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Biomechanical Effects of Squat Depth and Movement Speed on Knee Joint Loading in Tai Chi Novice

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Abstract

Purpose: This study investigates the effects of squat depth and movement speed on knee joint loading during the "Part the Wild Horse's Mane" (PWHM) movement in Tai Chi novices. Methods: Thirteen healthy males performed the movement under six randomized conditions combining three squat depths (high, medium, low) and two speeds (slow and fast). Kinematic and kinetic variables were analyzed using repeated-measures ANOVA, statistical parametric mapping (SPM), and linear mixed-effects models. Results: Increased squat depth significantly elevated knee flexion-extension range of motion (ROM), peak extension moments, and joint impulses in both the sagittal and transverse planes ($p < 0.01$). Higher movement speeds resulted in significantly greater flexion and abduction angular velocities as well as peak extension moments, but were associated with reduced joint impulses ($p < 0.01$). Significant interaction effects between squat depth and movement speed were observed for flexion-extension and internal-external rotation impulses ($p < 0.05$). Among all tested conditions, the combination of medium squat depth and slow movement speed produced relatively lower adduction-abduction impulses compared to other conditions. Conclusions: These findings suggest that moderate-depth squats performed slowly may reduce medial-lateral knee loading and offer a safer strategy for joint protection in Tai Chi training.

Keywords: traditional Chinese exercise; knee biomechanics; training strategy; injury prevention; kinematics and kinetics

1 Introduction

As a traditional Chinese martial art, Tai Chi has evolved into a widely practiced form of low-impact exercise that emphasizes balance, proprioception, and slow, controlled movements [10, 17]. Its simplicity and accessibility make it particularly appealing as a functional training modality for enhancing muscle strength, improving balance, and reducing the risk of falls and chronic diseases [18, 31, 32]. Tai Chi is frequently recommended for individuals with musculoskeletal disorders, such as knee osteoarthritis, due to its potential to modulate joint biomechanics and enhance neuromuscular control [11, 14, 44]. However, accumulating evidence suggests that Tai

Chi is not entirely risk-free. Certain movements may impose excessive or asymmetrical loading on the lower limb joints, potentially contributing to musculoskeletal discomfort or injury [37, 39]. This issue is particularly pertinent for novice practitioners, who often exhibit limited hip mobility and impaired motor control. Such limitations may shift mechanical demands toward the knee joint, thereby increasing joint impulse and contact stress [16, 21].

Tai Chi movements are structurally complex, involving coordinated weight shifts, variable movement speeds, and alternating patterns of force generation and relaxation [43]. Among these, the "Part the Wild Horse's Mane" (PWHM) is a fundamental yet mechanically demanding movement that integrates lunging with weight transfer, imposing multidirectional loads on the knee joint [19, 22]. The supporting leg is required to generate not only a vertical extension moment but also stabilizing moments in the frontal and transverse planes, all of which contribute to overall knee joint loading [37]. Research has demonstrated that both squat depth and movement speed are key factors influencing joint biomechanics [1, 19]. Increased squat depth and slower movements are associated with greater mechanical demand and prolonged muscle activation [6, 29, 41]. Although faster movement speeds may increase peak joint moments, they tend to reduce cumulative joint loading due to shorter loading durations. In contrast, slower movements lead to greater joint impulses because of extended loading periods. This cumulative effect is more accurately represented by joint impulse, which integrates both the magnitude and duration of loading and provides a more comprehensive assessment of joint stress [7, 9, 23, 28].

Despite increasing interest in the biomechanics of Tai Chi, prior studies have typically investigated squat depth or movement speed in isolation and have predominantly focused on experienced practitioners. The combined effects of these two variables, particularly in novice populations, remain insufficiently understood. Moreover, comprehensive analytical approaches such as joint impulse assessment, time-series analysis, and linear mixed-effects models (LMM) have seldom been applied to examine knee joint loading in this context.

Therefore, this study aimed to investigate how variations in squat depth and movement speed during the PWHM movement affect knee joint loading in Tai Chi novices. We hypothesized that increased squat depth would lead to greater knee flexion-extension range of motion and higher extension moments, while slower movement speeds would prolong the support phase and increase joint impulse. Furthermore, we expected that the combination of low squat (LS) and slow movement speed would result in the highest cumulative knee joint loading due to increased joint excursion and sustained mechanical demand.

2 Materials and Methods

2.1 Participants

The required sample size was determined a priori using G*Power 3.1.9.7, based on a previous study with an effect size of $f = 0.62$, $\alpha = 0.05$, and power = 0.80, which indicated a minimum of 10 participants [19]. To ensure sufficient statistical power and account for potential attrition, 13 healthy male participants were recruited.

All participants (mean age: 25.86 ± 1.35 years; height: 174.26 ± 6.09 cm; body mass: 68.64 ± 8.15 kg; Tai Chi experience: 4.45 ± 0.61 months) were classified as Tai Chi novices, defined as individuals with less than six months of Tai Chi practice and fewer than two sessions per week [15, 20, 41]. Inclusion criteria were: age between 20 and 30 years; no recent participation in other balance or lower-limb training programs; and the ability to perform the PWHM movement without pain or movement limitations. Exclusion criteria included any lower-limb injury or surgery within the past six months, diagnosed neurological or balance disorders, or previous professional training in martial arts or dance. All participants provided written informed consent prior to participation. The study protocol was approved by the Ethics Committee of Ningbo University (Approval No. R20231218).

