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Article

Biomechanical characteristics of lower limbs in Tai Chi Novices with different squatting depths: A pilot study

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Abstract: This study aimed to analyze the biomechanical characteristics of the lower limbs in Tai Chi novices performing the Part the Wild Horse's Mane (PWHM) movement at varying squatting depths to identify potential risk factors for joint pain and injuries. Eight Tai Chi novices, with an average age of 20.75 years participated in this study. Joint angles, joint moments, ground reaction forces (GRF), center of gravity (COG), and muscle force were measured during PWHM at various squat depths. Data were analyzed using the one-way ANOVA in Open-Source Statistical Parameter Mapping in MATLAB, with corrected post-hoc tests using the Bonferroni correction. Different squat depths resulted in differences in joint angles, joint moments, joint range of motion (ROM), COG, and muscle force ($p < 0.05$); however, no difference was observed in the joint stiffness or GRF. In comparison with a high squat depth, both low and medium squat depths exhibited greater peak knee and hip flexion angles, while the low squat depth also demonstrated a larger ROM in ankle inversion–extension, knee flexion-extension, hip flexion-extension, and hip adduction-abduction ($p < 0.05$). Compared with a low squat depth, a high squat depth resulted in smaller peak ankle inversion, ankle internal rotation, knee external rotation, hip extension, hip adduction moment, and smaller muscle force in the semitendinosus, rectus femoris, rectus femoris, medial gastrocnemius, and tibialis anterior muscles ($p < 0.05$). Different squat depths led to differences in lower limb biomechanics among Tai Chi novices. A low squat depth can bring more health benefits to Tai Chi novices; however, the higher demand for muscle strength may increase the load on the joints, causing joint pain or even injury.

Keywords: Tai Chi; muscle forces; biomechanics; joint angle; joint stiffness

1. Introduction

Tai Chi is a vital component of traditional Chinese health exercises involving the synchronization of breathing, body movement, and awareness during practice, thus playing a role in dredging meridians and collaterals, promoting blood circulation, and enhancing physical fitness [1]. Long-term Tai Chi practice has been shown to increase lower limb muscle strength and mobility [2], improve dynamic stability, reduce the risk of falls, and improve proprioception of the knee and ankle joints [3,4]. According to previous studies, Tai Chi can benefit patients with knee osteoarthritis by enhancing their mobility, thus alleviating their symptoms [5,6]. Therefore, Tai Chi has been recommended by the American College of Rheumatology as a therapeutic option for individuals with knee osteoarthritis [7]. However, with the increase in the number of Tai Chi practitioners, some have reported lower limb joint pain or even injuries, with knee joint injuries being more significant, particularly in novices [8,9]. In Tai Chi practice, incorrect techniques significantly contribute to the incidence of injuries among novices. Previous studies have found that Tai Chi novices have a greater hip abduction angle than professionals and that the knee may experience increased stress in the frontal plane, potentially contributing to joint discomfort or the risk of injury [10].

There are many styles of Tai Chi, with each category having between 10 and 108 forms, and the practice time also varies [11]. Excessive squat depth in Tai Chi practice is a significant factor for the induction of joint pain. Low squat depth and prolonged weight bearing in a flexed knee position may augment the load on the knee joints, potentially leading to articular discomfort [12,13]. Tai Chi is characterized by numerous bending and twisting motions in the knee, and researchers have theorized that novices in this practice might engage in improper movements and squat too low, thus triggering knee patella damage, meniscus strain, outward movement of the patella, collateral ligament injuries, and various other symptoms [14,15]. Currently, most pertinent research on lower limb biomechanics in Tai Chi has focused on theoretical and biomechanical analyses of classical Tai Chi movements. Few relevant studies have been conducted on how the lower limb biomechanics of novices are affected by varying squatting depths in Tai Chi [15,16].

The Part the Wild Horse's Mane (PWHM) is a typical movement in Tai Chi that consists of two parts: the lunge and the body center of gravity (COG) transfer phase. The lunge accounts for nearly half of all Tai Chi lower limb movements, and continuous weight shifting is essential in Tai Chi practice and is seamlessly integrated throughout the form [12]. In addition, compared to other Tai Chi movements, PWHM involves a larger shift in the body's COG from the previous position, which places higher demands on muscle strength and is more likely to lead to joint injuries [12]. A study by Liu et al. indicated that patellofemoral joint stress and quadriceps tendon force are significantly higher in professional Tai Chi practitioners adopting a low squatting depth than in those adopting a high squatting depth [17]. Currently, there is a dearth of research examining the biomechanical differences in the lower limbs of Tai Chi novices performing PWHM at varying squatting depths.

Therefore, the objective of this study was to investigate the biomechanical differences in the lower limbs of Tai Chi novices performing PWHM at different squatting depths. We hypothesized that, compared to a higher squatting depth, a lower squatting depth would exhibit greater joint angles, joint moments, joint range of motion (ROM), and ground reaction forces (GRFs), in addition to requiring greater muscle strength.

2. Research design and methodology

2.1. Participants

A total of eight participants were included (age 20.75 ± 1.83 years, height 1.69 ± 0.07 m, and body mass 63.86 ± 11.1 kg). The inclusion criteria were individuals aged 18–25 years, engaging in Tai Chi for up to 6 months with a maximum of 2 weekly sessions, free of lower limb injuries in the past 6 months, and devoid of lower limb joint ailments. The exclusion criteria included noticeable structural abnormalities, such as flat feet and high arches.

The study was approved by the Ethics Committee of Ningbo University, and all participants provided informed consent before the commencement of the study.

