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

M. Simic † † † †, T.V. Wrigley † †, R.S. Hinman † †, M.A. Hunt ‡ ‡, K.L. Bennell †

† Centre for Health, Exercise and Sports Medicine, Department of Physiotherapy, School of Health Sciences, University of Melbourne, Australia
† Discipline of Physiotherapy, Faculty of Health Sciences, University of Sydney, Australia
‡ Department of Physical Therapy, University of British Columbia, Canada

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S U M M A R Y

Objectives: To evaluate if altering the foot progression angle (FPA) by varying magnitudes during gait alters the external knee adduction moment (KAM), knee flexion moment (KFM), knee extension moment (KEM) and/or symptoms in people with medial knee osteoarthritis (OA). Potential influence of pain and knee malalignment on load-modifying effects of FPA was investigated.

Design: Participants (n = 22) underwent 3-dimensional gait analysis to measure KAM peaks, KAM impulse, KFM and KEM peaks. Following natural gait, five altered FPA conditions were performed in random order (10° toe-in, 0° FPA, 10° toe-out, 20° toe-out and 30° toe-out). A projection screen displayed their real-time FPA. Pain/discomfort at knees and feet/ankles were evaluated for each condition. Linear mixed models were used for statistical analysis.

Results: Toe-in reduced the early stance peak KAM and KEM but increased the KAM impulse, late stance peak and KFM. Toe-out reduced the KAM impulse, late stance peak and KFM (P < 0.001) but increased the early stance peak KAM and KEM. All effects were greater in participants with more varus knees. Pain significantly mediated the effect of altered FPA on the KAM impulse and late stance peak. In more painful individuals, toe-in was predicted to reduce the KAM impulse and late stance peak, and increase them for toe-out gait. There were no immediate symptomatic changes.

Conclusions: Effects of altered FPA vary across all medial knee load parameters and it is difficult to determine an optimal direction of FPA change. Future studies should consider Western Ontario McMaster Universities OA Index (WOMAC) pain to judge the likely effects of altered FPA.

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Introduction

Knee osteoarthritis (OA), which predominantly occurs in the medial tibiofemoral compartment1,2, imposes a large personal and societal burden3. Structural deterioration occurs in many people4 and excessive medial knee compartment load during walking is a major modifiable risk factor for OA progression5,6. Consequently, conservative knee load-modifying treatments have been recommended by leading OA and rheumatology associations7,8. Gait modification strategies have received increasing interest because they have demonstrated some ability to reduce surrogate measures of medial knee joint load9. One strategy is altering the foot progression angle (FPA), defined as the angle made between the line of walking progression and the long axis of the foot. Specifically, both toe-in gait (internally rotating the foot with respect to the line of walking progression) and toe-out gait (externally rotating the foot) have been reported to reduce different indices of medial knee load9.

Measured non-invasively using three-dimensional gait analysis, the external knee adduction moment (KAM) is a valid and reliable indicator of the distribution of dynamic compressive load between the medial and lateral tibiofemoral compartments10,11. The KAM is most commonly quantified by evaluating the peaks observed during early stance (approximately 25%) and late stance (approximately 75%), and by the adduction angular impulse (area under the KAM-time curve). Researchers investigating biomechanical interventions typically target a reduction in the early stance peak KAM...
and/or KAM impulse because these parameters have been associated with increased risk of OA progression\textsuperscript{5,6}. The clinical significance of a larger late stance peak KAM currently remains unknown.

Modifying gait to either a toe-out or toe-in position has been proposed as a conservative biomechanical intervention for people with medial knee OA\textsuperscript{9,12}, and larger toe-out angles have been shown to protect against OA progression\textsuperscript{13}. According to a recent systematic review of gait modification strategies in healthy individuals and those with knee OA\textsuperscript{3}, conscious alterations in toe-out angle exhibited inconsistent non-significant effects on the early stance peak KAM (55.2\% reduction to 12.7\% increase) but consistent significant reductions in the late stance peak (22.9–92.6\%). Reported effects of toe-in gait demonstrate inconsistency particularly in the early stance peak KAM, with 13\% reductions identified in two studies\textsuperscript{12,14} and a mean 20.0\% increase demonstrated in another study\textsuperscript{15}. To date, effect of altered FPA on the KAM impulse has only been evaluated in a single healthy individual and needs to be confirmed in larger samples\textsuperscript{16}. The variability in study findings may arise from methodological differences amongst studies, including variable magnitudes of FPA change, FPA measurement and participant characteristics. Accordingly, a more standardised FPA change in people with medial knee OA should be investigated. Implementation of specific FPA magnitudes may be achieved using real-time visual biofeedback, which was proven effective for other gait interventions in knee OA\textsuperscript{17,18}. Additionally, efficacy of some interventions designed to alter the KAM have shown to be mediated by participant-related factors, including pain severity and malalignment\textsuperscript{17–20}, suggesting that these should be investigated with altered FPA.