2.2 Experimental procedures

Upon arrival, participants' height and body mass were recorded. Squat depth was standardized using predefined ratios relative to each participant's standing height to account for individual anthropometric differences. Specifically, three target depths were defined: high squat (HS) at 97%, middle squat (MS) at 89%, and low squat (LS) at 81% of standing height, thereby ensuring consistent depth classification across participants regardless of their absolute height [19]. Movement speed was guided by auditory cues derived from the PWHM segment of the 24-form Tai Chi music. The slow speed condition followed the original tempo, while the fast-speed condition used the music adjusted to 1.2 times the original speed [20].

Participants practiced the required squat depths and movement speeds prior to data collection. All trials were performed barefoot, and participants wore tight-fitting clothing to ensure accurate marker tracking. A total of 38 reflective markers were affixed based on previously established protocols [5, 33, 36].

Kinematic data were collected at 200 Hz using a 10-camera motion capture system (Oxford Metrics Ltd., Oxford, UK), while ground reaction forces were recorded at 1000 Hz using two force platforms (AMTI, Advanced Mechanical Technology, Inc., Watertown, MA, USA), simultaneously [3, 34, 45]. Each participant completed six randomized test conditions (three squat depths × two movement speeds), with three successful trials recorded per condition. Each foot was positioned on a separate force platform. The movement cycle of the PWHM was defined using the vertical ground reaction force (vGRF) [43]. The onset of the cycle was identified when the vGRF on the first force platform exceeded 10N, and the cycle ended when the same signal dropped below 10N. The waveform was subsequently time-normalized from 0% (movement onset) to 100% (movement completion). Based on the vGRF profile, the cycle consisted of an initial double-support phase, a single-support phase, and a terminal double-support phase.

2.3 Data Preprocessing

Kinematic and kinetic data, including joint angles, joint angular velocities, and joint moments, were processed using Visual3D software (version 6, C-Motion, Germantown, MD, USA). Kinematic data were low-pass filtered at 8 Hz and kinetic data at 50 Hz using a fourth-order Butterworth filter with zero-phase lag. Joint moments were calculated using inverse dynamics and normalized to body weight. Time-series data were time-normalized to 101 data points, representing 0% to 100% of the movement cycle [38]. Joint impulses were computed in three planes—flexion-extension, adduction-abduction, and internal-external rotation—by integrating the joint moment over the stance phase using the following equation:

$$I = \int_0^T M(t), dt \tag{1}$$

where I represent the joint impulse, M(t) is the instantaneous joint moment at time t, and T denotes the duration of the stance phase.

2.4 Statistical Analysis

All statistical analyses were conducted using SPSS 26.0 (IBM Corp., Armonk, NY, USA), R version 4.3.1 (R Foundation for Statistical Computing, Vienna, Austria), and MATLAB R2023a (MathWorks Inc., Natick, MA, USA) Statistical significance was set at $p < 0.05$. Results are reported as mean ± standard deviation (SD).

Normality and homogeneity of variance were assessed using the Shapiro–Wilk and Levene's tests, respectively. For normally distributed variables, a two-way repeated-measures ANOVA was performed to evaluate the main effects of squat depth (HS, MS, LS), movement speed (fast, slow), and their interaction. When the assumption of sphericity was violated, the Greenhouse–Geisser correction was applied, followed by Bonferroni-adjusted post hoc comparisons. For non-normally distributed variables, we applied the aligned rank transform (ART) procedure with Bonferroni-adjusted post hoc tests. ART was chosen because it supports valid inference on main and interaction effects in factorial designs, which traditional non-parametric tests cannot accommodate [40]. Prior to ART-based ANOVA, aligned residuals were examined to confirm additivity and the absence of influential outliers. Two-way repeated-measures ANOVA based on statistical parametric mapping (SPM) was employed to assess the main and interaction effects of squat depth and movement speed on time-continuous biomechanical waveforms. Family-wise error rate was controlled using Random Field Theory (RFT)-based topological inference, whereby test statistics were thresholded at $\alpha = 0.05$ across the entire 0–100% movement cycle, and only supra-threshold clusters exceeding the RFT-derived critical threshold were considered significant [26, 27].

Correlation matrices were constructed to assess associations between variables. Pearson's or Spearman's correlation coefficients were calculated based on the distribution of each variable. Correlation strength (r) was interpreted following Hopkins et al. as follows: trivial (< 0.1), small (0.1–0.3), moderate (0.3–0.5), high (0.5–0.7), very high (0.7–0.9), and practically perfect (> 0.9) [12].

To identify biomechanical predictors of joint impulse, LMM were built using the lme4 package in R. The significance of fixed effects was assessed using the lmerTest package [24]. All continuous predictors were standardized (z-scored). Predictors with a pairwise correlation r > 0.7 or variance inflation factor (VIF) > 5 were excluded to address multicollinearity [25]. The final model included squat depth, movement speed, their interaction, and selected kinematic variables as fixed effects, with participant ID as a random intercept. The contribution of each predictor was calculated as the proportion of its absolute standardized coefficient relative to the total. Model assumptions were verified through residual-versus-fitted value plots and Q–Q plots. In this model, standardized regression coefficients (β) indicate both the direction and magnitude of each predictor's effect, serving as interpretable estimates of effect size [42].

3 Results

3.1 Joint angle

Squat depth had significant main effects on knee joint ROM in all three planes: flexion-extension (p = 0.001, η^2 = 0.726), adduction-abduction (p = 0.001, η^2 = 0.180), and internal-external rotation (p = 0.001, η^2 = 0.225) (Table 1).

Post hoc analysis showed that ROM increased progressively with squat depth in all planes. Specifically, LS > MS > HS in the flexion-extension plane (p < 0.01); in the other two planes, LS was greater than both MS and HS (p < 0.01), with no significant difference between HS and MS.

