Stride width independently reduces knee abduction moment but not medial contact force

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Title: Stride Width Independently Reduces Knee Abduction Moment but Not Medial Contact Force

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Running Title: Effects of Stride Width on Knee Moments

Abstract:

Gait modification targeting the internal peak knee abduction moment (PKAM1) is proposed as a conservative strategy to reduce medial compartment loading in knee osteoarthritis. However, prior studies have not isolated stride width effects from concomitant changes in spatiotemporal or kinematic changes or whether PKAM1 reductions translate to reduced medial contact force (MCF). This study investigated the independent effect of increased stride width on PKAM1 after controlling for covariates, with narrow gait as a directional mechanistic comparator. Sixteen healthy males performed five trials of baseline, narrow, and wide gait conditions. Mixed-effects models evaluated condition effects on temporospatial, kinematic, and kinetic outcomes with spatiotemporal and kinematic covariates included in kinetic models. Wide gait significantly reduced PKAM1 after covariate adjustment, driven by a lateral shift of the GRF line of action relative to the knee joint center. However, this did not translate to a significant reduction in estimated MCF. Narrow gait shifted the moment arm medially and did not reduce PKAM1 after covariate adjustment, suggesting its modest descriptive reduction was attributable to reduced walking speed. Wide and narrow gait produced opposing effects across frontal and sagittal plane moments, with neither achieving a net MCF reduction independent of temporospatial changes. Stride length was independently associated with sagittal plane loading, warranting further investigation as a modification target.

Keywords: gait modification, knee osteoarthritis, stride width, gait speed, knee moment

1. Introduction

Osteoarthritis (OA) is a leading cause of global disability, with the knee being the most commonly affected joint (Courties et al., 2024). One of the primary factors related to both the development and progression of KOA is the frontal plane moment (Chehab et al., 2014; Miyazaki et al., 2002; Sharma et al., 1998). This torque has been represented both by the external adduction (Gerbrands et al., 2014; Simic et al., 2013; Uhlrich et al., 2025) and internal abduction moment (Lindsey et al., 2020; Paquette et al., 2015; Prebble et al., 2023). Although the external adduction moment has been more commonly reported in KOA literature, the internal moment is equal but opposite in sign (Butler et al., 2009), and may be used interchangeably as indices of medial compartment loading. The peak of the internal knee abduction moment during the first half of stance (PKAM1) has been specifically linked to knee pain (Thorp et al., 2007), severity (Erhart-Hledik et al., 2015), and progression (Chehab et al., 2014). Therefore, reducing PKAM1 in KOA patients is hypothesized to reduce loading and tissue degeneration (Shull et al., 2013; Ulrich et al., 2023).

Another consideration for knee OA loading is the secondary effect of the peak sagittal plane moment, as in vivo force data from a KOA patient showed that a 33% reduction in PKAM1 failed to significantly reduce medial knee joint contact force due to a concomitant rise in peak internal knee extension moment (PKEM) (Walter et al., 2010). Subsequent investigations have found no significant change in estimated medial contact force (MCF) or simulated joint reaction forces (JRF) with gait modifications despite reductions in PKAM1, using both regression-based estimation (Lindsey et al., 2020) and musculoskeletal modeling (Prebble et al., 2023) approaches. These findings suggest that estimating MCF alongside PKAM1 is necessary to determine whether reductions in the moment translate to meaningful changes in medial compartment loading.

Gait retraining has shown potential as a non-invasive intervention to reduce PKAM1 in both healthy and KOA patients (Eddo et al., 2017; Richards et al., 2017). A commonly studied modification is increased stride width, with multiple studies indicating that increased stride width may effectively reduce PKAM1 in both healthy (Edd et al., 2020; Favre et al., 2016; Stief et al., 2021) and KOA patients (Baghi et al., 2025; Pereira et al., 2021). However, evidence suggests that PKAM1 reductions observed with increased stride width may be partially attributed to involuntary concomitant changes such as altered foot progression angle, trunk lean, and medial knee thrust (Booij et al., 2020; Favre et al., 2016). Additionally, increased stride width has been consistently associated with reduced walking speed (Baghi et al., 2025; Favre et al., 2016; Stief et al., 2021), therefore, it remains unclear whether the PKAM1 reductions observed in wide gait reflect an independent effect of increased stride width or are mediated by accompanying changes in other kinematic parameters and/or a decline in gait speed. Furthermore, greater stride width has been shown to increase PKEM (Edd et al., 2020; Favre et al., 2016; Pereira et al., 2021), raising the possibility that any reduction in PKAM1 may be offset by a concomitant rise in sagittal plane loading.

While increased stride width has received the most attention in prior literature, examination of the directional inverse, i.e., narrow gait, may help to clarify whether increased stride width itself drives PKAM1. The limited evidence on narrow gait is inconsistent. Street and Gage (2013) observed a significant reduction in PKAM1 during overground walking, however, only for the non-dominant limb, while Stief et al. (2021) found no significant change in frontal plane knee moments when stride width was halved. Neither study accounted for concomitant changes in walking speed, which may partially explain these findings.

