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Alterations of landing biomechanics from an inclined treadmill running-induced fatigue protocol

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Abstract

Purpose: This study examines the biomechanical effects of running-induced fatigue on the kinematic and kinetic changes of the lower limb during a countermovement jump (CMJ) via analyzing variations in joint biomechanics during landing. *Methods:* A running-induced fatigue protocol was employed to explore changes in joint angle, moments, stiffness, and loading rate during the CMJ landing pre and post -fatigue. Paired-sample t-tests assessed changes in discrete parameters of joint stiffness, loading rates, and time-varying parameters were compared with one-dimensional statistical parametric mapping. *Results:* Fatigue significantly reduced the range of motion (ROM) during landing, with significant differences in angles, specifically the dorsi-plantar flexion of right ankle, flexion-extension of left hip, rotation of left knee, and adduction-abduction of right knee ($P<0.001$). The first loading rate at touchdown decreased by 10%, and the time intervals between the first and second peak and the second and third peak reduced by 40% and 80%, respectively. Joint loading increased and the sagittal joint stiffness of left hip, right knee, and right ankle exhibited significant differences post-fatigue ($P<0.001$). Knee joint reduced the flexion angle ($P<0.001$) and the load of knee joint ($P<0.001$) during post-fatigue, with the role compensated by hip and ankle joints to achieve balance in the lower limb kinetic chain. *Conclusions:* These findings provide pilot evidence that running fatigue may lead to changes in lower limb joint loadings and provide a scientific foundation for fatigue prediction and injury assessment.

Keywords: CMJ, landing, biomechanics, kinetic chain, injury

Introduction

With increased public health awareness, individuals adopted running as a beneficial habit, leading to a global exponential rise of distance runners [2]. However, lower limb injuries associated with long-distance running remain high [51], as indicated that 40% to 50% of runners were injured yearly due to high mileage per week [36]. Running is a highly repetitive exercise that involves applying force to the body about 90 times per minute [44]. During running, the average leg repeated absorption is equivalent to 1.5 to 5 times the weight of the load [27]. Previous studies showed that most of the lower limb injuries in runners are related to fatigue, with excessive load and fatigue impairing neuromuscular control, leading to uncoordinated and abnormal movements[20].

Long-distance running fatigue reduced stride length with a slight increase in step frequency and corresponding lengthening of the support phase [52]. With the accumulation of running fatigue, the body maintains posture by preserving lower limb stiffness, thereby enhancing the transmission efficiency of vertical ground reaction forces and conserving energy expenditure [22]. In sports performance, stiffness plays a vital role in regulating the external force load in the movement process. This regulation enables the musculoskeletal system to store and utilize elastic potential energy more effectively [23]. Therefore, joint stiffness could cope with large external force loads, providing sufficient energy support for subsequent movements and ensuring continuity in activities such as jumping and other dynamic sports [12]. Moreover, Grimston et al,. [24] reported that the relationship between joint stiffness and mechanical properties can be used to predict the risk of bone injury. During running, vertical ground reaction forces typically range from two to three times body weight, potentially leading to increased skeletal deformation and injury[31], which could be seen that running fatigue affected the biomechanical loads of lower limbs.

CMJ is commonly used to assess acute fluctuations in athletic performance [25]. Due to its efficacy in evaluating leg strength, CMJ is a reliable tool for monitoring neuromuscular readiness and fatigue [26; 32]. Several studies demonstrated that the vertical ground reaction force of CMJ on the lower limbs during landing was much greater than the load during running [16; 47]. Moreover, lower limb joint injuries were reported during the landing of CMJ [10]. Therefore, CMJ was frequently utilized as a non-contact injury screening tool for athletes [45].

Previous studies provided valuable insights into the effects of long-distance running fatigue on the biomechanics of lower limb joints of runners [20]. However, the impact of long-distance running fatigue on the biomechanical load of lower limb joints during CMJ landing is still lacking, which requires a comprehensive analysis to understand the mechanisms of changes in lower limb biomechanical loading [9].

Thus, this study aimed to investigate the changes in contact angles, joint range of motion (ROM), moments, joint stiffness, and loading rates at the hip, knee, and ankle joints during CMJ landings pre and post -running-induced fatigue. Additionally, we explore the alterations in the lower limb kinetic chain throughout the continuous phase of the CMJ landing. The findings may provide a basis for quantitative analysis of joint mechanics under fatigue and a scientific basis for fatigue prediction and injury assessment. Further, the study formulated the following three hypotheses: (1) Biomechanical differences exist in the hip, knee, and ankle joints between the bilateral limbs between the pre and post -fatigue conditions during landing. (2) During landing, joint mobility is reduced post-fatigue compared to pre-fatigue. (3) The knee and ankle joints exhibit significantly larger joint loads post-fatigue than pre-fatigue during landing.

Materials and Methods

Participants

According to G power 3.1 software, the statistical power was (power, 1-β=0.8)[17; 40], and calculated that at least 12 participants should be recruited in this experiment. To reduce the experimental error and ensure the validity of the results, this study recruited 20 recreational healthy male runners from the Ningbo University Athletics Association with the right leg as the dominant leg. The information of the participants is shown in **Table 1**. All participants were required to meet the following inclusion criteria: (1) Recreational runners of heel strikes. (2) Running at least 2-3 times per week with no less than 45 minutes or a distance of 10 kilometers per session. (3) No lower limb or systemic deformities. (4) No history of trunk, pelvis, or lower extremities injuries in the six months before the experiment. (5) No history of surgery or medical correction in lower extremities. According to the inclusion and exclusion criteria, 20 eligible participants over 18 were selected.

Before the experiment, participants were thoroughly informed of the protocol, objectives, schedule, and anticipated risks of the study. All participants signed informed consent and voluntarily agreed to participate in the study. The protocol of this study was approved by the Ethics Committee of Ningbo University (approval number: RAGH202304127005.8).

Table. 1 Anthropometric Information

Information (unit)	Mean	SD
Age (yrs)	24.27	1.36
Height (cm)	177.00	4.33
Weight (kg)	69.80	8.46
BMI (kg/m^2)	22.20	1.7

Data collection

In this experiment, a previously validated OpenSim (Stanford University, Stanford) model was used [33]. According to the model's specifications, 38 reflective marker points were required to be placed on the hip, knee, and ankle joints based on the anatomical structure of the participants. The marker position is shown in **Figure 1**. To reduce the experimental error, all reflective marker points were marked by the same experimenter.