Table 1. Comparisons of knee joint angles ROM across different squat depths and movement speeds.

Joint angle ROM (°)	Squat Depths	Slow	Fast	Squat Depths		Speed		Squat Depths*Speed	
				p	η^2	p	η^2	p	η^2
flexion-extension	High	53.48±5.49	52.88±5.06	0.001[a]	0.726	0.408	0.009	0.660	0.005
	Medium	57.27±7.31	56.50±6.76						

	Low	69.00±7.50	67.11±9.07						
adduction-abduction	High	21.89±2.91	21.50±4.53	0.001[a]	0.180	0.371	0.004	0.207	0.014
	Medium	22.21±3.79	21.83±4.16						
	Low	23.68±3.13	24.27±3.87						
internal rotation-external rotation	High	29.48±4.23	30.45±3.39	0.001[a]	0.225	0.298	0.005	0.295	0.011
	Medium	31.09±3.08	30.78±2.90						
	Low	33.59±4.07	33.84±3.78						

Note: a denotes a significant main effect of squat depth.

The time-series statistical analysis using SPM further confirmed these findings. In the flexion-extension plane, significant differences were observed during 2–24%, 46–54%, and 60–81% of the normalized movement cycle (Figure 1A). In the adduction-abduction plane, significant differences occurred at 2–5%, 9–12%, and 43–48% of the cycle (Figure 1B). For internal-external rotation, significant differences were found during 50–53% of the cycle (Figure 1C). No significant main effects of movement speed, nor interaction effects between squat depth and movement speed, were observed in any of the three planes throughout the movement cycle ($p > 0.05$).

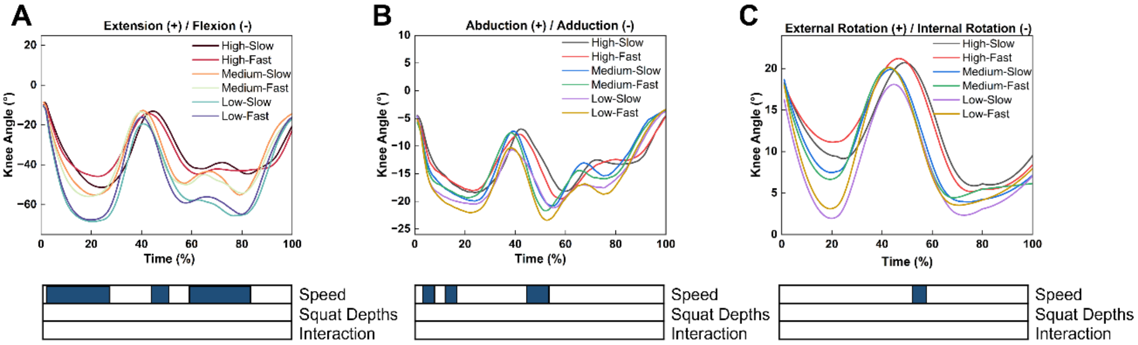

Figure 1 Time-series effects of squat depth and movement speed on knee joint angles in three movement planes: (A) flexion-extension, (B) adduction-abduction, and (C) internal-external rotation.

3.2 Joint velocity

Squat depth had significant main effects on peak angular velocity in all knee joint directions except adduction ($p = 0.817$, $\eta^2 = 0.001$). Movement speed significantly affected flexion, abduction, and internal rotation velocities. No interaction effects between squat depth and speed were observed ($p > 0.05$) (Table 2).

Post hoc analysis revealed that for extension, flexion, external rotation, and internal rotation velocities, LS was significantly higher than MS and HS ($p < 0.01$). For abduction velocity, LS was higher than HS ($p < 0.01$). Movement speed effects showed higher peak velocities at fast versus slow speeds in flexion, abduction, and internal rotation directions ($p < 0.01$).

Table 2. Comparisons of peak knee joint angular velocities across different squat depths and movement speeds.

Peak joint velocity (rad/s)	Squat Depths	Slow	Fast	Squat Depths		Speed		Squat Depths*Speed	
				p	η^2	p	η^2	p	η^2
knee extension	High	77.83±27.40	77.99±19.10						
	Medium	89.02±35.01	87.87±30.90	0.001[a]	0.152	0.051	0.017	0.206	0. 014
	Low	97.58±34.86	109.54±32.982						
knee flexion	High	-52.59±14.12	-53.87±13.04						
	Medium	-52.70±13.46	-59.42±14.07	0.001[a]	0.226	0.001[b]	0.071	0.171	0. 016
	Low	-61.48±10.21	-65.78±9.47						
knee abduction	High	64.97±9.74	70.28±14.99						
	Medium	68.84±18.79	76.22±18.67	0.004[a]	0.047	0.001[b]	0.076	0.261	0.012
	Low	71.99±19.80	84.73±24.62						
knee adduction	High	-61.76±18.10	-62.71±18.33						
	Medium	-62.22±20.83	-60.06±19.19	0.817	0.001	0.764	0.001	0.864	0.001
	Low	-60.00±18.38	-61.17±16.16						
knee external rotation	High	51.08±14.10	49.14±13.73						
	Medium	54.85±19.56	52.25±14.86	0.001[a]	0.065	0.647	0.001	0.329	0.010
	Low	59.80±22.75	65.84±24.38						
knee internal rotation	High	-47.47±17.75	-51. 80±15.72						
	Medium	-47.63±15.00	-52.63±18.10	0.001[a]	0.100	0.004[b]	0.036	0.646	0.004
	Low	-57.27±20.20	-62.41±19.86						

Note: a denotes a significant main effect of squat depth; b denotes a significant main effect of movement speed.