Therefore, the purpose of this study was to investigate the effect of stride width on PKAM1 while statistically controlling for changes in spatiotemporal and kinematic parameters. A secondary aim was to determine whether observed reductions in PKAM1 translate to a decrease in MCF. Narrow stride width was included as a directional comparator to provide insight into whether the effects of stride width on PKAM1 are consistent with a moment arm-driven mechanism. Due to the nature of narrow stride width as a modification that may be difficult for older, symptomatic patients to adopt, healthy individuals were tested for this initial investigation. We hypothesized that (1) wide gait would significantly reduce PKAM1 independent of potential covariates, and (2) this reduction would not translate to a proportional reduction in estimated medial contact force due to a concomitant increase in PKEM.

2. Methods:

2.1 Participants:

Sixteen healthy male participants volunteered for this study (age = 27.1 ± 4.0 years, height = 1.8 ± 0.1 meters, body mass = 70.1 ± 9.1 kg). The experimental procedure was reviewed and approved by the institution's ethics committee (details blinded for review) and all participants provided written informed consent prior to the study.

2.2 Instrumentation:

Fifty-three retroreflective markers were attached to the trunk and lower extremities of participants in the same manner as prior investigations (Lindsey et al., 2020). Fourteen high-speed motion analysis cameras (Vicon, Oxford, England) sampling at 200 Hz were used to track marker trajectories, and three floor-embedded force plates (AMTI, Watertown, MA) sampling at 1000 Hz were used to measure GRF during trials. A static calibration trial was collected by having participants stand on a force plate with both feet parallel to the anterior-posterior axis of the laboratory. Participants also performed a dynamic calibration to estimate hip joint center by completing three clockwise rotations of the pelvis (Schwartz and Rozumalski, 2005). From the static trial, a kinematic model was created for each participant using Visual3D software (C-Motion, Germantown, MD).

2.3 Individualization of stride width conditions:

Altered stride width conditions were individualized to each participant based on their limb length (LL) similar to Paquette et al. (Paquette et al., 2015). Limb length was measured as the vertical distance from the anterior superior iliac spine (ASIS) to the medial malleolus. Stride width for wide and narrow gait were then standardized to 39% and 10% of the participant's individual LL, respectively.

2.4 Gait trials:

Participants performed five walking trials per condition. For the wide condition, increased step width precluded simultaneous bilateral force plate contact, and therefore, five trials were collected separately for each limb. The order of altered stride width conditions was randomized across participants with baseline trials performed first at self-selected speed. Tape was placed on the walkway to indicate the target foot placement for each altered condition (Figure 1). Participants were instructed to land with the center of the foot on the tape while maintaining self-selected speed. Before each condition, participants completed a minimum of five familiarization trials to ensure stable adoption.

Insert Figure 1

2.5 Data Processing:

A kinematic model was created in Visual3D to quantify motion at the trunk, hip, knee, and ankle with rotations being expressed relative to the static trial. A cardan angle sequence was used to calculate joint angles (Grood and Suntay, 1983) and a standard inverse dynamics analysis was conducted to synthesize the trajectory and vertical GRF data for internal joint moment estimation. Internal, as opposed to external moments, were reported in this study as they represent, by definition, the net reactive moment generated by muscles, ligaments, and passive joint structures to resist the external loading environment, and are derived directly from the inverse dynamics analysis conducted here (Butler et al., 2009). Joint kinematics and kinetics were smoothed using a fourth-order low-pass Butterworth filter with a cut off frequency of 8 Hz to reduce effects of artifacts based on results from residual analysis (Winter, 1979). Joint angles were measured in degrees, and all internal joint moments were normalized to mass and height (Nm/(kg·m)). Ground reaction force data were normalized to body weight, and all gait trials were normalized to 100% of stance.

Joint angle sign conventions were defined such that toe-in foot progression, knee varus, and trunk lean toward the stance limb was positive, while knee flexion was negative. First peak of the internal knee abduction moment (PKAM1) and peak knee extension moment (PKEM) were defined as the minimum and maximum values, respectively, between heel strike and midstance (50% between heel contact and toe-off). Second peak of the internal knee abduction moment (PKAM2) was defined as the minimum values between midstance and toe-off. Discrete measures of joint angles were reported as values recorded at PKAM1.

The mediolateral moment arm of the knee was also computed as the mediolateral distance between the center of pressure (COP) and the knee joint center in the frontal plane, and served as a standard approximation of the frontal plane lever arm under the assumption that the GRF acts predominantly vertically during stance (Paquette et al., 2014). Both signals were expressed in the global laboratory coordinate system and subtracted to yield the moment arm, such that positive values indicate COP positioned medial to the knee joint center. Estimated medial compartment contact force was computed using the regression approach described by Walter et al. (2010):

Medial Contact Force ≈ (0.31*$PKAM1_{absolute}$) + (0.09*$PKEM_{absolute}$) + 0.82

Moment inputs were converted from Nm/(kg·m) to %BW·HT prior to applying the regression coefficients.