Fig. 1 Placement of Marker Locations

Three-dimensional (3D) kinematic and dynamic data were collected using the Vicon infrared 3D motion capture system (Vicon Metrics Ltd.Oxford) and the Kistler 3D force platform (Kistler, Switzerland). The experimental environment is shown in **Figure 2**. The heart rate band (Polar H10, Finland) and Borg's 20-point self-fatigue scale (perceived exercise level, RPE) were used to monitor the heart rate and fatigue level during the long-term running program [3].

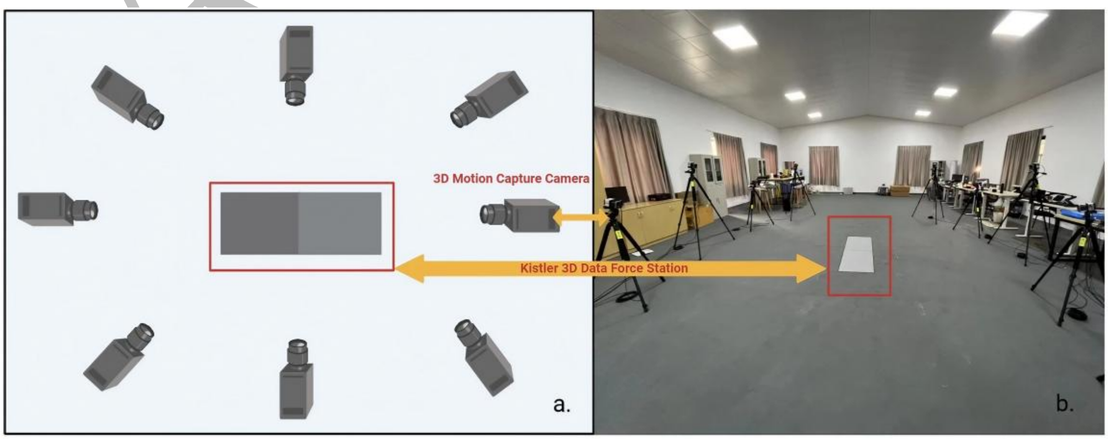

Fig. 2 3D Motion Capture System (a: simulation diagram, b: laboratory setup)

Experimental protocol

The experiment was divided into three phases: (1) pre-running fatigue CMJ test data collection, (2) running-induced fatigue protocol, and (3) post-running fatigue CMJ test data collection. All phases were completed within the same day. In the 24 hours before the experiment, the participants were restricted from strenuous exercise to ensure their physical condition. Before testing, participants were required to wear tights and sports shoes provided by the experimental center. A standardized warm-up was performed by jogging on a treadmill (Saturn h/p/cosmos, Nussdorf-Traunstein) for no more than 10 minutes, following the experimenter's guidance.

During the pre-fatigue and post-fatigue CMJ tests, participants were instructed to execute three pre-test jumps prior to the formal test as familiarization. Eight trials of jumping with maximum effort of the bilateral lower-limb jumping data were successfully collected [21; 53].

In the fatigue-inducing protocol, according to existing studies, the experimenter needs to set the incline of the treadmill to 1%, which makes it more suitable for the outdoor running environment [19; 54]. During this phase, participants wore a heart rate monitor to track changes in heart rate throughout the run. The protocol began with participants walking on the treadmill at a speed of 6 km/h, with the pace increasing by 1 km/h every 2 minutes until reaching a Borg perceived exertion level of 13. Participants maintained a stable running speed until reaching 90 % of the maximum heart rate (shown in **Equation 1**) or level 17 (very difficult). At this point, participants continued running for an additional 2 minutes until exhaustion, completing the fatigue-inducing run test [29; 48].

During the test, the experimenter recorded participants' perceived exertion scores and corresponding heart rates during the last 10 seconds of each minute. No visual or verbal stimuli were provided, and participants were unaware of the treadmill speed or duration of the experiment. The fatigue running test phase is shown in **Figure 3**.

$$HR_{max} = (220 - \text{yrs}) * 90\% \qquad \textbf{Equation 1}$$

Following our previous study [21], participants were required to complete the CMJ acquisition post-fatigue within 5 minutes after the induced fatigue test to ensure that the experiment was completed in the fatigue state.