2.2. Experimental equipment

Experiments were performed at the Sports Biomechanics Laboratory of Ningbo University. To gather lower-limb biomechanical data, we attached 38 reflective markers, each with a diameter of 14 mm, to the participants' lower extremities. Markers were placed based on the specifications of the OpenSim Gait 2392 model. The specific anatomical locations for marker placement are shown in **Figure 1**, as described in previous studies [18,19]. A Vicon motion analysis system (Oxford Metrics Ltd., Oxford, UK) was used to capture the three-dimensional trajectory coordinates of the markers. The system consisted of eight high-definition cameras and records at a sampling frequency of 200 Hz. Additionally, GRF parameters were collected using three-dimensional force plates (AMTI, Watertown, Massachusetts, USA) at a data acquisition rate of 1000 Hz [20].

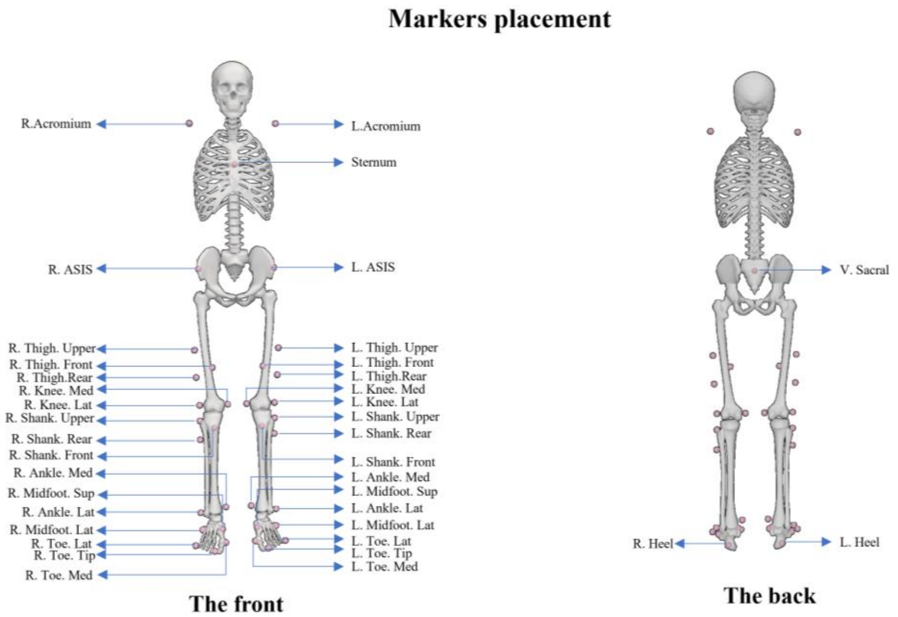

Figure 1. Placement of the reflective markers.

2.3. Experimental procedures

First, the participants completed a 10-min warm-up session, including 6 minutes of 24-form simplified tai chi movements and 4 minutes of static stretching, and became acquainted with the testing setup and procedures. We then obtained precise measurements of the participants' heights, based on which we calculated their eye-level heights at three different squat depths: high, medium, and low. Previous research indicated that the low squat depth was 0.81 times the height, the medium squat depth was 0.89 times the height, and the high squat depth was 0.97 times the height [21]. After fixing reflective markers to the participants' lower limbs, pelvis, and trunk, they were asked to stand in an anatomical position on a force platform for static data collection. Finally, the participants executed the PWHM Tai Chi movement based on the verified squat depths and instructions. Throughout the test, the participants were instructed to place their left and right feet on separate force platforms and the horizontal visual height was set to ensure that their squat depths were based on the requirements. Dynamic data were collected when the GRF on the first force plate exceeded 10 N [22]. Three successful tests were performed separately for each squat depth. Given that the PWHM was symmetrical on the right and left sides, we analyzed the data for the left leg only [23].

2.4. Data processing

Kinematic and kinetic data were collected using Vicon Nexus 1.8.5 (Vicon, Metrics Ltd., Oxford, UK), and the resultant data were exported in the form of C3D files. In this study, the OpenSim Gait 2392 model, which is characterized by 23 degrees of freedom and 92 musculotendon actuators, was employed [24]. This model has been validated for its exceptional fidelity in replicating the musculature of the lower limbs [25]. First, we scaled the model according to the height and weight of the participants so that the data from the test matched those of each participant. Subsequent analytical procedures involved calculating the inverse kinematics and dynamics using the OpenSim software [26,27]. Data filtration was performed using a low-pass Butterworth filter with designated cutoff frequencies of 10 Hz for kinematic data and 20 Hz for kinetic data [28]. The joint moments were normalized based on the participant's body mass. OpenSim software (version OpenSim 4.4, NCSRR, Stanford, CA, USA) was used to perform musculoskeletal modelling and extract the muscle forces. The kinematic and kinetic data obtained from the study were exported and analyzed for joint stiffness. The joint stiffness investigation focused on variations in the sagittal plane across various squat depths. Joint stiffness is delineated as the alteration in joint moment (ΔM) divided by the alteration in joint angle ($\Delta \theta$), expressed by the equation [29,30]:

$$\mathrm{K} = \Delta M / \Delta \theta \quad (1)$$

2.5. Statistical analysis

Kinematic and dynamic data were processed using MATLAB R2022a (MathWorks, MA, USA). A custom MATLAB script was used to generate time-series curves from the raw data, each consisting of 101 evenly spaced data points. The data were analyzed using a one-way ANOVA in open-source Statistical Parametric Mapping (SPM) software, and post-hoc tests were corrected using the Bonferroni correction [31,32]. The level of statistical significance was set at $p < 0.05$.

3. Result

3.1. Joint angles

For the ankle angle, the results showed that a low squat depth had a greater peak eversion angle than a high squat depth (**Table 1**). The results of the SPM analysis showed no significant difference between the ankle angles for different squat depths (**Figure 2**).