Toe-out is postulated to modify knee load by laterally displacing the centre of pressure location and hence the ground reaction force (GRF), resulting in a reduced frontal plane GRF lever arm at the knee and thus a lower KAM\textsuperscript{21}. Toe-in gait is postulated to modify the early stance peak KAM by either medially shifting the knee joint centre and/or externally rotating the heel, thereby laterally shifting the centre of pressure\textsuperscript{22}. A change in KAM in early stance with altered FPA may be accompanied by an increase in the external flexion moment, possibly transferring joint load from being predominantly located in the medial compartment to being more evenly distributed between the two compartments\textsuperscript{23}. Accordingly, a reduction in the KAM may be accompanied by an increase in the knee flexion moment (KFM) during early stance or knee extension moment (KEM) during the late stance, potentially counteracting the positive effects of a reduced KAM\textsuperscript{24}.

The primary aim of this study was to evaluate the immediate effect of varying FPA magnitudes on characteristics of the KAM in people with medial knee OA. The secondary aim was to investigate the effect of altered FPA on the peak KFM. Thirdly, we aimed to determine if participant characteristics, including mechanical knee alignment and pain severity, influence the load modifying ability of altered FPA gait. Finally, the immediate symptomatic effect of altered FPA gait at the knee and ankle joints was evaluated.

**Methods**

**Participants**

Individuals with medial tibiofemoral knee OA were recruited via community advertisements. A priori repeated measures analysis of variance (ANOVA) sample size calculation was conducted based on previous study findings of toe-out gait on the late stance peak KAM (effect size = 1.96)\textsuperscript{25}. As several magnitudes of FPA were to be implemented in this study, analysis was conducted on a more conservative estimated effect size of 0.30 (power: 90\%; alpha: 0.05) requiring 22 participants. Participants were included if they fulfilled the American College of Rheumatology clinical and radiographic criteria for knee OA\textsuperscript{24} and reported average knee pain on most days of the previous month \(>3\) on an 11-point numeric rating scale (NRS). Using a radiographic atlas\textsuperscript{25}, only participants with predominantly medial tibiofemoral OA were included (defined as greater medial osteophyte presence, or in cases of equal osteophytes in both compartments, greater joint space narrowing in the medial compartment was required). Exclusion criteria were: knee arthroscopy or injection in the previous 6 months, history of knee or hip surgery, neurological conditions affecting ambulation, gait aid use, other rheumatologic conditions, spinal pain with lower limb symptoms, body mass index (BMI) > 35 kg/m\(^2\) and anatomic valgus knee malalignment (\(\geq 5^\circ\)) on radiographs\textsuperscript{26}. The most symptomatic side was considered the study limb for participants with bilaterally eligible knees. The study was approved by the Institutional Ethics Committee and all participants provided written informed consent.

**Measurement of kinematics and kinetics**

Participants underwent three-dimensional gait analysis under six conditions in a single session. Firstly, the natural gait condition was recorded followed by the FPA gait modification conditions, implemented under five pre-determined FPA magnitudes in toe-in and toe-out directions. Walking in their own comfortable walking shoes, participants performed ‘natural’ gait at self-selected speed along the 8 m laboratory walkway for five successful force plate contact trials. During subsequent conditions when altered FPA gait was implemented, speed was matched to the natural gait trials (±5\% of mean) by use of photoelectric timing gates placed 4 m apart.

A Vicon motion analysis system captured kinematics using eight MX cameras recording at 120 Hz (Vicon, Oxford, UK), which was integrated with three Advanced Mechanical Technology, Inc. (AMTI, Watertown, MA) force plates in the laboratory floor to collect GRF data at 1200 Hz. Standard Plug-In-Gait lower body marker set was used, containing 20 retro-reflective markers adhered to anatomical landmarks\textsuperscript{27}. Medial knee and ankle markers were included during an initial static standing trial to determine positioning of knee and ankle joint centres using a custom-written BodyBuilder program (Vicon, Oxford, UK).