The SPM analysis further confirmed a significant main effect of squat depth on knee abduction-adduction angular velocity during 37–41% of the normalized movement cycle (Figure 2B). No significant main effects of movement speed, nor interaction effects between squat depth and movement speed, were observed in any direction across the time series ($p > 0.05$) (Figure 2A–C).

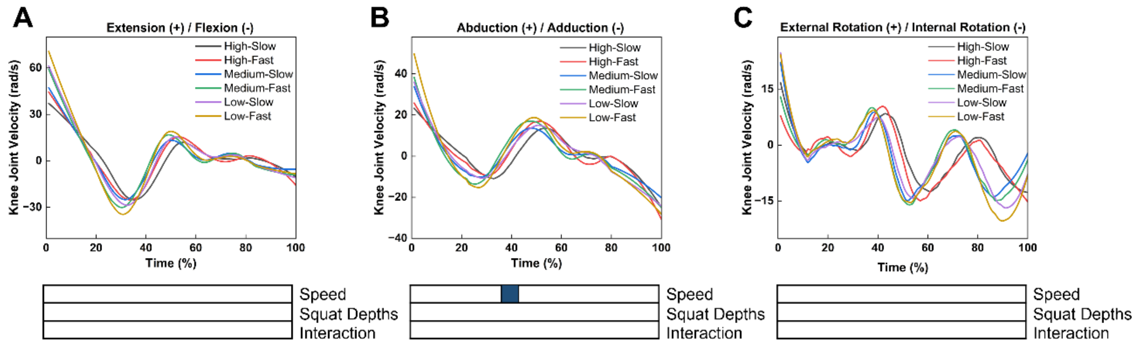

Figure 2 Time-series effects of squat depth and movement speed on knee joint angular velocity in three planes: (A) flexion-extension, (B) adduction-abduction, (C) internal-external rotation.

3.3 Joint moment

Significant main effects of squat depth were found for peak knee extension (p = 0.001, η^2 = 0.195), external rotation (p = 0.001, η^2 = 0.074), and internal rotation moments (p = 0.001, η^2 = 0.412). Movement speed significantly affected knee extension moment (p = 0.004, η^2 = 0.037). Significant interactions between squat depth and speed were observed for knee flexion (p = 0.032, η^2 = 0.030) and adduction moments (p = 0.004, η^2 = 0.047) (Table 3).

Post hoc analysis showed that knee extension and internal rotation moments increased with squat depth (LS > MS > HS, $p < 0.01$), and extension moment was greater at fast speeds ($p < 0.01$). For flexion moment, under HS, fast speed led to higher values than slow speed ($p < 0.05$); under slow speed, LS was higher than HS ($p < 0.05$). For adduction moment, under HS, fast speed was lower than slow speed ($p < 0.01$); under slow speed, LS was greater than HS ($p < 0.05$). External rotation moment was higher in LS than in HS and MS ($p < 0.01$).

Table 3. Comparisons of peak knee joint moments across different squat depths and movement speeds.

Peak joint moment (Nm/kg)	Squat Depths	Slow	Fast	Squat Depths		Speed		Squat Depths*Speed	
				p	η^2	p	η^2	p	η^2
knee	High	1.47±0.23	1.59±0.19	0.001[a]	0.195	0.004[b]	0.037	0.179	0. 022

extension	Medium	1.60±0.25	1.64±0.22						
	Low	1.73±0.27	1.76±0.22						
knee flexion	High	-0.17±0.14	-0.20±0.09						
	Medium	-0.19±0.12	-0.20±0.12	-	-	-	-	0.032[c]	0.030
	Low	-0.31±0.10	-0.31±0.13						
knee abduction	High	0.83±0.22	0.84±0.23						
	Medium	0.79±0.25	0.85±0.25	0.619	0.006	0.539	0.005	0.334	0.014
	Low	0.82±0.23	0.85±0.27						
knee adduction	High	-0.18±0.08	-0.13±0.06						
	Medium	-0.17±0.06	-0.20±0.12	-	-	-	-	0.004[c]	0.047
	Low	-0.21±0.06	-0.26±0.10						
knee	High	0.08±0.03	0.07±0.05						
external	Medium	0.09±0.05	0.09±0.06	0.001[a]	0.074	0.805	0.001	0.216	0.014
rotation	Low	0.14±0.12	0.16±0.11						
knee	High	-0.41±0.15	-0.40±0.10						
internal	Medium	-0.43±0.12	-0.46±0.11	0.001[a]	0.412	0.272	0.005	0.288	0.011
rotation	Low	-0.55±0.10	-0.55±0.11						

Note: a denotes a significant main effect of squat depth; b denotes a significant main effect of movement speed; c denotes a significant interaction between squat depth and movement speed.

The SPM analysis further revealed significant main effects of squat depth on knee joint moments across the entire movement cycle. For the flexion-extension moment, significant differences were observed during 12–18%, 54–57%, and 68–74% of the normalized cycle (Figure 3A). For the adduction-abduction moment, significant differences were identified during 2–6%, 9–12%, and 43–48% of the cycle (Figure 3B). No significant main effects of movement speed, nor interaction effects between squat depth and movement speed, were observed throughout the cycle ($p > 0.05$) (Figure 3A–C).