For the knee angle, the results showed that low and medium squat depths had a greater peak flexion angle than a high squat depth (**Table 1**). The results of the SPM analysis showed that low and medium squat depths exhibited smaller knee flexion angles during 11%–20% and 10%–17% of the stance phase, respectively, compared to high squat depths (**Figure 2**).

For the hip angle, the results showed that the low squat depth had a greater peak flexion angle than the medium and high squat depths; furthermore, the low squat depth had a greater peak adduction angle than the high squat depth (**Table 1**). The results of the SPM analysis showed that the low squat depth had greater flexion angles at 4%–12%, 14%–25%, and 45%–57% of the stance phase than the high squat depth, and the medium squat depth had greater flexion angles at 2%–4% and 21%–33% of the stance phase than the high squat depth (**Figure 2**).

For the joint ROM, the results showed that, compared to high squat depth, low squat depth had greater ankle inversion-eversion, knee flexion-extension, hip flexion-extension, and hip adduction-abduction ROM (**Table 2**). Furthermore, the medium squat depth group had a greater knee flexion-extension ROM than the high squat depth group (**Figure 3**).

Table 1. Comparison of peak joint angles at different squat depths (mean ± SD).

Peak value (°)	**Low**	**Medium**	**High**	**F**	***p***
Ankle Dorsiflexion	36.55 ± 4.63	34.75 ± 5.09	34.87 ± 4.61	1.068	0.349
Ankle Plantarflexion	−20.46 ± 7.13	−19.88 ± 8.16	−19.06 ± 6.47	0.223	0.801
Ankle Inversion	18.13 ± 3.31	18.67 ± 3.52	19.04 ± 4.51	0.344	0.710
Ankle Eversion	−24.12 ± 6.18[c]	−20.81 ± 3.88	−18.56 ± 4.66[a]	7.530	0.001*
Ankle Internal Rotation	12.10 ± 6.96	13.07 ± 8.16	12.87 ± 7.25	0.112	0.895
Ankle External Rotation	−9.00 ± 4.47	−6.72 ± 5.19	−6.85 ± 3.41	2.016	0.141
Knee Flexion	−74.90 ± 12.76[c]	−71.26 ± 10.66[c]	−62.20 ± 7.80[a, b]	9.141	0.000*
Knee Adduction	4.25 ± 2.84	4.28 ± 2.02	4.16 ± 3.08	0.013	0.987
Knee Abduction	−12.57 ± 6.23	−13.02 ± 6.04	−10.33 ± 5.16	1.459	0.239
Knee Internal Rotation	19.34 ± 7.82	21.66 ± 10.49	18.58 ± 7.18	0.831	0.440
Knee External Rotation	−7.80 ± 5.92	−9.10 ± 5.80	−6.75 ± 5.89	0.961	0.387
Hip Flexion	60.16 ± 10.40[b, c]	53.45 ± 6.80[a]	48.79 ± 9.79[a]	9.401	0.000*
Hip Extension	−11.69 ± 9.45	−11.42 ± 8.45	−13.01 ± 5.94	0.265	0.768
Hip Adduction	27.25 ± 10.24[c]	26.39 ± 8.94	20.31 ± 7.16[a]	4.374	0.016*
Hip Abduction	−10.07 ± 6.53	−7.98 ± 5.94	−8.25 ± 4.67	0.935	0.397
Hip Internal Rotation	31.70 ± 10.41	28.60 ± 9.99	32.31 ± 9.49	0.957	0.389
Hip External Rotation	−10.43 ± 8.57	−10.81 ± 8.76	−6.07 ± 7.94	2.335	0.104

* Significant differences among the three squat depths; a, significant difference compared to the low squat depth; b, significant difference compared to the medium squat depth; c, significant difference compared to the high squat depth.