2.6 Statistical Analysis:

Statistical analyses were conducted using R (R Core Team; Vienna, Austria) (R Core Team, 2021) with alpha level set *a priori* at 0.05. Descriptive statistics were computed for all variables by condition. Mixed-effects models evaluated condition effects on spatiotemporal and kinematic variables, with condition as a fixed effect and participant as a random effect. For kinetic outcomes, unadjusted models containing condition as the sole fixed effect were first estimated to characterize the overall kinetic response to stride width. Subsequently, adjusted models including spatiotemporal (gait speed and stride length) and kinematic (foot progression, trunk lean, and frontal plane knee angle) parameters were estimated to isolate the independent effect of stride width. Degrees of freedom were approximated using Satterthwaite's method. Parameter estimates are reported with 95% confidence intervals. Post-hoc pairwise comparisons with Tukey adjustment were conducted for significant condition effects. To quantify the variance explained by covariates beyond condition alone, marginal R^2 (R^2m) was computed for both unadjusted and adjusted kinetic models.

3. Results:

Average limb length across participants was 0.88 ± 0.05 meters, resulting in an average stride width for narrow and wide conditions of 0.09 ± 0.00 and 0.34 ± 0.02 meters, respectively. Mean within-participant trial-to-trial variability in stride width was 0.017, 0.012, and 0.015 m for baseline, narrow, and wide conditions respectively, indicating consistent adoption of the prescribed stride widths. Descriptive statistics for spatiotemporal, kinematic, and kinetic variables across conditions are shown in Table 1.

Insert Table 1

Results of the mixed-effects models are displayed in Table 2. Changes in stride width were accompanied by significant reductions in gait speed (narrow and wide: β = -0.17 [-0.20, -0.14] and [-0.20, -0.15], respectively) and stride length (narrow: β = -0.11 [-0.14, -0.08]; wide: β = -0.15 [-0.18, -0.12]). Significant concomitant changes to foot progression angle and frontal and sagittal plane knee angle were also observed. Both modified conditions significantly increased toe-in and reduced frontal plane knee angle (narrow: β = -0.7 [-1.1, -0.2]; wide: β = -1.0 [-1.4, -0.5]), with narrow gait producing a greater increase in toe-in relative to wide gait (narrow: β = +4.9 [3.9, 6.0]; wide: β = +1.4 [0.3, 2.4]). Wide gait significantly increased knee flexion angle relative to baseline (β = -1.5 [-2.3, -0.7]), while narrow gait produced no significant change (β = +0.3 [-0.5, 1.2]). Trunk lean angle was not significantly modified by either stride width condition (narrow: β = -0.1 [-0.8, 0.6]; wide: β = +0.2 [-0.5, 0.9]).

Insert Table 2

Modified stride width produced distinct kinetic responses before and after covariate adjustment. Time series of primary kinetic outcome variables across gait conditions are shown in Figure 2. In the unadjusted model, both modifications produced significant changes in all kinetic outcomes relative to baseline. Wide gait significantly reduced PKAM1 magnitude (β = +0.058 [0.045, 0.070]) while narrow gait produced a smaller but still significant reduction (β = +0.029 [0.016, 0.042]). Wide and narrow gait produced opposing effects on PKAM2, with narrow gait significantly increasing the magnitude (β = -0.027 [-0.039, -0.015]) and wide significantly reducing it (β = +0.037 [0.025, 0.049]). Similarly opposing effects were observed for PKEM, with wide gait significantly increasing magnitude (β = +0.037 [0.018, 0.056]) and narrow gait significantly reducing it (β = -0.054 [-0.073, -0.036]). Both narrow and wide gait produced large reductions in MCF (narrow: β = -0.144 [-0.188, -0.100]**;** wide: β = -0.157 [-0.201, -0.112]). Wide gait produced a large lateral shift in the mediolateral moment arm at both PKAM1 (β = -38.5 [-40.9, -36.1]) and PKAM2 (β = -30.2 [-33.1, -27.3]), while narrow gait produced a medial shift of comparable magnitude in the opposing direction (PKAM1: β = +7.8 [5.4, 10.1]; PKAM2: β = +17.9 [15.0, 20.7]). Both conditions produced modest reductions in vertical GRF at PKAM1 (narrow: β = -0.047 [-0.059, -0.035]; wide: β = -0.038 [-0.050, -0.026]) and PKAM2 (narrow: β = -0.033 [-0.042, -0.024]; wide: β = -0.051 [-0.060, -0.042]).

Insert Figure 2

After controlling for spatiotemporal and kinematic covariates in the adjusted model, condition effects on PKAM1 and MCF were substantially attenuated while effects on PKAM2 and PKEM were largely preserved (Table 3). For PKAM1, the effect of narrow gait was no longer significant after adjustment (β = -0.010 [-0.029, 0.009]) and reversed in direction relative to the unadjusted estimate, while the effect of wide gait was attenuated but remained significant (β = 0.023 [0.006, 0.040]). Covariates accounted for an additional 28.5% of variance in PKAM1 beyond condition alone (unadjusted R^2m = 0.080; adjusted R^2m = 0.366), with gait speed as the dominant independent covariate, with additional but smaller significant kinematic contributions from altered foot progression, trunk lean, and frontal plane knee angle. In contrast, the effects of narrow and wide gait on PKAM2 were minimally affected by covariate adjustment (narrow: β = -0.033 [-0.053, -0.014]; wide: β = 0.028 [0.010, 0.044]), with covariates collectively contributing only an additional 2.7% of variance beyond condition (unadjusted R^2m = 0.112; adjusted R^2m = 0.138). Similarly, PKEM effects persisted after adjustment (narrow: β = -0.049 [-0.078, -0.019]; wide: β = 0.079 [0.054, 0.104]), with covariates explaining an additional 9.5% of variance (unadjusted R^2m = 0.062; adjusted R^2m = 0.157), primarily driven by reductions in stride length.