The FPA was calculated as the angle between the foot vector (line joining the ankle joint centre and the marker over the second metatarsal head) and the forward laboratory axis, projected into the laboratory’s transverse plane\textsuperscript{28}. The FPA was calculated during foot flat (average FPA between 15\% and 50\% of stance). External knee moments were calculated about an orthogonal axis system in the shank segment using the Vicon Plug-In-Gait linked-segment model (v2) in Vicon Nexus software\textsuperscript{29} using Newton-Euler inverse dynamics. The following KAM parameters were chosen to indicate medial tibiofemoral load: early and late stance peaks (the former being the maximum in the first half of stance; the latter being the maximum value after the highest positive gradient during the second half of stance), and impulse. The maximum KFM (first half of stance) and KEM (second half of stance) were measured due to their possible association with changes in medial knee load\textsuperscript{30}. External moments were normalised to body weight and height (BW\(\times HT\)). Because of their potential to influence knee load, the following variables were evaluated: speed, step width and stride length\textsuperscript{31}. Step width was defined as the medio-lateral distance between ankle joint centres at each foot strike\textsuperscript{32}.

**Walking with altered FPA**

A research physiotherapist (MS) trained participants to walk with altered FPA. Five FPA conditions were implemented, with
participants instructed to perform: 10° toe-in; 0° FPA; 10° toe-out; 20° toe-out; and 30° toe-out, with the order randomised for each participant using a Latin square matrix. The magnitudes of FPA were selected based on results of previous studies and pilot research. Naturally, people with knee OA have been reported to walk on average with 11.4° toe-out (range from 2.2° toe-in to 28.4° toe-out)\(^2\). Previous studies which evaluated altered FPA gait have achieved mean FPA values of between 4.4° toe-in\(^14\) to 18.6° toe-out\(^2\) in participants with knee OA; whereas healthy participants achieved mean FPA values of between 9.1° toe-in to 40.2° toe-out\(^3\). Accordingly, absolute FPA magnitudes ranging from 10° toe-in to 30° toe-out were chosen to provide an understanding of the dose—response effects in people with medial knee OA.

Participants were encouraged to alter the FPA of their study limb to either toe-in or toe-out. Specifically, the physiotherapist encouraged participants to change their FPA during the terminal swing phase to ensure correct orientation at initial contact. They were encouraged to imagine forming a V' shape with both feet for toe-out conditions and a 'A' shape for the toe-in condition. Instructions, demonstration and feedback were provided for the study limb only, while no restrictions were given regarding the foot orientation of the contralateral limb and the most comfortable foot orientation was encouraged. To promote skill acquisition, several motor learning principles were implemented during training including standardised instructions, demonstration, verbal feedback and visual feedback using a full-length mirror\(^12,33\). The training phase typically lasted 10–15 min.

When gait modification performance was deemed appropriate by the physiotherapist (according to a qualitative movement checklist (Table I)), participants were trained to achieve absolute target FPA magnitudes (i.e., not relative to their natural FPA) using a real-time biofeedback system. The system provided visual biofeedback of the study limb absolute FPA, consisting of a 'protractor-like' display with a purple arrow indicating the FPA in real-time (Fig. 1). Foot marker position data were streamed from the Vicon Nexus v1.4 software to Matlab software R2009 (The Mathworks Inc, Natick, MA) in real-time via TCP/IP (Transmission Control Protocol/Internet Protocol). The Matlab software calculated and displayed FPA data of the study limb with indistinguishable time delay. This biofeedback system was previously shown to be feasible in the training of a trunk lean gait modification\(^18,34\). When participants mastered the technique and performed the target FPA, data collection of gait modification conditions commenced. For each condition, data capture required five trials ensuring appropriate performance of the gait modification. If participants could not achieve the target FPA, the physiotherapist provided additional verbal feedback and encouraged participants to continue attempting the target until they required a rest. Due to difficulty in obtaining precise FPA magnitudes by some participants, the closest five trials to the target condition were included in the analysis.

