eversion excursion across all insole conditions. Similarly, supinated foot types have been observed to have smaller ankle/subtalar range of motion during barefoot walking in other movement planes compared to pronated and neutral foot types [21]. Reduced motion in multiple movement planes may suggest that the ankle/subtalar joint of supinated feet are less mobile than other foot types and less likely to respond to biomechanical intervention with variations of LWI. This may explain why supinated feet consistently had the smallest changes in ankle/subtalar eversion moment impulse.

Ankle/subtalar eversion range of motion has been suggested as an important factor for reducing the KAM with LWI [5,22]. Notably, Chapman et al. found that ankle/subtalar eversion angle peak and angle at time of peak KAM during walking without LWI was predictive of whether patients with knee OA would experience a reduction in the KAM with LWI [5]. The KAM was reduced by the WEDG and WEDG + V-ARCH in all three foot posture groups in the current study, but significant differences in KAM reduction between foot posture groups were not observed. This contrasts Sawada et al. that found neutral feet experienced a reduction in the KAM peak with LWI, whereas pronated and supinated feet did not [9]. From the current study, the supinated foot posture group appeared to respond the least favourably by trending towards the smallest reductions in the KAM with WEDG and WEDG + V-ARCH (Appendix 1 in Supplementary material). Considering supinated feet experienced smaller changes in ankle/subtalar and knee joint moments than the remaining foot types, supinated foot types may be less likely to benefit biomechanically from any insole intervention. However, additional research incorporating larger sample sizes for each foot posture group, and patients with knee OA would improve exploration of this hypothesis.

Several limitations exist for the current study. First, foot posture group sizes were distributed unevenly despite concerted recruitment efforts to capture the spectrum of foot postures. However, our comparison between supinated, neutral, and pronated foot posture groups is an improvement from previous studies that assessed LWI effects that lacked comparisons between foot posture groups [9] or treated supinated and pronated feet as equivalent [23]. Second, our exploratory study used a sample of healthy adults to identify the foot postures and LWI designs that may safely exhibit a biomechanical benefit. This may justify future clinical evaluation of these novel insole designs in the intended population of patients with knee OA. Additionally, future research involving longer intervention periods would also improve our understanding of LWI designs on modifying clinical outcomes of knee OA.

5. Conclusions

The findings from this study suggest that supinated foot types respond differently than neutral and pronated foot types to various LWI designs, and subsequently may be less likely to respond biomechanically to these interventions. Supported-LWI using arch-support with a variable-stiffness design may be superior to a uniform-stiffness design for concurrently reducing magnitudes of the KAM while mitigating the increase in ankle/subtalar eversion moment compared to a LWI alone.

CRediT authorship contribution statement

Calvin T.F. Tse: Conceptualization, Methodology, Writing - review & editing, Investigation, Formal analysis, Writing - original draft, Visualization. **Michael B. Ryan:** Conceptualization, Methodology, Writing - review & editing, Supervision, Funding acquisition. **Michael A. Hunt:** Conceptualization, Methodology, Writing - review & editing, Supervision, Funding acquisition.

Declaration of Competing Interest

CT and MR are employed by Kintec Footwear + Orthotics, however, these authors do not receive any direct benefit from this research that could potentially bias these results. The authors declare no other profession or financial affiliations which would bias the results of this study.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.gaitpost.2020.06.026.

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