Mediolateral moment arm and vertical GRF also demonstrated distinct responses to covariate adjustment. Vertical GRF at PKAM1 was not independently affected by either condition after covariate adjustment, with gait speed being the primary independent determinant of vertical GRF at PKAM1. Only wide gait produced a significant independent reduction in vertical GRF at PKAM2 (β = -0.023 [-0.038, -0.008]), with gait speed, stride length, and foot progression angle all contributing independently. The large opposing shifts in mediolateral moment arm with wide and narrow gait were preserved after covariate adjustment, with foot progression angle and frontal plane knee angle independently associated with moment arm magnitude. Finally, overall reductions in MCF with both conditions were fully explained by covariate adjustment; neither narrow (β = 0.005 [-0.062, 0.072]) nor wide gait (β = -0.004 [-0.062, 0.055]) produced a significant independent effect on MCF after adjustment, with covariates accounting for an additional 27.1% of variance (unadjusted R^2m = 0.060; adjusted R^2m = 0.331). Consistent with PKAM1, gait speed was the dominant independent covariate for MCF with frontal plane knee angle also contributing independently to MCF reduction. Differences between unadjusted and adjusted model estimates for primary kinetic variables are visualized in Figure 3.

Insert Figure 3

4. Discussion:

In agreement with our first hypothesis, wide gait significantly reduced PKAM1, even after controlling for concomitant spatiotemporal and kinematic changes. However, consistent with our second hypothesis, this did not translate to a significant reduction in estimated MCF after adjustment. A concomitant significant increase in PKEM with wide gait provides a plausible mechanical explanation for this null finding, supporting the theory that frontal and sagittal plane moments must be considered jointly when evaluating the clinical utility of gait modifications for medial compartment offloading (Manal et al., 2015; Walter et al., 2010).

Our findings suggest that overall reductions in PKAM1 during wide gait are driven by a combination of reduced vertical GRF through reduced gait speed, and lateralization of the GRF line of action relative to the knee joint center due to the combined effects of increased step width in addition to concomitant changes to foot progression, trunk lean, and frontal plane knee angle. This finding is consistent with prior research demonstrating that combined modification schemes eliciting the greatest reductions in PKAM1 frequently involve increased stride width as part of a broader pattern of kinematic changes rather than in isolation (Booij et al., 2020; Favre et al., 2016). Specifically, prior research has shown that instructions to increase step width in isolation may elicit secondary changes to kinematic parameters such as foot progression angle and trunk sway (Favre et al., 2016) and reductions in inter-knee distance (Booij et al., 2020). Additionally, relationships have been observed between kinematic parameters such as foot progression and knee abduction during single-parameter gait modifications (Lindsey et al., 2021a). This suggests that such that a secondary change to either as a result of increased stride width may then propagate to a change in the other. Our data supports these findings as instructions to walk with greater stride width naturally resulted in greater toe-in and knee abduction in our sample. The finding that all three kinematic covariates were significant predictors of PKAM1 beyond condition alone, support prior work suggesting that 'general' multi-parameter gait modification schemes may be more effective to reduce PKAM1 and feel more natural for knee OA patients compared to isolated modifications (Favre et al., 2016; Lindsey et al., 2021a, 2021b).

However, wide gait continued to demonstrate a reduction in PKAM1 after controlling for covariates, suggesting an independent mechanical effect. This appears to operate primarily through a lateral shift in the GRF line of action, displacing the mediolateral moment arm laterally relative to the knee joint center; an effect which was maintained after covariate adjustment unlike the reduction in vertical GRF. Although it might be expected that wider foot placement in isolation would increase the frontal plane moment arm as the knee joint center moves further laterally relative to the COM, this is only true if the GRF line of action remains fixed. Stief et al. (2021) proposed that wider foot placement reduces the frontal plane moment arm by lateralizing the COP relative to the knee joint center. This mechanism has been observed in other studies where a wider base of support allowed greater lateral center of mass (COM) displacement over the stance leg, further reducing the mediolateral moment arm (Anderson et al., 2018) and is consistent with the opposing moment arm shifts observed across conditions in the present study.

The lack of significant reduction in PKAM1 after adjustment during narrow gait supports the paradigm that the direction of the GRF line of action relative to the knee joint center is more important than absolute joint position. The observed medial shift in the mediolateral moment arm during narrow gait is consistent with evidence showing that a narrower base of support constrains lateral COM displacement (Anderson et al., 2018). This constraint would be expected to position the COP medial to the knee joint center, increasing the abduction moment arm and thereby medial compartment loading (Miyazaki et al., 2002; Sharma et al., 1998). In fact, the condition estimate for PKAM1 in narrow gait reversed direction relative to the unadjusted model, indicating that the descriptive reduction was primarily attributable to concomitant reductions in gait speed and stride length rather than a beneficial change to the moment arm. Together, these findings suggest that where the COP lands relative to the knee joint center is a more important determinant of PKAM1 than the position of the knee joint center relative to the COM.