### Descriptive measures

The Western Ontario McMaster Universities OA Index (WOMAC) was used to assess self-reported pain and physical function, where higher scores indicate worse pain and poorer function respectively\(^35\). Radiographic OA severity was obtained via standardised semi-flexed antero-posterior knee radiographs, evaluated by a single reviewer (MS) using the Kellgren and Lawrence (K&L) grading scale\(^36\). Knee alignment was obtained from the measured anatomical alignment and then converted to mechanical alignment using a published regression equation\(^26\).

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Table I

<table>
<thead>
<tr>
<th>Movement/Action</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical ankle plantarflexion</td>
<td>Observation of participant’s terminal stance phase to ensure that plantarflexion during the push-off phase was comparable to the natural gait condition.</td>
</tr>
<tr>
<td>Usual knee flexion/extension</td>
<td>Participants were prompted to avoid keeping their knee in a sustained position throughout stance, thus avoiding changes in knee sagittal plane motion.</td>
</tr>
<tr>
<td>Speed appropriate</td>
<td>Participants were prompted to walk at the same gait speed as natural gait trials.</td>
</tr>
<tr>
<td>Usual step width</td>
<td>Observation of participants’ step width was conducted to ensure tandem gait or gait utilising wide steps was discouraged.</td>
</tr>
<tr>
<td>Usual step length</td>
<td>Any obvious change in step length was discouraged.</td>
</tr>
</tbody>
</table>

Fig. 1. The real-time movement biofeedback system used for training and walking with altered FPA. Participants walked towards the projection screen which displayed the FPA of their study limb in real-time (purple arrow) as well as the target to be achieved. The arrow was only clearly visible during the limb’s contact with the ground (during swing it was dimmed). A green band represented the target area (corresponding to the target angle ± 2°). Participants were instructed to reach the target when the foot of the study limb was on the ground.
Effects on symptoms

Pain and discomfort during each walking condition were evaluated for each knee and each foot/ankle complex. The 11-point NRS ranged from 0 to 10 (0 represented no pain/discomfort and 10 represented worst pain/discomfort imaginable).

Statistical analysis

Analyses were performed using GenStat (13th edition, VSN International, UK) with an alpha level of 0.05. Prior to analysis, data were inspected for normality and homogeneity of variance by observation of histograms and normal probability plots. Repeated measures ANOVA was used to establish if the FPA differed between conditions, evaluate changes in spatiotemporal gait variables (speed, stride length, step width), and changes in symptoms (NRS pain). Where results were significant, evaluation of the least significant differences between conditions was performed to locate the change.

The effect of FPA on knee load parameters was evaluated using restricted maximum likelihood (REML) linear mixed modelling, with participants considered as the random factor. Dependent variables were the KAM early and late stance peaks, impulse and the KFM and KEM peaks. The primary independent variable was the average FPA between 15% and 50% of stance. A negative FPA value represented an externally rotated foot (toe-out) whilst a positive FPA represented an internally rotated foot (toe-in). To determine if WOMAC pain and/or mechanical knee alignment mediated the gait modification’s ability to alter load, interactions between the independent variable and abovementioned participant-related factors were assessed. Any significant interactions were interpreted using simple slope tests.

Results

Twenty-two individuals (13 females, nine males) participated. One additional participant who was initially eligible was later excluded due to inability to perform the appropriate gait patterns during training. Participant characteristics are shown in Table II.

Discrete gait variables across conditions are reported in Table III. Although, on average, participants did not readily achieve the target toe-out gait magnitudes, the FPA differed cross all gait conditions ($P < 0.001$). The ANOVA identified that participants walked with larger step widths when targeting the 10° toe-in and 30° toe-out gait conditions compared to their natural gait ($P = 0.021$). Speed, stride length and symptoms did not change across conditions ($P > 0.05$).

Altered FPA produced a dose–response effect on all kinetic outcomes, with opposing effects during the early and late stance phases of the KAM and KFM, as illustrated by the ensemble average graphs (Fig. 2). Confirmed by the linear mixed models evaluating the sole effect of FPA on kinetics (Table IV), the early stance peak KAM and KEM were reduced with toe-in gait and increased with toe-out gait ($P < 0.001$). Conversely, the late stance peak KAM, KAM impulse and peak KFM all increased with toe-in gait and were reduced with toe-out gait ($P < 0.001$).