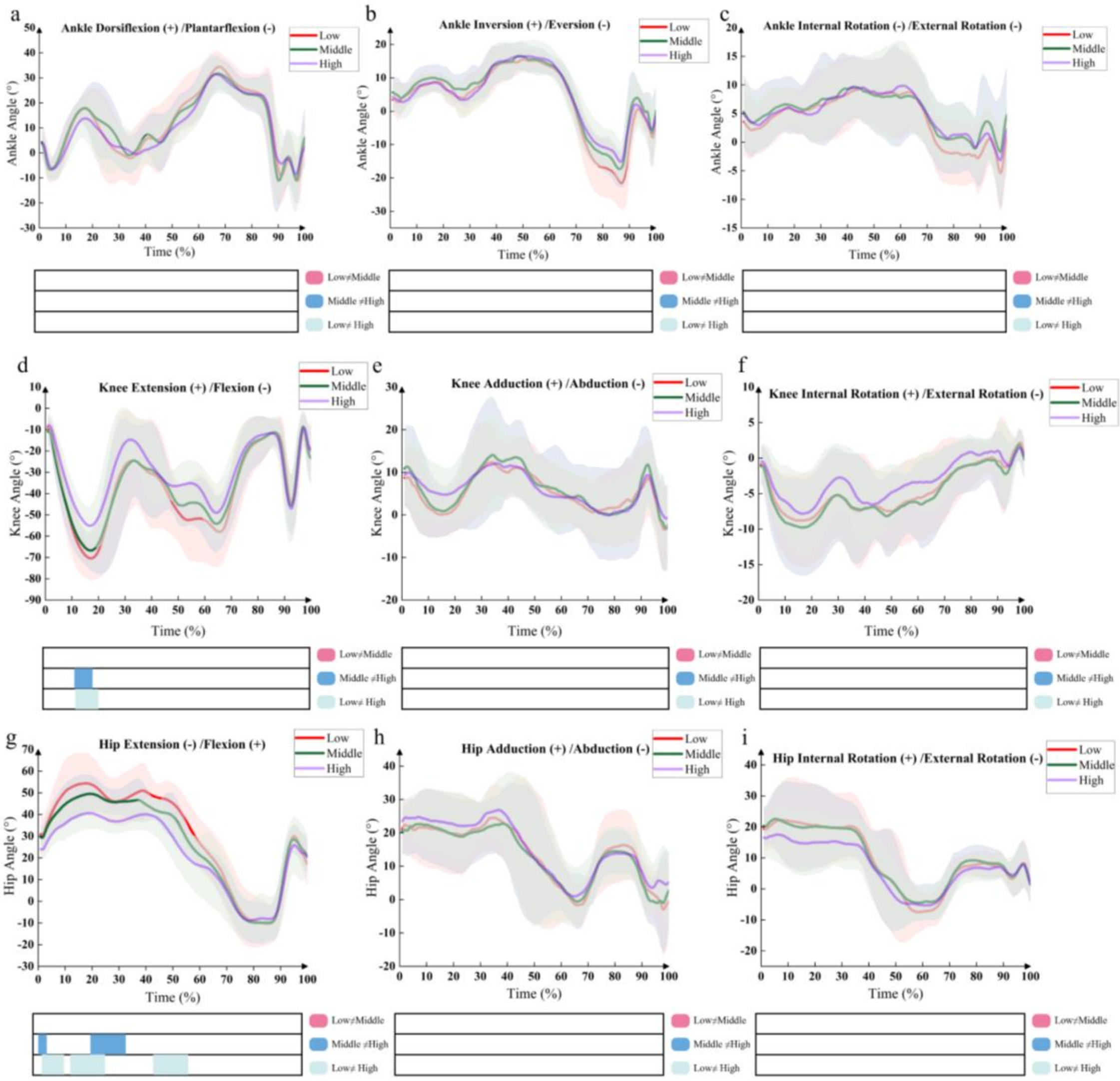

Figure 2. Comparison of joint angles for different squat depths.

Table 2. Comparison of joint angles ROM at different squat depths (mean ± SD).

Range of motion (°)	**Low**	**Medium**	**High**	**F**	***p***
Ankle Dorsiflexion-Plantarflexion	57.01 ± 9.80	54.63 ± 10.33	53.92 ± 9.02	0.663	0.519
Ankle Inversion-Eversion	42.25 ± 7.79[c]	39.48 ± 5.23	37.59 ± 4.83[a]	3.547	0.034*
Ankle Internal Rotation- External Rotation	21.10 ± 6.61	19.78 ± 6.12	19.71 ± 6.38	0.360	0.699
Knee Flexion-Extension	70.84 ± 13.34[c]	67.30 ± 8.23[c]	58.76 ± 8.74[a, b]	8.624	0.000*
Knee Adduction-Abduction	16.82 ± 4.40	17.29 ± 4.89	14.49 ± 3.14	3.043	0.054
Knee Internal Rotation- External Rotation	27.14 ± 7.80	30.76 ± 10.04	25.33 ± 5.87	2.800	0.068
Hip Flexion-Extension	71.85 ± 13.78[c]	64.87 ± 8.88	61.80 ± 9.42[a]	5.348	0.007*
Hip Adduction-Abduction	37.32 ± 11.05[c]	34.37 ± 7.76	28.55 ± 7.83[a]	5.886	0.004*
Hip Internal Rotation- External Rotation	42.13 ± 8.37	39.41 ± 7.08	38.39 ± 5.79	1.751	0.181

* Significant differences among the three squat depths; a, significant difference compared to the low squat depth; b, significant difference compared to the medium squat depth; c, significant difference compared to the high squat depth.

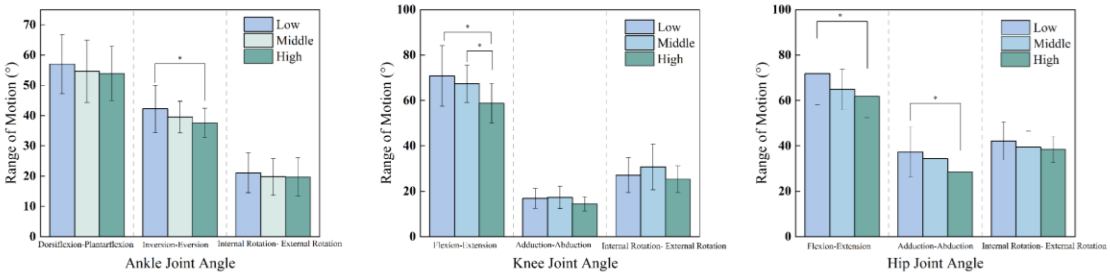

Figure 3. Comparison of joint range of motion for different squat depth.

3.2. Joint moment

For ankle moments, the results showed that low squat depths had greater peak inversion and internal rotation moments than high squat depths (**Table 3**). The results of the SPM analysis showed that the ankle inversion moment was greater at the low squat depth than at the medium squat depth during 53%–55% of the stance phase. Compared to the high squat depth, the ankle internal rotation moment was greater at the low squat depth during 16%–20% of the stance phase (**Figure 4**).

For knee moments, the results showed that the medium squat depth had greater peak extension and internal rotation moments than the high squat depth. The low squat depth group had a greater external rotation moment than the high squat depth group (**Table 3**). The results of the SPM analysis showed a greater knee external rotation moment during 50%–51% of the stance phase for the medium squat depth and 49%–55% of the stance phase for the low squat depth compared to the high squat depth (**Figure 4**).

For hip moments, the results showed that, compared with the high squat depth, the medium squat depth had a greater peak hip extension moment. Compared with the high squat depth, the low squat depth had greater peak hip extension and abduction moments (**Table 3**). The results of the SPM analysis showed no significant differences between the hip moments at different squat depths (**Figure 4**).