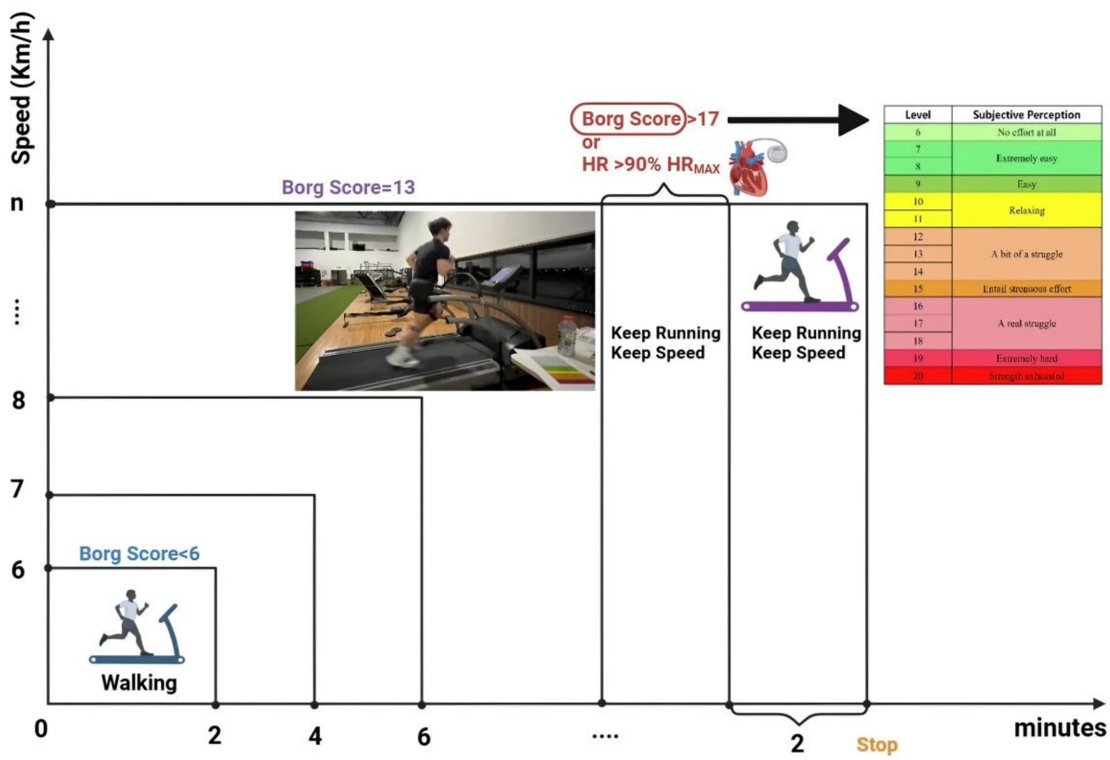

Fig. 3 Protocol of Inclined Treadmill Running-induced Fatigue

Data processing

The initial processing of kinematic parameters was performed using Vicon Nexus 2.8.2 (Vicon Metrics Ltd., Oxford) software. Based on the position of the reflective markers, each dataset was labeled, and the 3D kinematic data of the hip, knee, and ankle joints from the vertical jump touchdown phase to the return phase were extracted. The extraction was primarily determined by the frame count when the vertical ground reaction force on the force platform reached 0N [34]. The intercepted data is imported into OpenSim (Stanford University, Stanford) software in C3D format and remodeled to calculate the three-dimensional inverse kinematics data of each group of actions To reduce noise in the force plate signals, a bidirectional second-order low-pass Butterworth filter was applied with a cut-off frequency of 6 Hz [34; 35].

Joint stiffness was primarily calculated based on joint moment and joint angle [4; 8]. As shown in **Equation 2**, ΔM is the amount of change in joint moment from touchdown cushioning to recovery, and ROM is the change in joint angle.

$$K_{joint} = \frac{\Delta M}{ROM} \qquad \textbf{Equation 2}$$

In this study, we mainly focus on the changes in parameter indicators in the landing stage of fatigue CMJ. The landing phase was divided into three periods: the grounding phase, the recovery phase, and the stance phase [28]. When the toe first contacts the ground, the first peak vertical ground reaction force (VGRF) is generated, termed VGRF1. The force then shifts to the heel, generating the second peak, VGRF2. Finally, returning to the standing position produced the third peak, VGRF3. In this study, the touchdown cushioning phase was defined as the period beginning at initial contact

(VGRF > 10 N) and ending when the foot completely leaves the force platform.[18] The time from touchdown to VGRF1 was defined as T1 (**Figure 4**). Similarly, the time intervals from VGRF1 to VGRF2, and VGRF2 to VGRF3 were defined as T2 and T3. The loading rate (LR) was the vertical ground reaction force loading per unit time. With the specific formula for the unit (BW/ms) provided in **Equation 3**.

$$LR = \lim_{\triangle t \to 0} \frac{\triangle F}{\triangle t} \qquad \textbf{Equation 3}$$

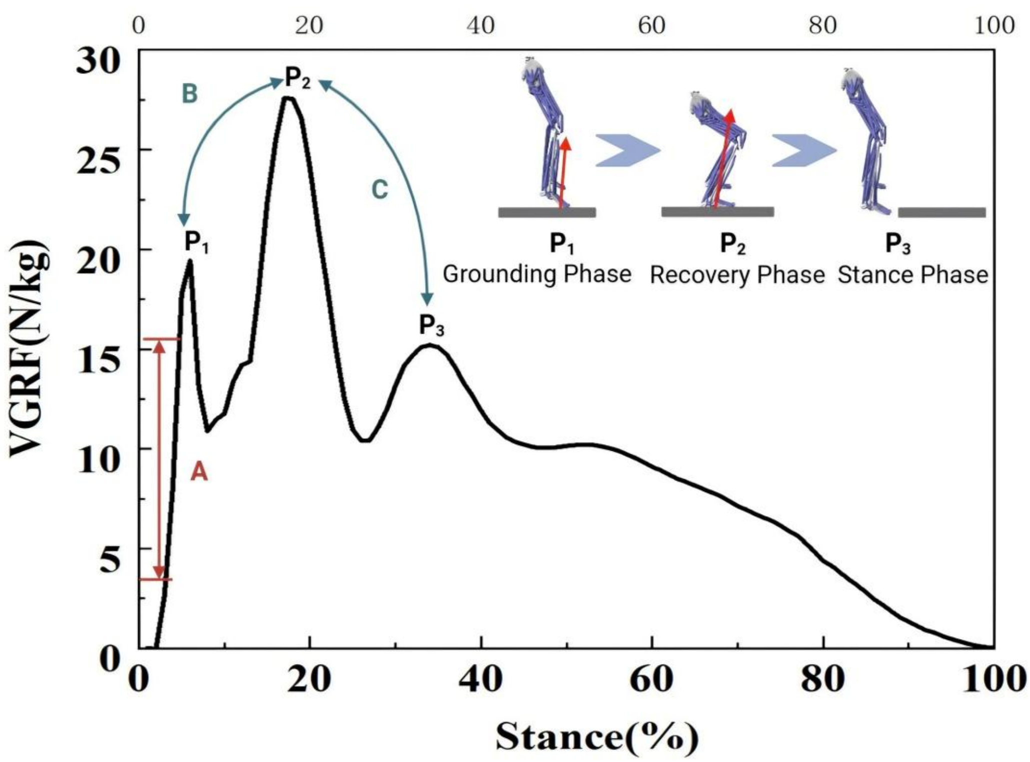

Fig. 4 Loading Rate (P1: First peak; P2: Second peak; P3: Third peak; A: The first vertical peak loading rate; B: The time difference from the first peak to the second peak; C: The time difference from the second peak to the third peak.)

Statistical analysis

In this study, data were presented as mean ± standard deviation (Mean ± SD). The joint angles, joint moments, range of motion (ROM), peak joint moments, joint stiffness, and ground loading rates, calculated pre and post fatigue, were analyzed using SPSS software (Statistical Product and Service Solutions, USA). Paired-sample t-tests were used to examine the significance of changes in ROM, joint stiffness, moments, and ground loading rates in the sagittal, coronal, and horizontal planes in the pre and post fatigue conditions.

Due to the one-dimensional time-varying characteristics, the joint angle and moment parameters, based on the Statistical Parameter Mapping (SPM) random field theory, the topological analysis was performed to determine the statistical significance of data clusters exceeding the threshold (t) [34]. The SPM1d method, typically used for continuous data analysis of time-varying data, was applied to test the statistical differences in the angle and moment of the hip, knee, and ankle joints across the landing phase [42]. The SPM1d was performed in MATLAB R2018a (The MathWorks, MA, USA), with the significance level of two-way ANOVA set at 0.05.