Wide and narrow gait also demonstrated opposing effects on PKEM, with wide gait significantly increasing its magnitude while narrow gait significantly reduced it. These opposing patterns provide a mechanistic explanation for lack of MCF reduction after controlling for covariates. Wide gait independently reduced PKAM1 through a lateral shift of the moment arm but simultaneously increased PKEM, driven by greater knee flexion at PKAM1. Just as a lateral shift of the GRF line of action relative to the knee joint center in the frontal plane increases the abduction moment arm and PKAM1, greater knee flexion at the time of PKAM1 increases the perpendicular distance of the GRF line of action from the knee joint center in the sagittal plane, thereby increasing the extension moment arm and demanding greater quadriceps force to stabilize the joint. In contrast, narrow gait produced a medial shift of the moment arm but a significant reduction in sagittal plane loading, consistent with the observed reduction in knee flexion during that condition. This tradeoff is consistent with prior observations that gait modifications effective at reducing frontal plane loading frequently increase sagittal plane demands and vice versa (Edd et al., 2020; Favre et al., 2016; Lindsey et al., 2020). As estimated MCF is sensitive to both PKAM1 and PKEM jointly (Walter et al., 2010), the simultaneous increase in PKEM with wide gait offset the beneficial reduction in PKAM1. Conversely, for narrow gait the beneficial reduction in PKEM was accompanied by a medial moment arm shift that descriptively increased rather than decreased PKAM1. Consistent with this interpretation, gait speed was the dominant covariate for MCF, with its coefficient substantially exceeding either condition effect. This strongly suggests that the overall MCF reductions observed in both conditions were primarily attributable to slower walking speeds rather than the independent effects of stride width on joint loading.

Beyond the effect of stride width alone, an independent positive relationship between stride length and PKEM was observed across conditions, such that longer strides were associated with greater extension moment magnitude and vice versa. This extends prior evidence from Edd et al., who demonstrated that shorter stride lengths significantly reduced PKAM1, KAM impulse, and PKEM in healthy participants, and aligns with preliminary evidence in KOA patients suggesting that decreased stride length can improve knee kinetics without universally increasing sagittal plane loading (Ulrich et al., 2023). These findings suggest stride length reduction may simultaneously reducing frontal plane knee loading without the adverse sagittal plane effects observed with wide gait, warranting further investigation in KOA populations.

This study has several limitations. Healthy participants were recruited as an initial investigation given that narrow gait may present balance and safety challenges for older adults with KOA. While prior work suggests that the effects of altered foot progression and stride width on gait mechanics are often similar between healthy individuals (Favre et al., 2016; Lynn and Costigan, 2008; Shull et al., 2011) and KOA patients (Paquette et al., 2015; Shull et al., 2013a; Simic et al., 2013), our specific findings require validation in the target population to test generalizability. Additionally, MCF was estimated using a regression-based approach derived from a single subject with an instrumented knee implant (Walter et al., 2010). Finally, while this study provides evidence for an independent effect of stride width on PKAM1, the data cannot definitively isolate the COP shift as the sole driver of moment arm lateralization, as contributions from altered COM trajectory, shank orientation, or additional kinematic adaptations cannot be excluded.

These findings suggest that increased stride width independently reduces PKAM1 by lateralizing the GRF line of action relative to the knee joint center but that this benefit is potentially offset by increased sagittal plane loading demands, resulting in no net reduction in estimated MCF. A substantial portion of the loading reductions observed across both conditions were attributable to concomitant reductions in spatiotemporal and kinematic variables rather than stride width alone, highlighting the critical importance of covariate control when evaluating the independent mechanical efficacy of gait modifications. Future work should explore whether combining increased stride width with stride length reduction could simultaneously address both planes of loading, potentially maximizing medial compartment offloading while minimizing sagittal plane demands.

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Table 1. Descriptive statistics (mean and standard deviation) for spatiotemporal, kinematic, and kinetic gait parameters across condition.