Table 3. Comparison of peak joint moments at different squat depths (mean ± SD).

Peak Joint Moment (Nm/kg)	**Low**	**Medium**	**High**	**F**	***p***
Ankle dorsiflexion	0.04 ± 0.02	0.04 ± 0.02	0.05 ± 0.03	0.478	0.622
Ankle plantarflexion	−1.30 ± 0.18	−1.30 ± 0.30	−1.34 ± 0.25	0.227	0.797
Ankle inversion	0.28 ± 0.07 [b, c]	0.20 ± 0.09 [a]	0.20 ± 0.10 [a]	6.429	0.003*
Ankle eversion	−0.11 ± 0.09	−0.19 ± 0.15	−0.18 ± 0.13	2.366	0.101
Ankle internal rotation	0.30 ± 0.09 [c]	0.26 ± 0.09	0.24 ± 0.08 [a]	3.432	0.038*
Ankle external rotation	−0.04 ± 0.02	−0.05 ± 0.03	−0.04 ± 0.03	0.486	0.617
Knee flexion	1.42 ± 0.30	1.45 ± 0.33	1.32 ± 0.23	1.297	0.280
Knee extension	−0.22 ± 0.07	−0.28 ± 0.13 [c]	−0.20 ± 0.05 [b]	4.567	0.014*
Knee adduction	0.83 ± 0.16	0.80 ± 0.19	0.73 ± 0.16	2.172	0.122
Knee abduction	−0.14 ± 0.06	−0.17 ± 0.06	−0.14 ± 0.05	2.306	0.107
Knee internal rotation	0.04 ± 0.02	0.05 ± 0.03 [c]	0.03 ± 0.02 [b]	3.717	0.029*
Knee external rotation	−0.56 ± 0.16 [c]	−0.49 ± 0.10	−0.41 ± 0.08 [a]	10.146	0.000*
Hip flexion	0.52 ± 0.18	0.51 ± 0.17	0.58 ± 0.19	1.127	0.330

Table 3. (*Continued*).

Peak Joint Moment (Nm/kg)	Low	Medium	High	F	*p*
Hip extension	−1.11 ± 0.17 [c]	−1.12 ± 0.20 [c]	−0.97 ± 0.17 [a, b]	5.038	0.009*
Hip adduction	1.36 ± 0.17 [c]	1.28 ± 0.12	1.21 ± 0.16 [a]	6.304	0.003*
Hip abduction	−0.33 ± 0.15	−0.39 ± 0.20	−0.28 ± 0.13	2.935	0.060
Hip internal rotation	0.65 ± 0.17	0.62 ± 0.15	0.55 ± 0.17	2.533	0.087
Hip external rotation	−0.20 ± 0.08	−0.23 ± 0.11	−0.20 ± 0.07	1.418	0.249

* Significant differences among the three squat depths; a, significant difference compared to the low squat depth; b, significant difference compared to the medium squat depth; c, significant difference compared to the high squat depth.