Results

Kinematic Variables

The SPM1d statistics of the right limb from fatigue are shown in **Figure 5**. Post-fatigue, a significant increase in internal rotation of the right hip ($P<0.001$) was found. Similarly, during 21%–76% of stance, the hip adduction post-fatigue was significantly higher than pre-fatigue ($P<0.001$). Dorsiflexion of the right ankle was significantly higher in pre-fatigue than post-fatigue ($P<0.001$) during 2%-48% of the touchdown-to-return phase. The right knee joint exhibited significant abduction during the 9%-86%

phase after fatigue (P<0.001). Additionally, during the 0%-34% of the landing phase, the degree of internal rotation pre-fatigue was significantly higher than post-fatigue (P<0.001).

The SPM1d statistics of the left limb from fatigue are shown in **Figure 6**. Pre-fatigue, the left hip joint had significant flexion, adduction, and internal rotation (P<0.001). The left knee showed significant extension (P=0.018), mainly in the landing phase and 39%-58% return phase. Moreover, during the 12%-100% of the landing phase, the left knee had a significantly higher degree of internal rotation than pre-fatigue (P<0.001). Post-fatigue, the left knee demonstrated a significant degree of abduction during the 0%-27% of the touchdown phase (P<0.001).

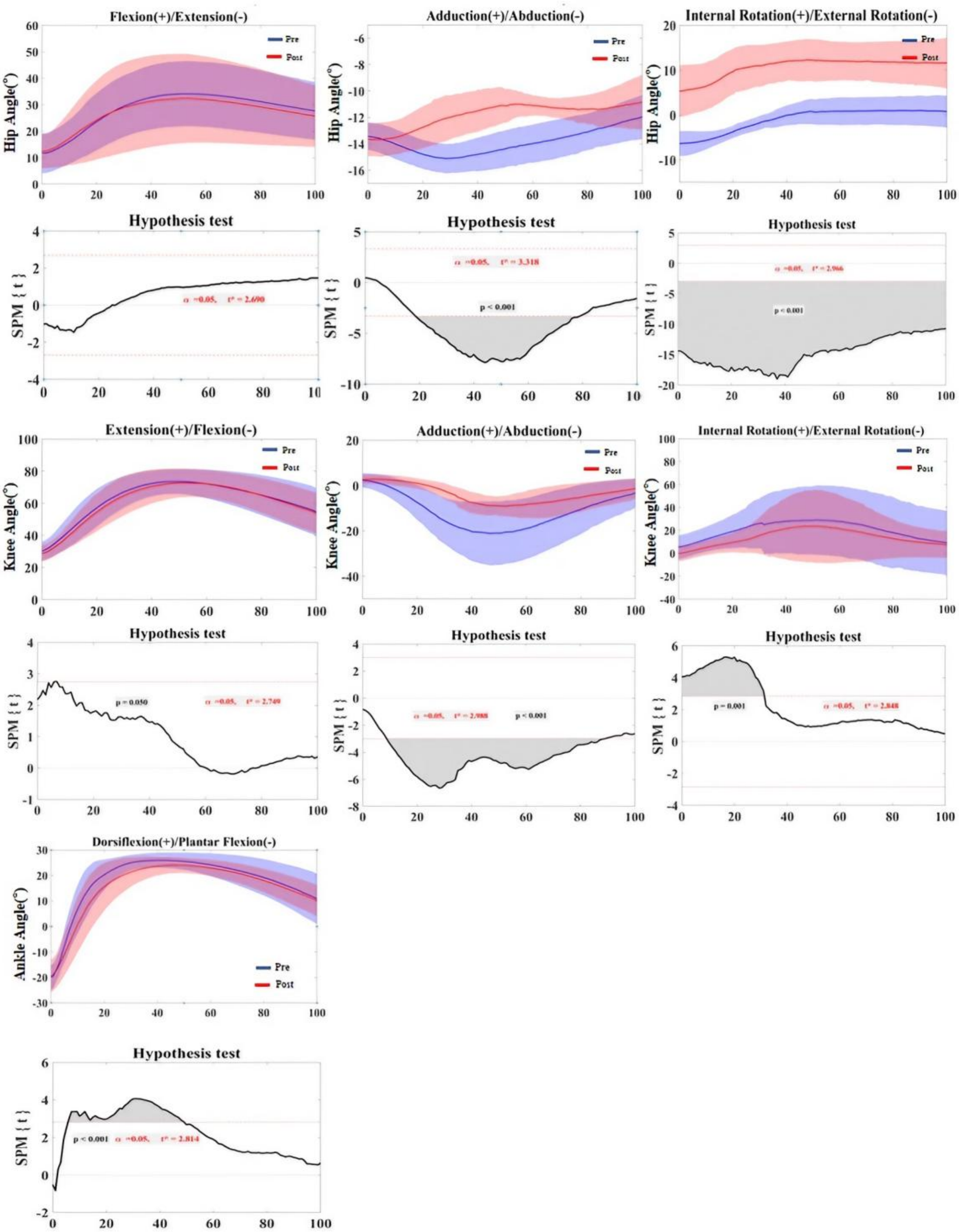

Fig. 5 SPM1d Statistics of Joint Angles Pre and Post Fatigue of the Right Lower Limb during Landing