Knee pain and malalignment mediated the effect of altered FPA on KAM parameters and the KEM (Table V). Specifically, the effects of altered FPA were amplified in people with more varus aligned knees for the KAM early stance peak ($P = 0.042$), late stance peak KAM ($P < 0.001$) and the KEM ($P = 0.002$). An interaction was identified between WOMAC pain and FPA for the late stance peak KAM ($P < 0.001$) and KAM impulse ($P = 0.016$). These results indicate that participants with lower pain scores had greater ability to change the KAM late stance peak and impulse with altered FPA gait. However, the model also indicates that the effect of altered FPA is reversed in individuals with greater pain (WOMAC pain over 11 for the late stance KAM and over eight for the KAM impulse); in these individuals the KAM late stance peak and impulse would be reduced with toe-in gait and increased with toe-out gait.

Discussion

Results from this study demonstrate that altering FPA in both toe-in and toe-out directions significantly affects the external knee joint moments in people with medial knee OA. Specifically, toe-out gait reduced the late stance peak KAM, KAM impulse and peak KFM but increased the early stance peak KAM and late stance peak KEM. In contrast, toe-in gait reduced the early stance peak KAM and late stance peak KEM but increased the late stance peak KAM, KAM impulse and peak KFM. As hypothesised, a dose–response effect was demonstrated with varying FPA magnitudes. However, effects on the KAM were significantly mediated by individual factors (knee malalignment and WOMAC pain). Gait modification did not result in any immediate changes in symptoms at the knees or the feet/ankles.

Opposing effects of toe-in and toe-out gait on primary outcomes were identified. When participants performed on average 9.7° of toe-in, a resultant 7.0% reduction in early stance peak KAM was achieved, with accompanying increases in the KAM late stance peak and impulse (22.3% and 5.7% respectively). These findings help clarify the previously observed conflicting biomechanical effect of toe-in gait on measures of the KAM, potentially due to variability in the magnitude of FPA change and varying participant cohorts[4,15,31]. While this is the first study to report effects of toe-in gait on both the KAM impulse and early stance peak KFM, the early stance peak KAM reductions are consistent with the small non-significant reductions (2.5–13.5%) achieved in two previous studies involving healthy and OA participants (mean toe-in angles = 4.4° and 9.1°)[4,31], and consistent with a significant 13% reduction achieved in 12 participants with knee OA (mean toe-in angle = 2.1°)[12].

This is the first study to demonstrate that toe-out significantly increases the early stance peak KAM. When participants walked with a mean 20.8° toe-out, a 9.4% increase in the early stance peak KAM was identified, which is higher than non-significant effects previously reported in individuals with knee OA (0–6.4%) for mean
reported toe-out angles of 17.1 and 18.6°. Although one study reported a 55% reduction with toe-out, it was conducted in children and may therefore not be applicable to this cohort. In this study, toe-out gait conversely achieved reductions in the KAM late stance peak and impulse (35.5% and 4.9% respectively). The reduction in late stance KAM is similar (31.1–39.7%) to previous studies involving participants with knee OA. The KAM impulse reductions with toe-out gait are consistent with the 14.3% reduction identified in one healthy participant. Although previous research hypothesised that toe-out gait would cause an increase in the peak KFM, this study demonstrated that toe-out reduced the KFM (12.0% mean) and increased the KEM (19.9% mean). The previously hypothesised effect on the KFM was based on research which simulated the effect of toe-out gait on knee kinetics. But Jenkyn and colleagues’ simulation predicted that toe-out would reduce the early stance peak KAM, and that this would be associated with an increased KFM. However, toe-out gait in this study resulted in a larger early stance peak KAM rendering the model unsupported.

In this study, toe-in gait increased the KFM (20.7% mean) and a reduction in the KEM (16.2% mean). While a recent study investigating toe-in gait in 12 participants with knee OA did not identify significant changes in the KFM with an average 5° FPA change from natural gait, the small change in FPA may have been inadequate to change the KFM. Biomechanically, the theory of partial transformation of moment between the frontal and sagittal planes suggested by Jenkyn et al. is plausible and likely given the inverse effects seen in the early stance peak KAM and KFM in this study, just possibly opposite in direction.

Biomechanically, altered FPA likely influences the KAM by shifting the centre of pressure location (the GRF origin). As the centre of pressure progresses anteriorly along the foot during stance, this biomechanical shift is most pronounced during the late stance phase of gait (evidenced by consistent changes in the late stance KAM). In contrast, during the early stance phase of gait, the centre of pressure is primarily located at the hindfoot, thus a different mechanism likely caused the early stance KAM changes. Shull and colleagues suggest that toe-in laterally shifts the centre of pressure by externally or laterally rotating the heel about a relatively constant footforefoot position. As step width increases were identified during maximal toe-in gait in this study, participants likely achieved toe-in by moving the heel laterally. The opposite may be expected with toe-out gait; however step width also increased with toe-out gait and therefore may alter the early stance KAM via a different mechanism.