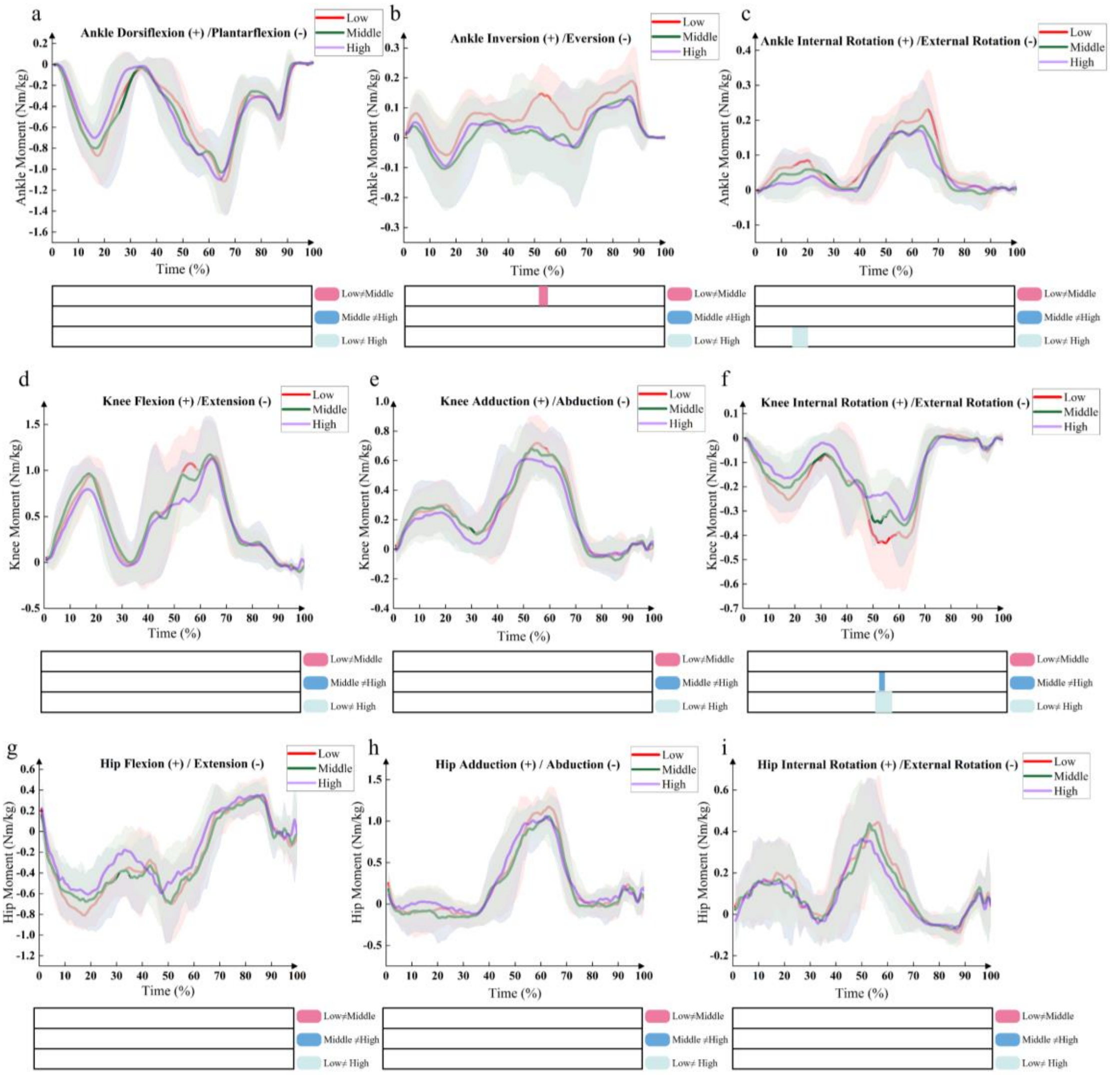

Figure 4. Comparison of joint moments for different squat depths.

3.3. Joint stiffness

Regarding joint stiffness, the results showed no significant differences between the different squat depths in the sagittal plane (**Table 4**, **Figure 5**).

Table 4. Comparison of joint stiffness at different squat depths (mean ± SD).

Joint Stiffness (Nm/°)	Low	Medium	High	F	*p*
Ankle Joint Stiffness	0.024 ± 0.006	0.026 ± 0.008	0.026 ± 0.007	0.537	0.587
Knee Joint Stiffness	0.024 ± 0.005	0.026 ± 0.007	0.026 ± 0.006	1.262	0.290
Hip Joint Stiffness	0.023 ± 0.006	0.005 ± 0.001	0.005 ± 0.001	1.284	0.283

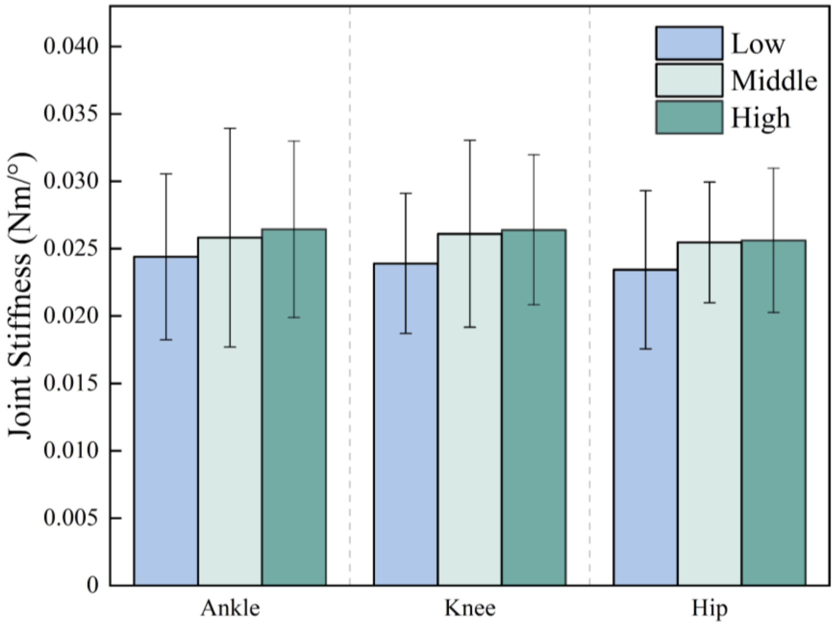

Figure 5. Comparison of joint stiffness for different squat depths.

3.4. GRF

The results showed no differences in GRFs among the different squat depths (**Table 5**, **Figure 6**).

Table 5. Comparison of peak GRFs at different squat depths (mean ± SD).

GRF (BW)		Low	Medium	High	F	*p*
Medial-lateral	Max	0.02 ± 0.01	0.01 ± 0.01	0.02 ± 0.01	1.491	0.232
	Min	−0.06 ± 0.01	−0.06 ± 0.02	−0.06 ± 0.02	0.232	0.794
Anterior-posterior	Max	0.18 ± 0.04	0.17 ± 0.03	0.16 ± 0.02	2.112	0.129
	Min	−0.20 ± 0.05	−0.18 ± 0.04	−0.19 ± 0.05	0.273	0.762
Vertical	Max	1.06 ± 0.03	1.07 ± 0.04	1.06 ± 0.03	0.309	0.736
	Min	0.09 ± 0.05	0.08 ± 0.04	0.08 ± 0.04	0.391	0.678

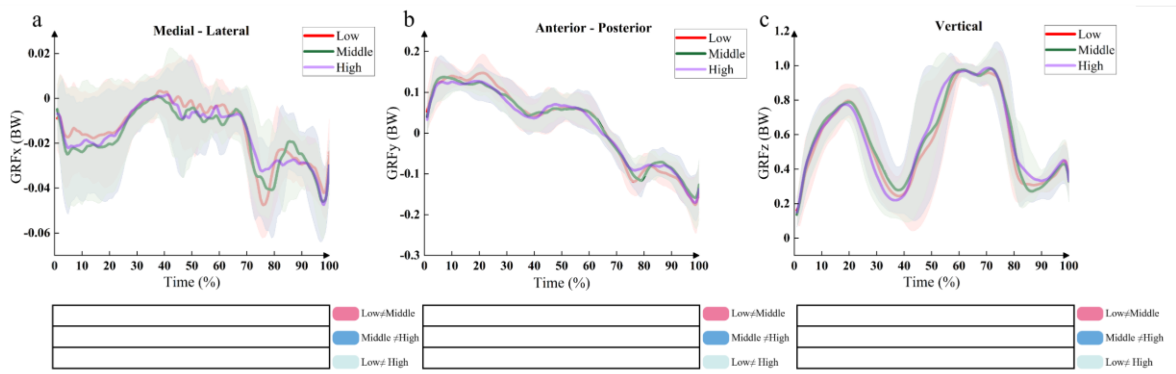

Figure 6. Comparison of GRFs for different squat depths.