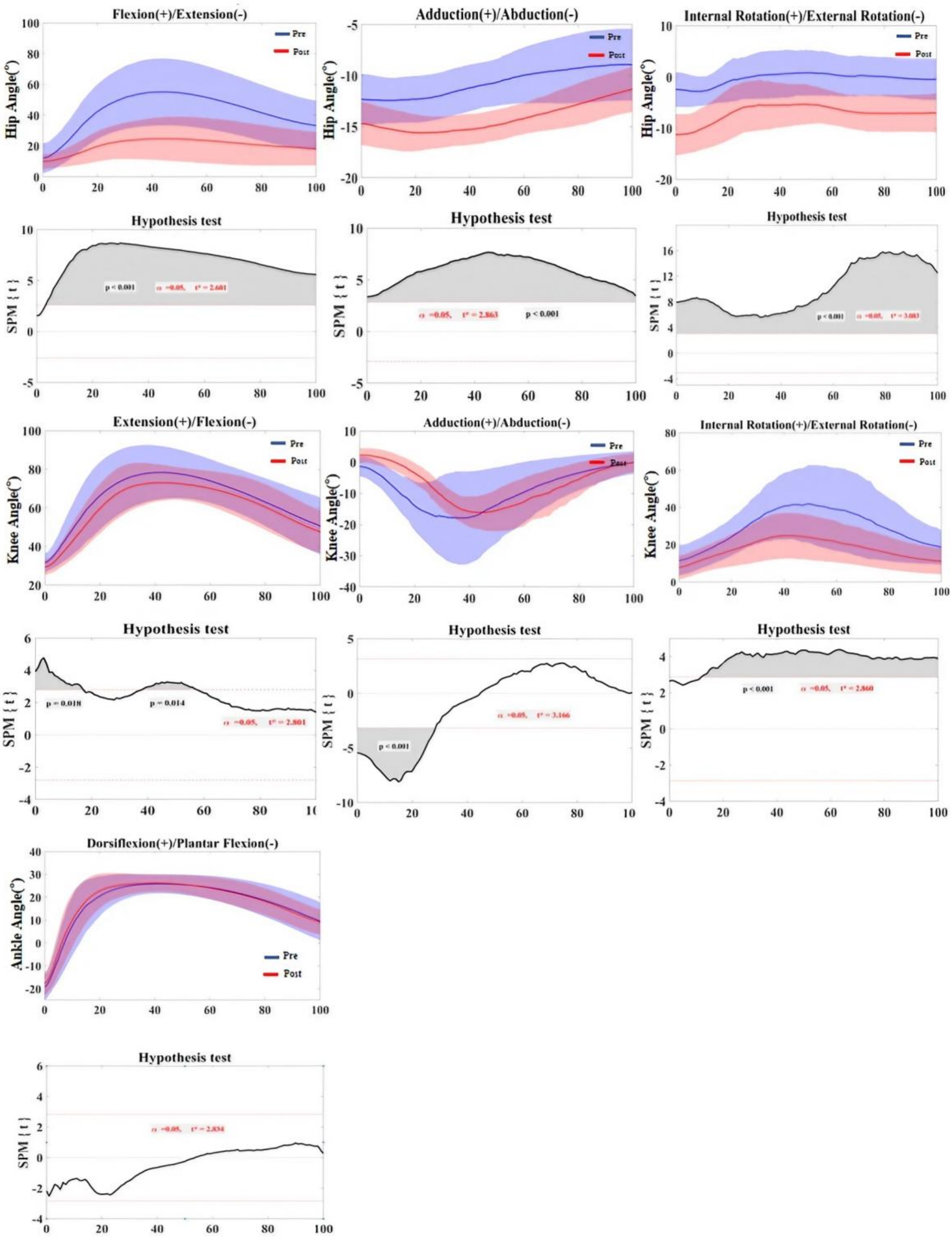

Fig. 6 SPM1d Statistics of Joint Angles Pre and Post Fatigue of the Left Lower Limb during Landing

Table 2 shows the comparison of joint range of motion (ROM) pre and post fatigue. A significant difference in the sagittal changes of the right ankle pre-fatigue (p=0.001) was found. Similarly, highly significant differences were noted in the sagittal ROM of the left hip, the horizontal plane of the left knee, and the coronal plane of the right knee post-fatigue ($P<0.001$).

Kinetic Variables

The SPM1d statistics of the right leg from fatigue are presented in **Figure 7**. Compared to post fatigue experiment, the hip had a more pronounced abduction moment at 42% pre-fatigue ($P=0.05$). Similarly, the knee showed higher adduction moments at 11% of the touchdown stage ($P=0.05$) during the 22%-61% ($P<0.001$) and 86%-97% of stance ($P<0.001$) pre-fatigue. Increased flexion moments were observed during the 2%-3% ($P=0.042$), 12%-14% ($P=0.025$), and 17%-24% ($P=0.005$) of return phases pre-fatigue. Likewise, higher internal rotation moments occurred in the 12%-13% ($P=0.036$) and 15% ($P=0.049$) phases. The ankle joint showed a pronounced plantar flexion moment between 19%-77% of landing ($P < 0.001$). In contrast, during the 2%-3% and 5%, significantly higher plantar flexion moments were observed post-fatigue than pre-fatigue ($P<0.001$).

The SPM1d statistics of the left leg from fatigue are presented in **Figure 8**. Compared to post fatigue test, the hip had a higher external rotation moment in 71%-91% of the return to stance phase ($P<0.001$). The knee joint showed higher abduction moments ($P<0.001$) and external rotation moments ($P<0.001$) during the return to stance phase. Similarly, the ankle joint showed higher plantar flexion moments ($P<0.001$) in 24%-73% of the return phase. In contrast, post-fatigue, the hip joint exhibited higher extension moments during the 11%-13% (P=0.012) and 23%-26% (P=0.007) phases. The knee joint showed significantly higher external rotation moments during the 10%-16% touchdown phase (P=0.004). The ankle joint showed higher plantar flexion moments in the 2%-6% touchdown phase (P=0.031) and 91%-100% stance phase (P<0.001).

Table 3 presents the comparison of joint moments in lower limbs pre and post fatigue. The horizontal plane of the left hip showed more obvious moment changes pre-fatigue (P=0.000, t=4.974). Conversely, the knee demonstrated significant moment changes in the coronal plane post-fatigue (P=0.05, t=-1.961). Similarly, the right knee joint showed more substantial moment changes post-fatigue in both the sagittal plane (P=0.000, t=-5.171) and the coronal plane (P=0.000, t=-4.100). In addition, the sagittal plane of the right ankle also showed more obvious moment changes post-fatigue (P=0.001, t=-3.352). In contrast, the coronal plane of the right hip (P=0.01, t=2.642) and the right knee (P=0.000, t=4.349) showed more significant moment changes pre-fatigue.

Table 4 shows the comparison of joint stiffness in lower limbs pre and post-bilateral fatigue. Joint stiffness in the horizontal plane of the left hip was significantly higher pre-fatigue than post-fatigue (P=0.002, t=3.321). In contrast, post-fatigue, joint stiffness significantly increased in the sagittal plane of the left hip (P <0.001, t =-6.683), the sagittal plane of the right knee (P<0.001, t=-4.134), and the sagittal plane of the right ankle (P<0.001, t=-5.456). Similarly, joint stiffness in the left knee post-fatigue was greater than pre-fatigue in both the horizontal plane (P=0.021, t=-2.368) and the coronal plane (P=0.033, t=-2.205).