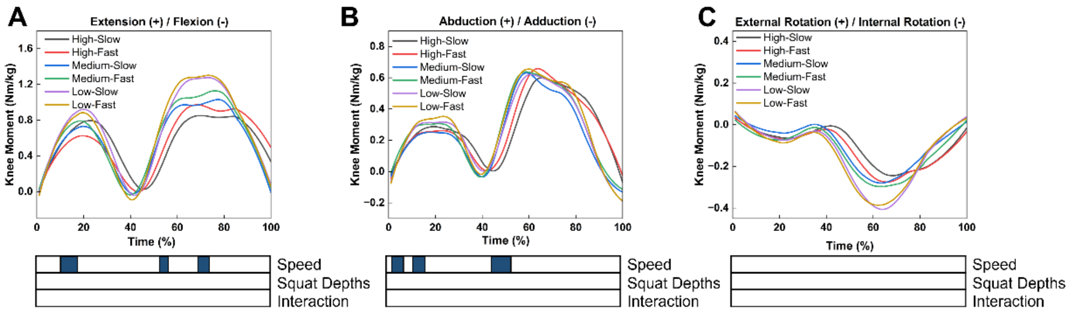

Figure 3 Time-series effects of squat depth and movement speed on knee joint moments in three planes: (A) flexion-extension, (B) adduction-abduction, and (C) internal-external rotation.

3.4 Joint impulse

Squat depth and movement speed had significant main effects on knee joint impulse in the adduction-abduction direction ($p = 0.001$, $\eta^2 = 0.059$ and $\eta^2 = 0.177$, respectively). Significant interaction effects were observed for flexion-extension ($p = 0.015$, $\eta^2 = 0.037$) and internal-external rotation impulses ($p = 0.001$, $\eta^2 = 0.082$) (Table 4).

Post hoc analysis showed that, in flexion-extension, fast speed produced lower impulses than slow speed under LS ($p < 0.05$). In adduction-abduction, impulse at MS was lower than HS and LS ($p < 0.05$), and fast speed was lower than slow speed ($p < 0.01$). In internal-external rotation, slow speed resulted in greater impulses than fast speed across all depths ($p < 0.05$); under slow speed, HS and MS were lower than LS, and under fast speed, MS was lower than LS ($p < 0.05$).

Table 4. Comparisons of knee joint impulse across different squat depths and movement speeds.

Joint impulse (N·m·s/kg)	Squat Depths	Slow	Fast	Squat Depths		Speed		Squat Depths*Speed	
				p	η^2	p	η^2	p	η^2
flexion-extension	High	6.26±1.13	5.15±1.13	-	-	-	-	0.015[c]	0.037
	Medium	6.43±1.35	5.47±1.19						
	Low	7.84±1.34	6.17±1.28						
adduction-abduction	High	3.31±0.94	2.67±0.86	0.001[a]	0.059	0.001[b]	0.177	0.067	0.024
	Medium	2.98±0.93	2.67±0.90						
	Low	3.32±0.96	2.88±0.95						

internal rotation-external rotation	High	1.29±0.37	1.15±0.22	-	-	-	-	0.001^{c}	0.082
	Medium	1.32±0.23	1.21±0.18						
	Low	1.89±0.24	1.54±0.21						

Note: a denotes a significant main effect of squat depth; b denotes a significant main effect of movement speed; c denotes a significant interaction between squat depth and movement speed.

3.5 Correlation Analysis Between Kinematic Variables and Joint Impulses

The correlation matrix revealed several significant relationships between knee joint kinematics and joint impulses (Figure 4). The flexion-extension impulse was negatively correlated with peak flexion angle (r = –0.61, p < 0.01) and peak external rotation angle (r = –0.66, p < 0.01), while showing a positive correlation with peak adduction angular velocity (r = 0.44, p < 0.01). The adduction-abduction impulse was positively associated with peak extension angular velocity (r = 0.37, p < 0.01). For the internal-external rotation impulse, positive correlations were observed with both flexion-extension ROM (r = 0.40, p < 0.01) and internal-external rotation ROM (r = 0.47, p < 0.01).