3.5. COG

The results showed that a low squat depth had a smaller peak minimum COG on the vertical axis than a high squat depth (**Table 6**). The SPM analysis results indicated no significant difference in the COG on the vertical axis for various squat depths (**Figure 7**).

Table 6. Comparison of peak COG at different squat depths (mean ± SD).

COG (M)		Low	Medium	High	F	*p*
	Max	0.82 ± 0.07	0.86 ± 0.07	0.86 ± 0.05	2.570	0.084
Z-Axis	Min	0.69 ± 0.06 [c]	0.72 ± 0.05	0.75 ± 0.05 [a]	6.152	**0.003***
	ROM	0.13 ± 0.04	0.13 ± 0.06	0.12 ± 0.03	1.113	0.334

* Significant differences among the three squat depths; a, significant difference compared to the low squat depth; c, significant difference compared to the high squat depth.

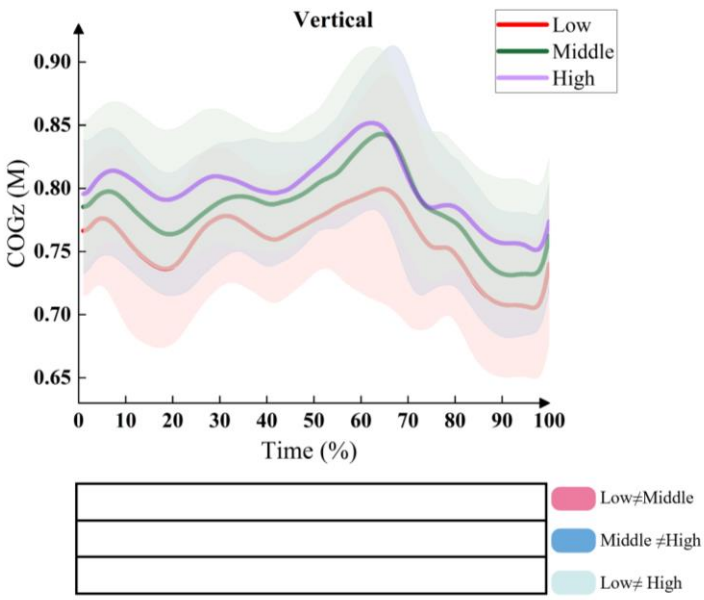

Figure 7. Comparison of the COG for different squat depths.

3.6. Muscle force

The results showed greater peak muscle force in the tibialis anterior for the medium squat depth compared to the high squat depth, while the low squat depth in the semitendinosus, biceps femoris, rectus femoris, medial gastrocnemius, and tibialis anterior had greater peak muscle force than the high squat depth (**Table 7**).

Table 7. Comparison of peak Muscle force at different squat depths (mean ± SD).

Peak muscle force (BW)	**Low**	**Medium**	**High**	**F**	***p***
Semitendinosus	0.74 ± 0.35[c]	0.58 ± 0.20	0.54 ± 0.20[a]	3.891	0.025*
Biceps femoris	4.77 ± 5.00[c]	2.67 ± 3.78	1.18 ± 1.20[a]	5.743	0.005*
Rectus femoris	13.78 ± 5.78[c]	11. 5 ± 3.77	8.77 ± 2.67[a]	8.269	0.001*
Vastus medialis	0.81 ± 1.48	0.39 ± 0.19	0.5 ± 0.50	1.394	0.255
Vastus lateralis	1.23 ± 2.93	0.6 ± 0.29	0.66 ± 0.59	1.035	0.361
Medial gastrocnemius	10.7 ± 6.17[c]	7.81 ± 3.90	4.93 ± 2.57[a]	9.993	0.000*
Lateral gastrocnemius	1.69 ± 2.49	1.27 ± 1.24	0.72 ± 0.31	2.151	0.124
Tibialis anterior	8.5 ± 2.76[c]	7.12 ± 2.40[c]	5.28 ± 2.13[a,b]	10.533	0.000*

* Significant differences among the three squat depths; a, significant difference compared to the low squat depth; b, significant difference compared to the medium squat depth; c, significant difference compared to the high squat depth.

4. Discussion

The main objective of this study was to investigate biomechanical differences in the lower limbs of Tai Chi novices at different squat depths. Consistent with our hypothesis, we found differences in joint angles, joint moments, joint ROM, and muscle force between different squat depths, which were mainly observed between low and high squat depths. In addition, we found no significant differences in the GRF among the three different squat depths.

An appropriate joint ROM can enhance body posture control by improving stability and coordination [33]. Previous studies have demonstrated that the depth of the Tai Chi squat is significantly associated with the peak knee flexion angle, which is consistent with the findings of this study [13]. Our study found that, compared to a high squat depth, a low squat depth had a greater joint ROM in the coronal plane at the ankle and hip and a greater joint ROM in the sagittal plane at the knee and hip. In addition, we found that the knee flexion angle was not greater in the low squat depth group than in the high squat depth group during the entire PWHM phase. This suggests that the body COG of Tai Chi novices is not always maintained within an optimal range for stability during low squatting practices. Fluctuating squatting depth could elevate knee joint stress, potentially causing injuries. Exceeding a certain flexion angle increases the knee rotation range, increasing the risk of contact stress between the tibial and femoral components, and thus increasing the risk of medial meniscus injuries [13,34,35].