Table 5 shows the characteristics of the first VGRF peak loading rate during the touchdown phase. The first VGRF peak loading rate of the right foot before the induced fatigue test was significantly higher than post-fatigue, with a significant difference (p<0.001, t=7.758). **Table 6** shows the time difference between the first and second VGRF peaks of the touchdown phase. The time difference between the first and second VGRF peaks in the left foot was significantly shorter pre-fatigue compared to post-fatigue (p<0.001, t=-5.090). **Table 7** shows the time difference between the second and third VGRF peaks of the touchdown phase. The time difference between the second and third VGRF peaks was smaller in the left foot pre-fatigue than post, with significant difference (p=0.001, t=-4.051).

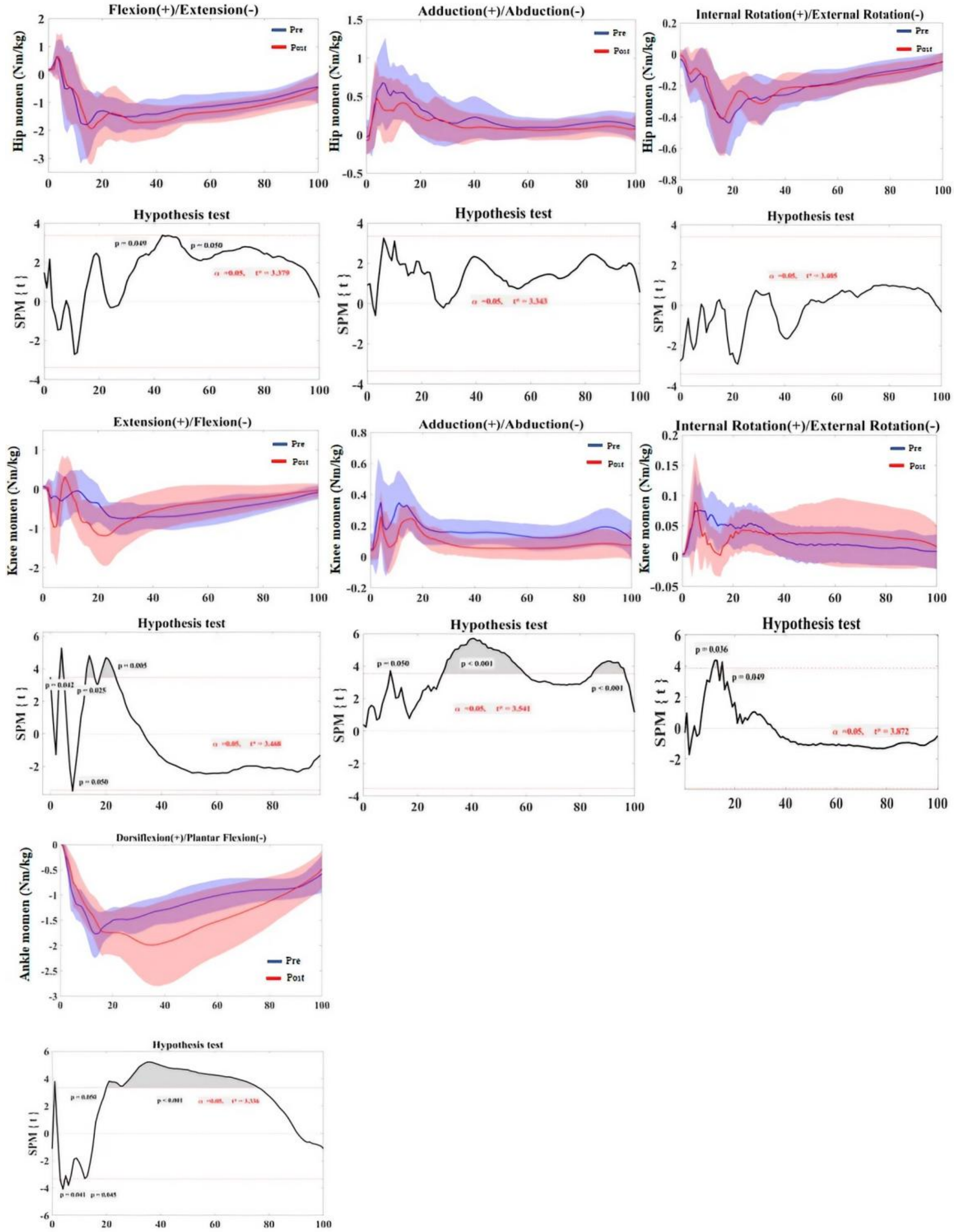

Fig. 7 SPM1d Statistics of Joint Moments Pre and Post Fatigue of the Right Lower Limb During Landing