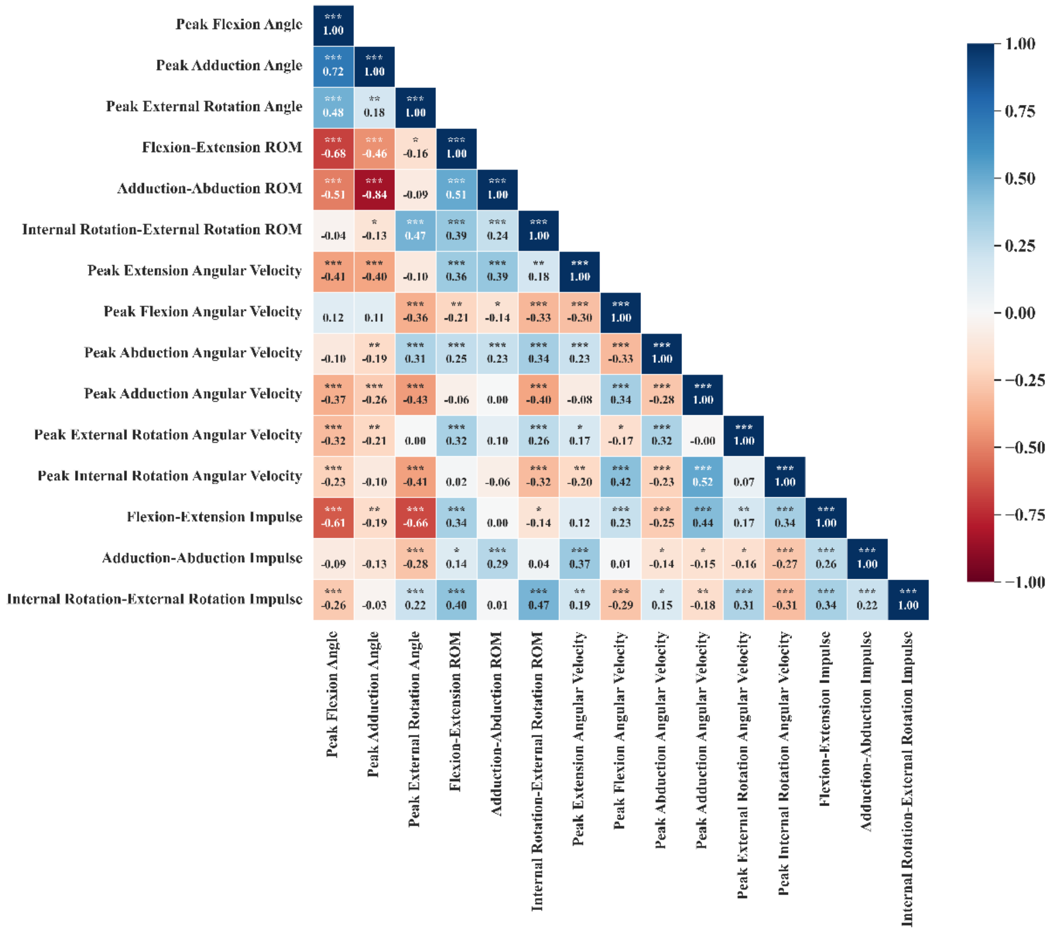

Figure 4 Correlation matrix between knee joint kinematic variables and joint impulses. Blue indicates positive correlation; red indicates negative correlation. $p < 0.05$; $p < 0.01$; $p < 0.001$.

3.6 Fixed effects and relative contributions in the linear mixed-effects model

Among fixed effects, movement speed showed the largest contribution, with fast speed significantly reducing flexion-extension impulse compared to slow speed (β = –1.05, 28.7%, $p < 0.001$). LS was associated with a significant increase in impulse (β = 0.38, 10.4%, $p < 0.05$). The LS × fast speed interaction accounted for 7.9% of the variance but was not significant ($p > 0.05$).

Among kinematic predictors, peak flexion angle had the greatest influence (18.0%) and was significantly associated with higher impulse (β = –0.66, $p < 0.001$), indicating that greater knee flexion contributed to increased loading. This was followed by peak external rotation angle (β = –0.40, 11.1%, $p < 0.001$), internal-external rotation ROM (β = 0.17, 4.7%, $p < 0.01$), and peak adduction angular velocity (β = 0.13, 3.6%, $p < 0.01$). Other predictors contributed less than 3% and were not significant ($p > 0.05$).

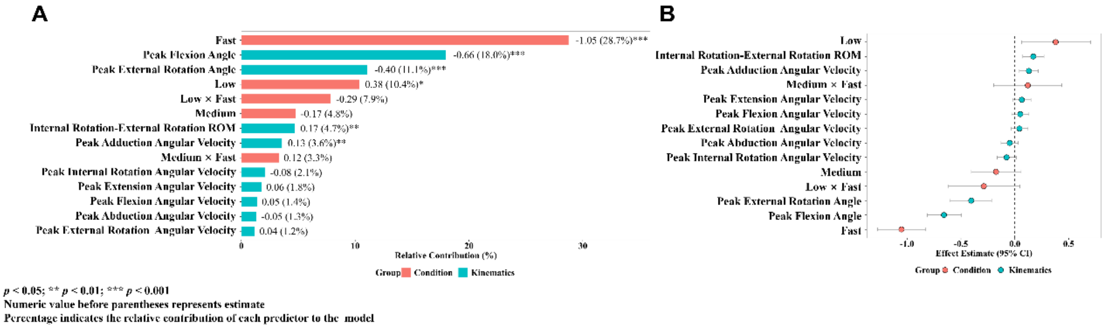

Figure 5 Relative contributions and standardized effect estimate of predictors for knee flexion-extension impulse. (A) Bar lengths represent each predictor's relative contribution, calculated as the proportion of its absolute standardized coefficient. (B) Standardized effect estimates with 95% confidence intervals. Red and blue markers represent condition-related and kinematic predictors, respectively. The dashed line indicates the null effect (β = 0). Squat depth and speed were coded using treatment contrasts, with HS and slow speed as reference levels.

Among fixed effects, fast speed showed the largest contribution (25.7%) and was significantly associated with reduced impulse (β = –0.67, $p < 0.001$). The MS × fast speed interaction (15.1%) and MS alone (12.2%) were also significant, with opposing effects (β = 0.39, $p < 0.05$; β = –0.32, $p < 0.01$, respectively). The LS × fast speed interaction accounted for 10.5% of variance but was not significant ($p > 0.05$).

Among kinematic predictors, peak flexion angle was the strongest contributor and positively associated with impulse (β = 0.21, $p < 0.01$), suggesting that reduced knee flexion was linked to higher loading. Other significant predictors included internal-external rotation ROM (β = 0.11, 4.4%, $p < 0.05$), peak extension angular velocity (β = 0.11, 4.2%, $p < 0.01$), and peak internal rotation angular velocity (β = –0.11, 4.3%, $p < 0.01$). All other predictors contributed less than 3% and were not significant.