Efficacy of KAM change with altered FPA was mediated by knee alignment and pain. The greater ability for individuals with varus knees to modify knee load may be due to their inherently larger KAM compared to individuals with valgus alignment, providing greater opportunity for reduction. It was also discovered that in individuals with moderate to severe pain (WOMAC pain >10.8), the previously reported load-reducing effect of toe-out on the KAM late stance peak and impulse was predicted to reverse. This may be because individuals with more pain exhibit different gait characteristics to those with less pain including smaller dynamic knee flexion-extension range, greater trunk lean, reduced gait speed and flat feet. Hence, movement patterns giving rise to altered FPA may differ amongst individuals with greater pain and require further investigation.

Altered FPA gait did not result in immediate symptomatic changes in this cohort of participants with medial knee OA. However, this cohort expressed low pain levels during natural gait, limiting detection of improvement. This study has several strengths. To our knowledge, it is the first to investigate immediate symptomatic effects and changes in a full range of medial knee load-related parameters with altered FPA gait in a cohort of participants with medial knee OA. The use of real-time biofeedback permitted evaluation of dose–response effects.
Fig. 2. Ensemble averages for the (a) FPA, (b) external KAM and (c) external KFM during the stance phase for each of the six conditions: natural gait, targeting 10° of toe-in, targeting 0° FPA, targeting 10° of toe-out, targeting 20° of toe-out, and targeting 30° of toe-out.
on knee kinetics. Additionally, the linear mixed model statistical method conducted is considered more powerful than regression analysis or repeated measures ANOVA.7,14

There are some limitations to this study. Although basic training recommendations of either toe-in or toe-out gait for people with symptomatic knee OA is currently not possible due to the variability of mechanical loading of the knee including muscle activation patterns.54 The immediate effects were studied.

There are several directions for future research in the area of gait modification strategies. Given the identified mediating effects of WOMAC pain and malalignment, future studies should consider these factors and other potential mediators of response when evaluating gait modification strategies. Current literature investigating contributions of the KFM to medial compartment mechanical load in other contexts shows inconsistencies.11,12,22,49 Further research is required to ensure that a shift in moment from one plane to another with altered FPA does not result in an overall detrimental load increase in the medial compartment, in other knee compartments (such as the patella-femoral joint) or the contralateral limb. Whilst biomechanical conservative strategies aim to reduce medial knee load with the aim of slowing disease progression, this has not yet been proven for any such interventions by empirical research and should be the aim of future investigations.50 Lastly, research is needed to explore any symptomatic benefits with prolonged gait modification.

Altered FPA can modify the external KAM and KFM in people with medial knee OA. While frontal plane kinetic changes imply an altered medial knee joint load, these findings should be confirmed with more comprehensive evaluations of the local mechanical loading of the knee including muscle activation patterns, and/or estimates of joint forces. Results suggest that effects of altered FPA are mediated by knee alignment and pain. Recommendations of either toe-in or toe-out gait for people with medial knee OA is currently not possible due to the variability demonstrated on external kinetic parameters and the limitations of estimating joint load from inverse dynamics. Future research should expand current knowledge through longitudinal studies to determine if and which gait modification has greatest clinical benefit.

**Contributions**

All authors have made substantial contributions to all three of the sections listed below:

1. the conception and design of the study, or acquisition of data, or analysis and interpretation of data
2. drafting the article or revising it critically for important intellectual content
3. final approval of the version to be submitted.

Author responsibility for the integrity of the work undertaken: Milena Simic and Kim Bennell.