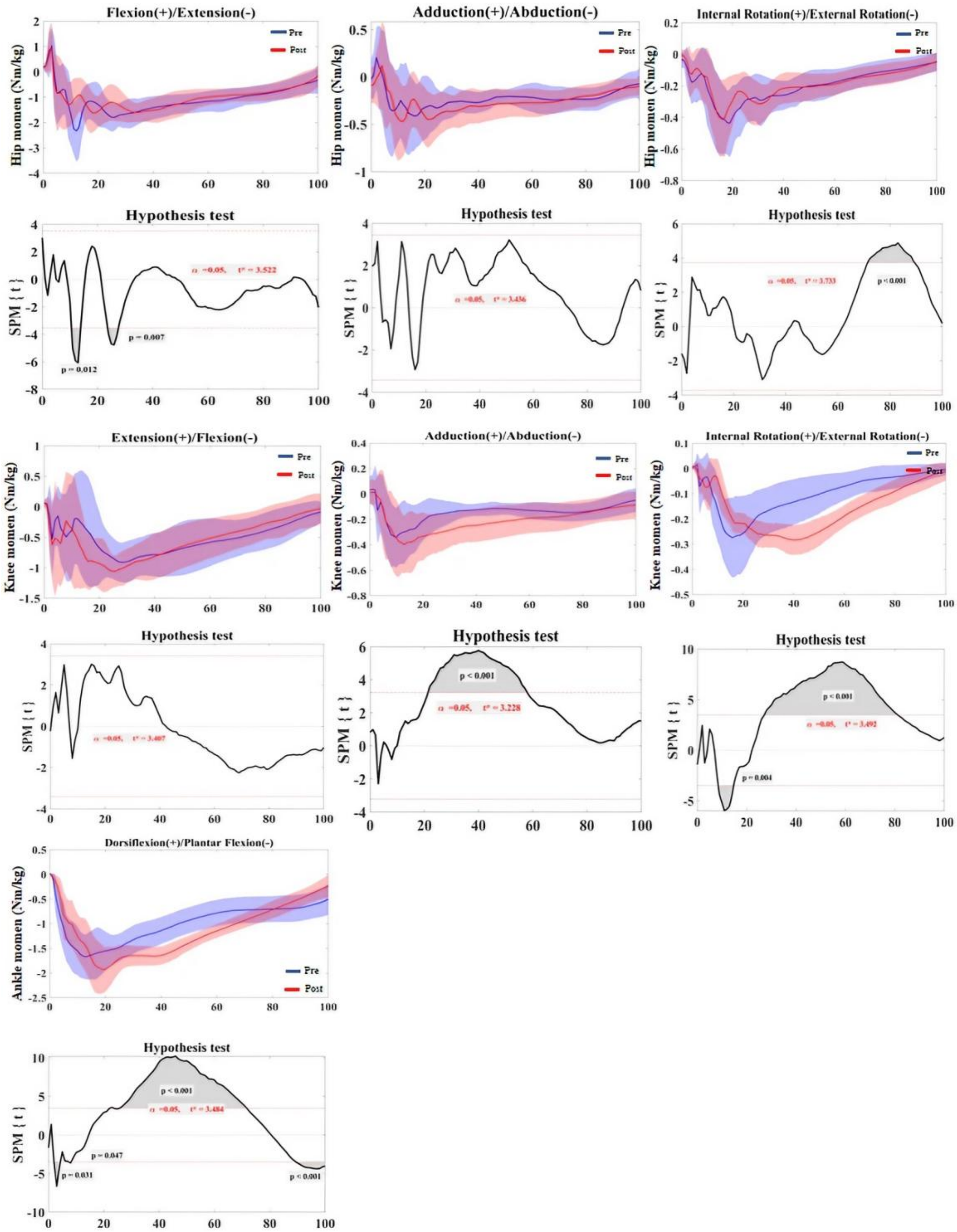

Fig. 8 SPM1d Statistics of Joint Moments Pre and Post Fatigue of the Left Lower Limb during Landing

Tab. 2 Comparison of Lower Limb Joint Range of Motion (ROM) Pre and Post Fatigue

Joint Angle (°)		Left (Mean±SD)			Right (Mean±SD)		
		Pre-fatigue	**Post-fatigue**	**Sig.**	**Pre-fatigue**	**Post-fatigue**	**Sig.**
Hip	**Flex (+)/Ext (-)**	44.18(17.46)	16.71(12.27)	**0.000****	23.75(10.19)	21.86(13.19)	0.345
	Add (+)/Abd (-)	4.94(2.27)	5.31(1.71)	0.509	3.78(1.19)	3.87(1.20)	0.858
	Intr (+)/Extr (-)	6.15(3.00)	7.66(3.01)	0.075	8.83(2.61)	9.19(4.50)	0.692
Knee	**Ext (+)/Flex (-)**	48.89(13.13)	46.36(8.01)	0.175	46.01(6.36)	45.4(8.79)	0.657
	Add (+)/Abd (-)	22.72(9.12)	20.38(5.88)	0.278	27.28(11.55)	15.14(1.6)	**0.000****
	Intr (+)/Extr (-)	36.51(24.71)	20.80(7.86)	**0.000****	35.07(33.98)	28.60(27.41)	0.274
Ankle	**Dors (+)/Flex (-)**	45.65(5.68)	44.73(5.23)	0.298	46.72(1.95)	43.80(4.733)	**0.001****

Note: *means significance ($p < 0.05$); ** means very significance ($p < 0.01$); Left: Left lower limb (non-dominant); Right: Right (dominant) lower limb; Dors: Dorsiflexion, flex: Plantar flexion, Add: Adduction, Abd: Abduction, Intr: Internal rotation, Extr: External rotation.

Tab. 3 Comparison of Joint Moment of Lower Limbs Pre and Post Bilateral Fatigue

Joint moment (Nm/kg)		Left (Mean±SD)				Right (Mean±SD)			
		Pre-fatigue	Post-fatigue	t	Sig.	Pre-fatigue	Post-fatigue	t	Sig.
Hip	Flex (+)/Ext (-)	4.65(1.24)	4.52(1.20)	0.432	0.667	4.73(1.07)	4.48(1.62)	0.876	0.384
	Add (+)/Abd (-)	1.22(0.38)	1.25(0.59)	-0.233	0.816	1.50(0.51)	1.25(0.32)	2.643	**0.01***
	Intr (+)/Extr (-)	0.57(0.12)	0.40(0.11)	4.974	**0.000****	0.68(0.17)	0.63(0.17)	1.339	0.185
Knee	Ext (+)/Flex (-)	2.16(0.61)	2.17(0.84)	-0.076	0.940	2.01(0.39)	2.79(0.74)	-5.171	**0.000****
	Add (+)/Abd (-)	0.63(0.20)	0.75(0.34)	-1.961	**0.05***	0.66(0.18)	0.46(0.09)	4.349	**0.000****
	Intr (+)/Extr (-)	0.38(0.14)	0.36(0.49)	0.757	0.454	0.14(0.35)	0.21(0.50)	-4.100	**0.000****
Ankle	Dors (+)/Flex (-)	2.01(0.44)	2.18(0.40)	-1.665	0.101	2.04(0.35)	2.43(0.68)	-3.352	**0.001****

Note: *means significance ($p < 0.05$); ** means very significance ($p < 0.01$); Left: Left lower limb (non-dominant); Right: Right (dominant) lower limb; Dors: Dorsiflexion, flex: Plantar flexion, Add: Adduction, Abd: Abduction, Intr: Internal rotation, Extr: External rotation.