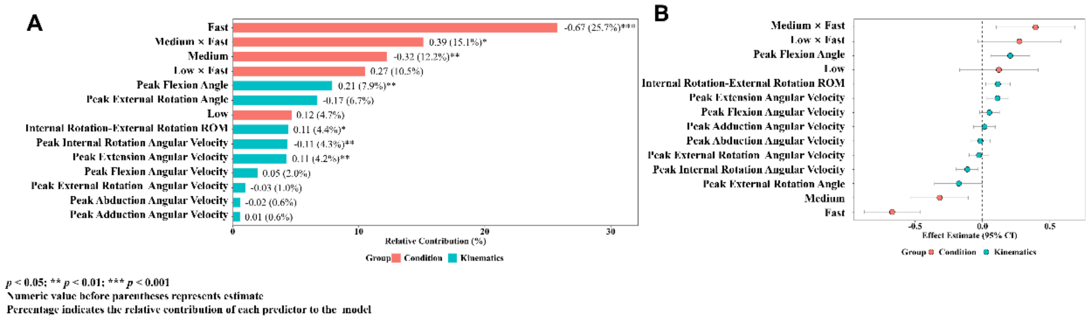

Figure 6 Relative contributions and standardized effect estimate of predictors for knee adduction-abduction impulse. (A) Bar lengths represent each predictor's relative contribution, calculated as the proportion of its absolute standardized coefficient. (B) Standardized effect estimates with 95% confidence intervals. Red and blue markers represent condition-related and kinematic predictors, respectively. The dashed line indicates the null effect (β = 0). Squat depth and speed were coded using treatment contrasts, with HS and slow speed as reference levels.

Among fixed effects, LS showed the largest contribution (23.8%) and was significantly associated with increased impulse (β = 0.29, $p < 0.001$). Fast speed (β = –0.17, 13.9%, $p < 0.001$) and its interaction with LS (β = –0.17, 13.7%, $p < 0.05$) were associated with reduced impulse, indicating that faster movements, particularly under deep squats, attenuate rotational loading. MS and its interaction with speed contributed less than 5.4% and were not significant ($p > 0.05$).

Among kinematic predictors, peak flexion angle (β = –0.14, 11.4%, $p < 0.001$) and peak external rotation angle (β = 0.14, 11.1%, $p < 0.001$) were the strongest contributors, with greater flexion and external rotation linked to increased impulse. Peak internal rotation angular velocity showed a significant negative effect (β = –0.07, 5.8%, $p < 0.001$), while peak external rotation angular velocity (β = 0.04, 3.0%, $p < 0.05$) and internal-external rotation ROM (β = 0.03, 2.5%, $p > 0.05$) had modest effects. Remaining predictors contributed less than 2% and were not significant.

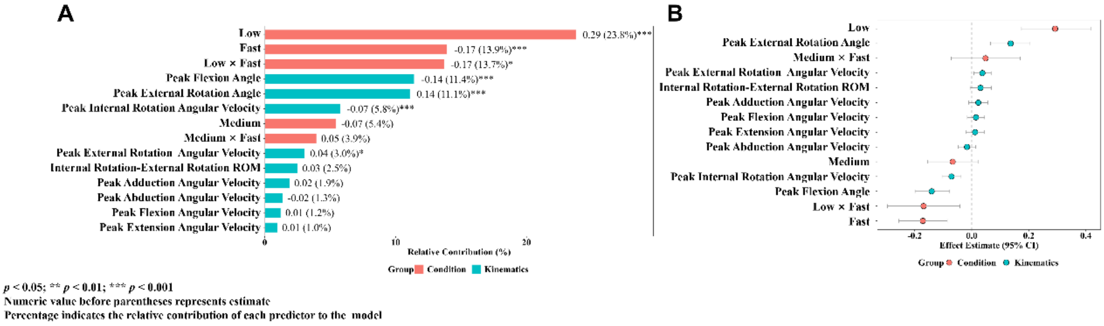

Figure 7 Relative contributions and standardized effect estimate of predictors for knee internal-external rotation impulse. (A) Bar lengths represent each predictor's relative contribution, calculated as the proportion of its absolute standardized coefficient. (B) Standardized effect estimates with 95% confidence intervals. Red and blue markers represent condition-related and kinematic predictors, respectively. The dashed line indicates the null effect (β = 0). Squat depth and speed were coded using

treatment contrasts, with HS and slow speed as reference levels.

4 Discussion

This study aimed to evaluate the biomechanical effects of squat depth and movement speed during the PWHM movement on knee joint loading in Tai Chi novices. The results support the initial hypothesis that both squat depth and movement speed significantly influence knee joint biomechanics. To be specific, increased squat depth was associated with greater knee flexion-extension ROM and higher peak extension moments, while faster movement speeds resulted in greater angular velocities but reduced joint impulses. These findings suggest that squat depth and movement speed independently and interactively modulate cumulative mechanical loading on the knee joint.

Increased squat depth significantly elevated knee joint impulses in both the sagittal and transverse planes. This is likely attributable to the greater knee flexion angles observed in lower postures, which require higher quadriceps-generated extension moments to maintain postural control. The sustained muscular demand under these conditions contributes to increased cumulative mechanical loading. These findings are consistent with those of Liu et al. [22], who noted that Increased squats in Tai Chi impose greater demands on quadriceps strength. Inadequate muscular support under such conditions may lead to joint instability, increased cartilage stress, and an increased risk of injury. Our SPM analysis further revealed that differences in flexion-extension moments across squat depths were concentrated during the single-leg support phase of the PWHM cycle (Figure 3A). This phase is critical for maintaining postural stability, as the supporting leg must bear the body's weight and facilitate the transition of the center of gravity. Increased squats increase the muscular tension required for stabilization, thereby intensifying flexion-extension moment and impulse during this period. These results highlight the importance of monitoring knee loading during the support phase, particularly when performing LS [22].