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**Table IV**

Effect of FPA on knee loading parameters

<table>
<thead>
<tr>
<th>Linear mixed model</th>
<th>Estimate</th>
<th>95% CI</th>
<th>Probability</th>
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</thead>
<tbody>
<tr>
<td><strong>Early stance peak KAM</strong></td>
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<td></td>
</tr>
<tr>
<td>Intercept</td>
<td>3.77</td>
<td>(3.28, 4.25)</td>
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<tr>
<td>FPA</td>
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<td>$(-1.80 \times 10^{-2}, -2.44 \times 10^{-2})$</td>
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<tr>
<td>$R^2$</td>
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<tr>
<td><strong>Late stance peak KAM</strong></td>
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<td></td>
</tr>
<tr>
<td>Intercept</td>
<td>2.06</td>
<td>(1.71, 2.40)</td>
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<tr>
<td>FPA</td>
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<td>$(3.59 \times 10^{-2}, 4.20 \times 10^{-2})$</td>
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<td>$R^2$</td>
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<tr>
<td>Intercept</td>
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<td>(1.04, 1.45)</td>
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<tr>
<td>FPA</td>
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<td>$(3.03 \times 10^{-3}, 5.12 \times 10^{-3})$</td>
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<td>$R^2$</td>
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<td><strong>Peak KFM</strong></td>
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<tr>
<td>Intercept</td>
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<td>$(-1.66, -1.03)$</td>
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<tr>
<td>FPA</td>
<td>$1.39 \times 10^{-2}$</td>
<td>$(1.06 \times 10^{-2}, 1.73 \times 10^{-2})$</td>
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<tr>
<td>$R^2$</td>
<td>0.988</td>
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**Table V**

Final linear mixed models for the effects of altered FPA on knee loading parameters, with consideration of participant characteristics

<table>
<thead>
<tr>
<th>Linear mixed model</th>
<th>Estimate</th>
<th>95% CI</th>
<th>Probability</th>
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<tr>
<td><strong>Early stance peak KAM</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Intercept</td>
<td>3.77</td>
<td>(3.28, 4.25)</td>
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<tr>
<td>FPA</td>
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<td>FPA</td>
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<tr>
<td><strong>Late stance peak KAM</strong></td>
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<td></td>
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<tr>
<td>Intercept</td>
<td>2.06</td>
<td>(1.72, 2.40)</td>
<td></td>
</tr>
<tr>
<td>FPA</td>
<td>$-1.44 \times 10^{-3}$</td>
<td>$(-6.31 \times 10^{-4}, -2.26 \times 10^{-3})$</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td><strong>Main effects</strong></td>
<td></td>
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</tr>
<tr>
<td>FPA</td>
<td>$-3.51 \times 10^{-3}$</td>
<td>$(-2.08 \times 10^{-3}, -4.94 \times 10^{-3})$</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.958</td>
<td></td>
<td></td>
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<tr>
<td><strong>KAM Impulse</strong></td>
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</tr>
<tr>
<td>Intercept</td>
<td>1.24</td>
<td>(1.04, 1.45)</td>
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</tr>
<tr>
<td>FPA</td>
<td>$-4.98 \times 10^{-4}$</td>
<td>$(-9.34 \times 10^{-5}, -9.02 \times 10^{-4})$</td>
<td>0.016</td>
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</tr>
<tr>
<td>FPA</td>
<td>$3.99 \times 10^{-3}$</td>
<td>$(2.94 \times 10^{-3}, 5.03 \times 10^{-3})$</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.998</td>
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<tr>
<td><strong>KFM</strong></td>
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</tr>
<tr>
<td>Intercept</td>
<td>2.82</td>
<td>(2.19, 3.44)</td>
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<tr>
<td>FPA</td>
<td>$2.62 \times 10^{-2}$</td>
<td>$(2.16 \times 10^{-2}, 3.08 \times 10^{-2})$</td>
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<tr>
<td>$R^2$</td>
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<tr>
<td><strong>KEM</strong></td>
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</tr>
<tr>
<td>Intercept</td>
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<td>$(-1.66, -1.03)$</td>
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<tr>
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<tr>
<td>FPA</td>
<td>$1.45 \times 10^{-2}$</td>
<td>$(1.11 \times 10^{-2}, 1.78 \times 10^{-2})$</td>
<td>&lt;0.001</td>
</tr>
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</table>
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Completing interests
No financial support or other dependent relationships have been identified which may lead to conflict of interest.

References
10. Birmingham TB, Hunt MA, Jones IC, Jenkyn TR, Gif
43. Hunt MA, Wrigley TV, Hinman RS, Bennell KL. Individuals with severe knee osteoarthritis (OA) exhibit altered proximal walking mechanics compared with individuals with less severe OA and those without knee pain. Arthritis Care Res 2010;62:1426–32.