Variable	**Condition**		
Spatiotemporal	**Baseline**	**Narrow**	**Wide**
Gait Speed (m/s)	1.26 (0.14)	1.09 (0.18)	1.09 (0.22)
Stride Width (m)	0.13 (0.04)	0.10 (0.02)	0.30 (0.03)
Stride Length (m)	1.36 (0.11)	1.25 (0.12)	1.21 (0.19)
Δ Stride Width (m)	-	-0.03 (0.03)	0.17 (0.04)
Δ Stride Length (m)	-	-0.11 (0.06)	-0.15 (0.12)
Kinematic			
Foot Progression (°)	-12.2 (7.1)	-7.3 (6.0)	-10.9 (6.6)
Knee Abduction (°)	3.6 (3.7)	2.9 (3.5)	2.6 (3.6)
Knee Flexion (°)	-9.3 (7.7)	-9.0 (8.4)	-10.8 (8.4)
Trunk Lean (°)	1.2 (3.3)	1.1 (3.3)	1.2 (3.3)
Kinetic			
First Peak Knee Abduction Moment (Nm/(kg·m))	-0.27 (0.07)	-0.24 (0.08)	-0.21 (0.08)
Second Peak Knee Abduction Moment (Nm/(kg·m))	-0.16 (0.07)	-0.19 (0.08)	-0.12 (0.07)
Peak Knee Extension Moment (Nm/(kg·m))	0.24 (0.16)	0.18 (0.12)	0.28 (0.15)
Mediolateral Moment Arm at PKAM1 (mm)	14.66 (13.51)	22.43 (15.82)	-23.85 (13.0)
Mediolateral Moment Arm at PKAM2 (mm)	4.19 (16.16)	22.06 (20.11)	-25.94 (16.05)
Vertical GRF at PKAM1 (%BW)	1.11 (0.09)	1.07 (0.08)	1.07 (0.09)
Vertical GRF at PKAM2 (%BW)	1.10 (0.07)	1.07 (0.06)	1.05 (0.06)
Medial Contact Force (%BW·HT)	1.91 (0.25)	1.77 (0.28)	1.75 (0.30)

Kinematic variables are reported at the instant of first peak knee abduction moment. Δ values represent mean change from baseline. Statistical comparisons against baseline are reported in Table 2.

Table 2. Fixed effect parameter estimates from mixed-effects models for spatiotemporal, kinematic, and kinetic variables.

Variable	Condition	Estimate	Covariate Estimates
Spatiotemporal			
Gait Speed (m/s)	Narrow:	-0.17 [-0.20, -0.14]***	
	Wide:	-0.17 [-0.20, -0.15]***	
Stride Width (m)	Narrow:	-0.03 [-0.04, -0.03]***[w]	
	Wide:	+0.17 [0.16, 0.18]***[n]	
Stride Length (m)	Narrow:	-0.11 [-0.14, -0.08]***[w]	
	Wide:	-0.14 [-0.18, -0.12]***[n]	
Kinematic			
Foot Progression (°)	Narrow:	+4.9 [3.9, 6.0]***[w]	
	Wide:	+1.4 [0.3, 2.4]*[n]	
Knee Abduction (°)	Narrow:	-0.7 [-1.1, -0.2]**	
	Wide:	-1.0 [-1.4, -0.5]***	
Knee Flexion (°)	Narrow:	+0.3 [-0.5, 1.2][w]	
	Wide:	-1.5 [-2.3, -0.7]***[n]	
Trunk Lean (°)	Narrow:	-0.1 [-0.8, 0.6]	
	Wide:	+0.2 [-0.5, 0.9]	
Kinetic			**Covariate Estimates**
First Peak Knee Abduction Moment (Nm/(kg·m))	Narrow:	-0.010 [-0.029, 0.009][w]	Speed: -0.126* FP:+0.002*
	Wide:	+0.023 [0.006, 0.040]**[n]	TL: +0.007* KA: -0.013*
Second Peak Knee Abduction Moment (Nm/(kg·m))	Narrow:	-0.033 [-0.053, -0.014]***[w]	TL: +0.007*
	Wide:	+0.028 [0.011, 0.044]**[n]	
Peak Knee Extension Moment (Nm/(kg·m))	Narrow:	-0.049 [-0.078, -0.019]**[w]	SL: +0.206* FP: +0.007*
	Wide:	+0.079 [0.054, 0.104]***[n]	KA: +0.014*
Mediolateral Moment Arm at PKAM1 (mm)	Narrow:	+15.0 [11.4, 18.7]***[w]	FP: -1.051*
	Wide:	-34.9 [-38.0, -31.7]***[n]	KA: +1.542*
Mediolateral Moment Arm at PKAM2 (mm)	Narrow:	+15.5 [10.8, 20.1]***[w]	-
	Wide:	-31.8 [-35.8, -27.7]***[n]	
Vertical GRF at PKAM1 (%BW)	Narrow:	-0.010 [-0.029, 0.009]	Speed: +0.206*
	Wide:	-0.004 [-0.012, 0.020]	KA: +0.008*
Vertical GRF at PKAM2 (%BW)	Narrow:	-0.010 [-0.023, 0.004][w]	Speed: +0.221* SL: -0.067*
	Wide:	-0.023 [-0.035, -0.011]***[n]	FP: +0.002*
Medial Contact Force (%BW·HT)	Narrow:	0.005 [-0.062, 0.072]	Speed: +0.534*
	Wide:	-0.003 [-0.062, 0.055]	KA: +0.045*

Values represent model estimates (with 95% confidence intervals) relative to baseline gait. For kinetic outcomes, models were additionally adjusted for spatiotemporal (gait speed and stride length) and kinematic (foot progression angle, trunk lean, and frontal plane knee angle) covariates; only significant covariate effects are reported. Abbreviations are as follows: FP = foot progression angle; TL = trunk lean angle; KA = dynamic frontal plane knee angle; SL = stride length. Significant post-hoc differences between conditions are indicated by: 'n' = different from narrow, 'w' = different from wide. Asterisks denote levels of statistical significance: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

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2. Author Contributions:

All authors were fully involved in the study and preparation of the manuscript. The material has not been and will not be submitted for publication elsewhere. BL and DC carried out the experimental data collection, data processing, and statistical analyses. BL drafted the manuscript. BL, DC, NC, and PS conceived of the study and participated in its design and coordination and helped to draft the manuscript. All authors have read and approved the final version of the manuscript and agree with the order of presentation of the authors.