Variations in squat depth affect the ROM of the lower limb joints, consequently influencing joint loading [13]. Our research discovered that low and medium squat depths resulted in higher peak knee extension, internal rotation, and external rotation moments than a high squat depth, which is consistent with prior studies. However, compared to previous studies, the knee adduction moment in this study did not change significantly between the different squat heights [13]. Compared with the Tai Chi professionals in the previous study, the participants in the present study were Tai Chi novices; therefore, we speculate that the standardization of the participants' Tai Chi movements may be the main reason for this difference [13]. A moderate increase in joint loading during exercise can provide beneficial stimulation to joints by enhancing joint stability and promoting cartilage nutrition. However, sustained exposure to high-intensity loading may lead to joint damage through mechanisms such as cartilage degradation or ligament strain [36]. The study found that an increase in the peak knee extension and adduction moment was associated with increased loading of the medial compartment of the knee, and that excessive peak knee internal rotation and external rotation moments led to patellar ligament injury [37,38]. Therefore, moderate contact stress can provide greater benefits to joint health, whereas prolonged excessive loading may lead to joint damage.

The GRF reflects the forces produced by the lower limbs on the ground during exercise and is directly related to lower limb joint injuries [39,40]. In this study, we did not find any differences in the GRF of novices in Tai Chi at different squat depths. A high GRF leads to high loads on the lower limb joints. Zhu et al. found that the GRF of Tai Chi was significantly smaller than that of walking [41]. Tai Chi emphasizes gentle and slow movements during practice, maintaining consistency in shifting the COG, resulting in a lower GRF compared to walking. Wang et al. concluded that Tai Chi exhibits a greater GRF at low squat depths than at high squat depths; however, while the participants in that study were professional athletes, those in the current study were novices in Tai Chi. The difference in skill level was likely a significant factor contributing to the variation in the GRF observed in the two studies [13]. Matijevich et al. suggested that an increase in the GRF may be related to muscle strength and does not always indicate an increased risk of injury [42]. We speculate that the low squat depth in Tai Chi places a greater demand on the lower limb joints and muscles than the high squat depth, potentially resulting in a larger GRF. In this study, the Tai Chi novices may not have effectively managed the speed of ground contact upon heel strike, possibly because of inadequate movement techniques. This could explain the lack of observed differences in the GRF between squat depths.

This study found that low squat depths had smaller peak COG heights than high squat depths, and SPM analyses showed no differences between squat depths. Performing PWHM requires the body's COG to be maintained at all times. In this study, a low squat depth had a smaller peak minimum COG on the vertical axis than a high squat depth; however, there was no difference in the peak maximum COG, which implies that Tai Chi novices are unable to keep their COG smooth when performing low squat depth exercises. This finding aligns with earlier observations in this study that Tai Chi novices, constrained by insufficient lower limb muscle strength, especially in terms of endurance, struggle to maintain a lower squat depth for extended durations.

Strong muscles can reduce joint load and provide stability [43]. The PWHM demands substantial lower limb muscle strength, particularly during stages in which the supporting leg must bear the entire body weight. Insufficient lower limb muscle strength may result in excessive mechanical loading of the joints, potentially contributing to joint damage [38]. Although multiple factors are involved, excessive loading could be a risk factor for the development of osteoarthritis [43]. In this study, we found that a low squat depth resulted in greater peak muscle force than a high squat depth in the semitendinosus, biceps femoris, rectus femoris, medial gastrocnemius, and tibialis anterior muscles. This indicates that there is a higher demand for lower limb strength when performing at low squat depths than when performing at high squat depths. In other words, a low squat depth demands greater lower limb strength than a high squat depth, and engaging in low squat depth exercises over an extended period is likely to lead to enhanced lower limb strength. Wang et al. found that in Tai Chi, the body COG transfer phase has a higher demand for muscle strength of the biceps femoris, semitendinosus, medial gastrocnemius, and tibialis anterior than the lunge [44]. Previous studies have shown that the body COG transfer phase of PWHM requires significantly greater lower limb muscle strength than deep squatting; when muscle strength is insufficient, this may lead to instability of the knee joint, increasing the mechanical loading on the knee and leading to knee osteoarthritis [38].

In general, a lower squat depth offers a greater joint ROM and potential benefits; however, it also increases the demand for lower limb muscle strength, leading to a higher risk of injury. Tai Chi, which has a more even stress distribution and a lower contact pressure, is generally safe [45]. Tai Chi novices should start practicing under the supervision of an expert, beginning with a higher squatting depth and gradually lowering it as strength and flexibility improve, guided by a qualified instructor. This approach aims to reduce joint strain, promote muscle growth, and minimize the risk of injury using appropriate training and recovery techniques.

In this study, we analyzed the biomechanics of the lower limbs at different squat depths during PWHM to guide the scientific training of Tai Chi novices. This study had several limitations. First, as a pilot study, the sample size was small, limiting the generalizability of our findings. Second, sex was not considered in our analysis, which is considered a limitation as it may influence biomechanical outcomes. Future studies should consider sex as a variable. Finally, a control group of professional Tai Chi athletes was not established, which is essential for distinguishing the effects of Tai Chi training from inherent biomechanical differences. Future studies should include a control group for a comparative analysis. In a follow-up study, we plan to employ finite element analysis and machine learning to systematically investigate the biomechanical factors influencing lower-limb movement in Tai Chi to identify the key predictors of performance and risk of injury.

5. Conclusion

Different squat depths in the PWHM can affect the lower limb biomechanics of Tai Chi novices. A low squat depth offers greater joint ROM, joint moments, and muscle strength than a high squat depth. Despite the potential health benefits of a low squat depth, the increased demand for muscle strength may result in injuries to Tai Chi novices. Therefore, opting for a high squat depth during practice sessions can help reduce joint strain and the risk of injury.

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