It is worth mentioned that the adduction-abduction impulse was significantly lower under the MS compared to the HS. This may be explained by improved frontal plane stability at moderate depths. When performing PWHM at HS, the elevated center of gravity and narrower base of support reduce balance control, increasing reliance on the hip abductor and adductor muscles to correct lateral deviations. This results in greater frontal plane joint moments and impulses. MS may offer a biomechanical advantage by sufficiently lowering the center of gravity to enhance stability without requiring excessive muscular compensation. These findings support the notion that a MS can reduce medial-lateral knee loading and may help prevent frontal plane overuse injuries [13]. Moreover, the non-linear increase in adduction–abduction impulse observed at LS may reflect the combined effects of posture-related stability and muscular demand. Although deeper postures lower the center of mass, they also substantially increase knee and hip flexion, which requires greater activation of the hip abductors and adductors to control medio-lateral deviations. Prior studies have shown that deeper squats impose higher stabilization torque and greater frontal-plane hip muscle demand due to altered muscle force–length relationships and increased joint moments [30].

Meanwhile, our study also found that movement speed exerted a distinct effect on knee joint loading. Faster movement speeds resulted in increased angular velocities of flexion, abduction, and internal rotation, as well as higher peak extension moments (Tables 2 and 3). These findings are consistent with previous studies showing that increased movement velocity elevates joint forces, potentially raising the risk of both acute and overuse injuries [2, 6, 8]. However, despite the greater peak moments observed under fast conditions, joint impulses were significantly lower compared to others. This can be attributed to the reduced duration of force application, which limits the total mechanical exposure of the joint. In contrast, slower movements, although associated with lower peak moments, resulted in prolonged muscle activation and increased cumulative loading. Wu et al. [41] also reported that slower Tai Chi movements require extended lower-limb muscle activation, thereby placing greater demands on muscular endurance and neuromuscular control. These findings highlight the importance of considering both instantaneous and cumulative loading when evaluating mechanical stress on the knee joint. Furthermore, the beneficial effect of MS was most pronounced during slow movements. Slow speeds prolong stance duration and impose sustained activation demands on the hip abductors, quadriceps, and trunk stabilizers, which collectively enhance neuromuscular control and allow more precise regulation of the center of mass relative to the base of support [41, 43]. Under MS, this prolonged activation can be used more effectively because MS provides an optimal balance between postural stability and muscular effort.

A significant interaction effect was identified for the knee flexion-extension impulse, indicating that the influence of movement speed was modulated by squat depth (Tables 4). Specifically, during LS condition, the difference in impulse between movement speeds became more pronounced, suggesting that increased squats amplify the effect of speed on joint loading. For Tai Chi novices, this interaction highlights a potential risk, which is, performing LS at inappropriate speeds may lead to abrupt increases in joint stress, thereby elevating the risk of structural damage. Our LMM analysis further supported these findings by demonstrating that movement speed contributed most substantially to variations in both flexion-extension and adduction-abduction impulses, whereas squat depth had the greatest influence on internal-external rotation impulses. Notably, the combination of LS and fast movement resulted in a lower flexion-extension impulse than the HS and slow speed, suggesting that appropriate speed control may mitigate excessive loading under certain conditions. With regard to the adduction-abduction impulse, the two-way ANOVA indicated that the MS yielded the lowest values, with no significant interaction effect. However, the LMM results provided additional insight, revealing that fast speed combined with MS resulted in a relative increase in impulse. This finding implies that the reduction in adduction-abduction impulse observed at MS is contingent upon maintaining a slower tempo, and that this benefit diminishes at faster speeds. Nevertheless, these interaction effects should be interpreted with caution. Although the statistical design was powered based on prior effect sizes, the relatively small sample size of 13 participants may have limited the ability to detect subtle interaction effects between squat depth and movement speed. Several interaction terms in the two-way ANOVA failed to reach statistical significance, which may reflect limited statistical power rather than a true absence of interaction effects. Therefore, future studies with larger sample sizes are warranted to validate the interaction patterns observed in the present study.

Collectively, our findings underscore the importance of considering both squat depth and movement speed when prescribing Tai Chi exercises, particularly for novices or individuals at increased risk of knee injury. The combination of MS and slow movement speed appears to provide the most favorable loading profile, especially in the frontal plane. This condition was associated with the lowest adduction-abduction impulse, which may reduce medial-lateral joint stress and enhance postural stability during practice.

This study has several limitations. First, although the sample met the a priori sample-size requirement, the relatively small number of participants may have reduced the statistical power to detect interaction effects, thereby increasing the risk of Type II errors. Second, the participant sample consisted exclusively of young male novices, which limits the generalizability of the findings to other age groups and experience levels. Future research should include participants of varying ages, genders, and levels of Tai Chi proficiency, particularly middle-aged and older adults who are more likely to engage in Tai Chi for physical health. Third, the present study focused solely on external biomechanical parameters, without direct assessment of internal joint loading or neuromuscular activity. The absence of electromyographic (EMG) data precludes analysis of muscle co-contraction patterns, and cartilage contact forces were not measured. Future studies should incorporate EMG and advanced computational approaches, such as finite element modeling, to provide a more comprehensive understanding of internal joint loading mechanisms [4, 35].

5 Conclusions

This study demonstrates that both squat depth and movement speed significantly affect knee joint loading during PWHM in Tai Chi. Increased squat depth and slower speeds increased cumulative loading, particularly in flexion-extension and rotational planes. Importantly, the combination of moderate squat depth and slow movement reduced frontal-plane impulse and peak adduction-abduction moments, suggesting a safer strategy to minimize medial-lateral knee loading. These findings support the use of moderate-depth, slow movements for joint protection in Tai Chi novices.

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