3. Competing Interests:

The authors declare that they have no competing interests.

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	Wide:	-0.17 [-0.20, -0.15]***	
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	Wide:	+0.17 [0.16, 0.18]***^{n}	
Stride Length (m)	Narrow:	-0.11 [-0.14, -0.08]***^{w}	
	Wide:	-0.14 [-0.18, -0.12]***^{n}	
Kinematic			
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	Wide:	+1.4 [0.3, 2.4]*^{n}	
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	Wide:	-1.0 [-1.4, -0.5]***	
Knee Flexion (°)	Narrow:	+0.3 [-0.5, 1.2]^{w}	
	Wide:	-1.5 [-2.3, -0.7]***^{n}	
Trunk Lean (°)	Narrow:	-0.1 [-0.8, 0.6]	
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	Wide:	-34.9 [-38.0, -31.7]***^{n}	KA: +1.542*
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	Wide:	-0.004 [-0.012, 0.020]	KA: +0.008*
Vertical GRF at PKAM2 (%BW)	Narrow:	-0.010 [-0.023, 0.004]^{w}	Speed: +0.221* SL: -0.067*
	Wide:	-0.023 [-0.035, -0.011]***^{n}	FP: +0.002*
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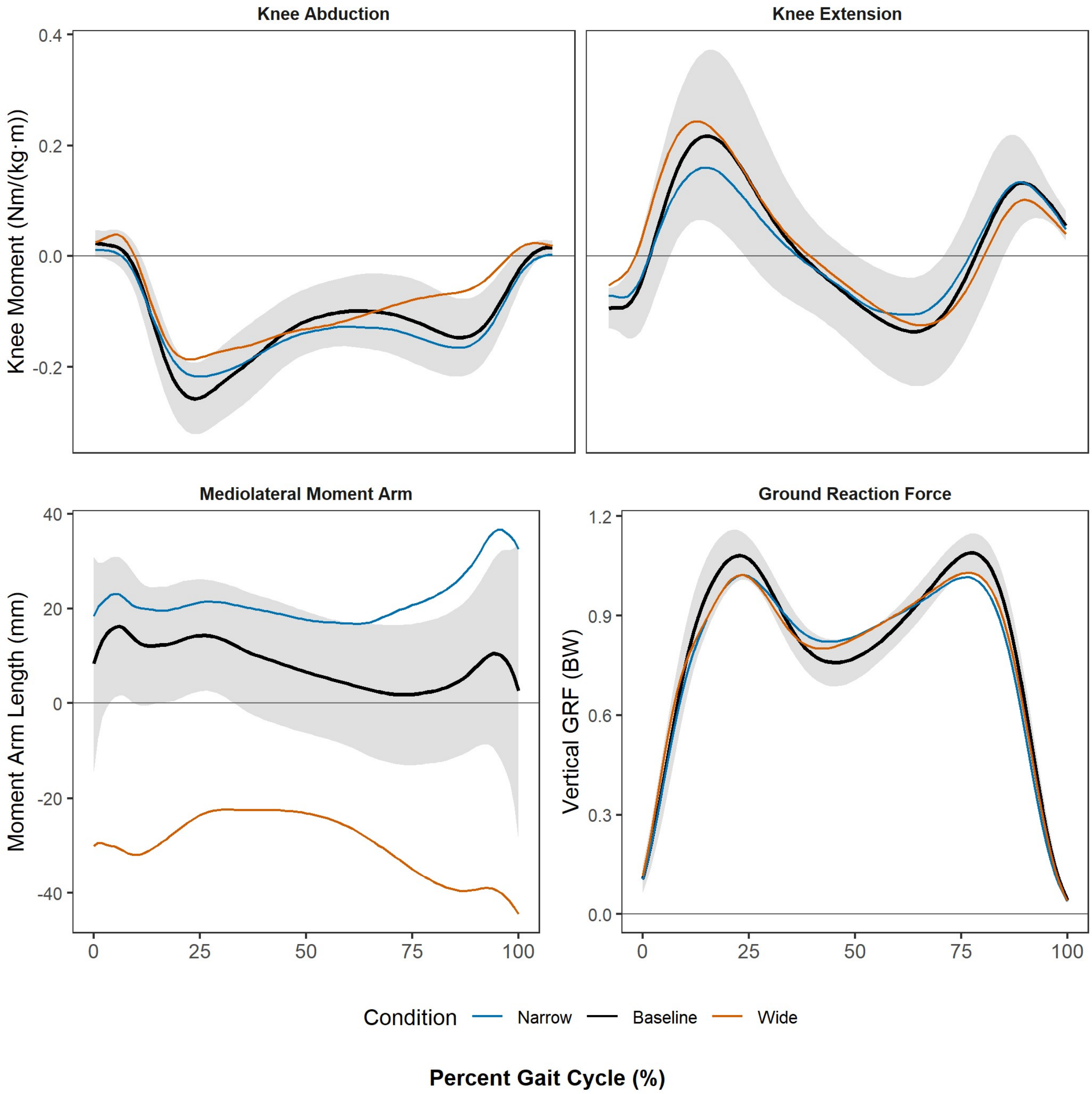
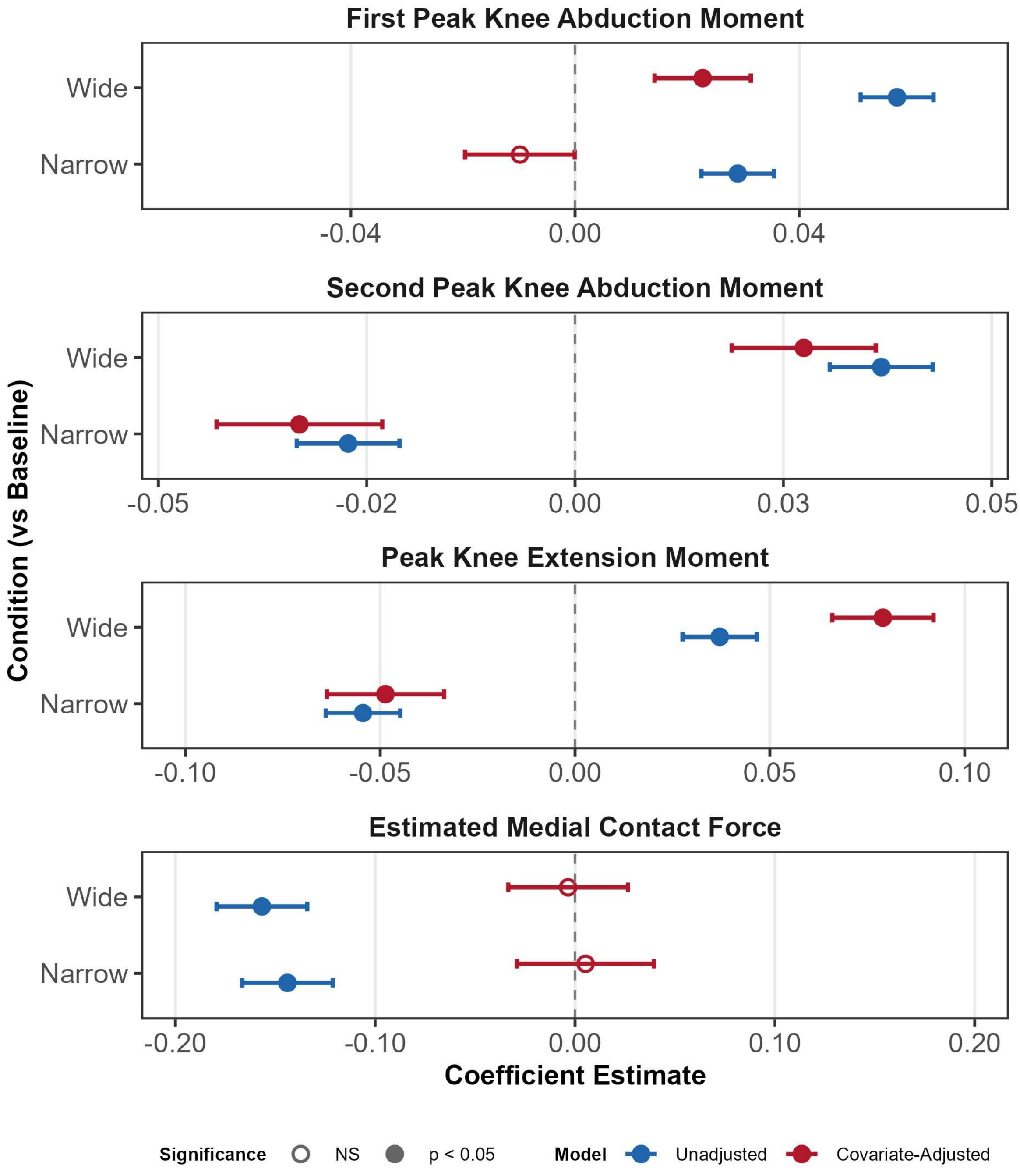
BERTEC



Knee Abduction
Knee Extension
Knee Moment (Nm/(kg·m))
0.4
0.2
0.0
-0.2
Mediolateral Moment Arm
Moment Arm Length (mm)
40
20
0
-20
-40
Ground Reaction Force
Vertical GRF (BW)
1.2
0.9
0.6
0.3
0.0
0
25
50
75
100
Condition
Narrow
Baseline
Wide
Percent Gait Cycle (%)


First Peak Knee Abduction Moment
Wide
Narrow
-0.04
0.00
0.04
Second Peak Knee Abduction Moment
-0.05
-0.02
0.00
0.03
0.05
Peak Knee Extension Moment
-0.10
-0.05
0.00
0.05
0.10
Estimated Medial Contact Force
-0.20
-0.10
0.00
0.10
0.20
Condition (vs Baseline)
Coefficient Estimate
Significance
NS
p < 0.05
Model
Unadjusted
Covariate-Adjusted