Tab. 4 Comparison of Joint Stiffness of Lower Limbs Pre and Bilateral Fatigue

Joint stiffness (Nm/deg)		Left (Mean±SD)				Right (Mean±SD)			
		Pre-fatigue	Post-fatigue	t	Sig.	Pre-fatigue	Post-fatigue	t	Sig.
Hip	Flex (+)/Ext (-)	0.09(0.02)	0.52(0.38)	-6.883	**0.000****	0.24(0.16)	0.30(0.24)	-1.440	0.154
	Add (+)/Abd (-)	0.37(0.37)	0.29(0.21)	0.871	0.388	0.44(0.23)	0.37(0.22)	0.713	0.482
	Intr (+)/Extr (-)	0.10(0.05)	0.06(0.035)	3.321	**0.002****	0.09(0.04)	0.08(0.04)	0.281	0.779
Knee	Ext (+)/Flex (-)	0.04(0.02)	0.05(0.02)	-1.030	0.306	0.04(0.01)	0.06(0.02)	-4.314	**0.000****
	Add (+)/Abd (-)	0.03(0.01)	0.04(0.3)	-2.205	**0.033 ***	0.05(0.05)	0.04(0.02)	0.772	0.448
	Intr (+)/Extr (-)	0.01(0.007)	0.02(0.01)	-2.368	**0.021 ***	0.02(0.01)	0.01(0.005)	2.570	0.190
Ankle	Dors (+)/Flex (-)	0.01(0.13)	0.049(0.01)	-1.499	0.139	0.04(0.007)	0.06(0.01)	-5.456	**0.000****

Note: *means significance ($p < 0.05$); ** means very significance ($p < 0.01$); Left: Left lower limb (non-dominant); Right: Right (dominant) lower limb; Dors: Dorsiflexion, flex: Plantar flexion, Add: Adduction, Abd: Abduction, Intr: Internal rotation, Extr: External rotation.

Tab. 5 Characteristics of the First VGRF Peak Loading Rate during Landing

Loading rate (N/kg%)	Left			Right		
	(Mean±SD)	t	Sig.	(Mean±SD)	t	Sig.
Pre-fatigue	1.87±0.39	0.891	0.386	2.43±0.54	7.758	**0.000****
Post-fatigue	1.58±0.91			1.02±0.2		

Note: *means significance ($p < 0.05$); "**" means very significance ($p < 0.01$)

Tab. 6 The Time Difference Between the First and Second VGRF Peaks

T (%)	Left			Right		
	(Mean±SD)	t	Sig.	(Mean±SD)	t	Sig.
Pre-fatigue	7.89±1.167	-5.090	**0.000****	9.4±1.77	-0.427	0.675
Post-fatigue	11.44±1.74			9.7±1.33		

Note: *means significance ($p < 0.05$), "**" means very significance ($p < 0.01$)

Tab. 7 The Time Difference Between the Second and Third VGRF Peaks

T (%)	Left			Right		
	(Mean±SD)	t	Sig.	(Mean±SD)	t	Sig.
Pre-fatigue	11.78±3.27	-4.051	**0.001****	14.8±2.66	1.658	0.115
Post-fatigue	19.22±4.44			13.3±1.06		

Note: *means significance ($p < 0.05$), "**" means very significance ($p < 0.01$)

Discussion

This study aimed to compare the biomechanical alterations during the continuous action cycle of the CMJ touchdown stage, return stage, and standing stage pre and post fatigue. It also sought to investigate the risk of lower limb injuries caused by fatigue during running-induced fatigue in the CMJ landing stage. The results revealed significant differences in the biomechanical parameters of the dominant and non-dominant lower limbs pre and post the fatigue intervention. Specifically, the significant changes in lower limb stiffness were mainly concentrated post-fatigue. The ROM changes were significantly greater pre-fatigue than post-fatigue. These findings are consistent with hypothesis (1)(2)(3). However, a few parameters contradicted the hypotheses, potentially due to the continuous movement period. Additionally, fatigue significantly extended the time intervals between the first, second, and third peaks.

The experimental results indicated that running fatigue induced changes in the kinematic parameters of the hip, knee, and ankle joints during CMJ landing. The significant ROM differences were observed primarily pre-fatigue. Specifically, the ROM pre-fatigue was greater than the ROM post-fatigue, which may relate to muscle fatigue, as suggested by the reduction in ankle torque, which may be due to fatigue of the ankle plantarflexors [43]. This is also the reason for the decrease in running economy during long-term fatigue running [46]. In this study, the knee exhibited a small flexion angle at touchdown, gradually increasing to the maximum during the cushioning phase of landing. Simultaneously, the ankle joint reached the maximal dorsiflexion, consistent with the previous findings [11]. Ondatje et al.[41] believed that in the stage of recovery, the knee joint gradually changed from flexion angle to extension. The change of joint angle in this study is consistent with the research findings [41]. Dabbs et al. concluded that the knee reduced flexion angle post-fatigue, which may be a compensatory mechanism post-fatigue. The knee joint fully absorbed the ground reaction force, thus weakening the influence of ground reaction force and impact force on the joint [13]. The knee joint thus played a critical role in shock absorption and cushioning. During running, apart from the role of knee damping buffer, the ankle joint may also serve this function. However, no definitive values were established for the ankle joint's role in absorbing diagonal impulses and energy [1]. Therefore, future research should investigate the effects of running fatigue on the ankle joint, particularly regarding angular impulse and energy absorption.

The results suggested that locomotor fatigue changed the kinetic parameters of the hip, knee, and ankle joints. In this study, a continuous action cycle composed of three stages, the CMJ touchdown stage, the return stage, and the standing stage, was selected in this study, rather than a single stage. In subsequent studies, it was to predict further and analyze the damage analysis and synergistic effects of fatigue on the lower limb kinematic chain. The moment of the hip joint changes significantly, and the hip and knee joint have more than one significant change, indicating that the increase of peak knee joint moment may be associated with greater hip and knee flexion during heel strike. This is mainly reflected in the increase of knee joint moments during the touchdown phase, consistent with a previous finding [5]. Post-fatigue, the dominant ankle joint exhibited increased sagittal stiffness and moment changes, while no significant differences were observed on the non-dominant side. We also found significant changes in knee moments measured by the dominant side pre-fatigue. A comparison of left and right knee joints revealed significant differences between the dominant and non-dominant sides [49]. Specifically, the dominant side showed increased flexion, consistent with our findings. Therefore, these differences may adversely affect the body balance, potentially contributing to increased risks of fatigue-induced injuries. However, related studies also compared the left and right sides, finding that joint loading in the non-dominant limb was not less than the dominant limb [6]. Therefore, Future research should investigate the potential injury mechanisms of the non-dominant side.

Joint stiffness measured the relationship between joint moments and changes in angular displacement. The joint working plane was not simply the sagittal plane, but the coronal and horizontal planes, which was ignored in most studies [7]. Therefore, in previous studies, the knee joint moment was identified as only an estimated value [37]. Therefore, this study examined joint stiffness across all three planes of the landing motion. Regarding exercise performance, joint stiffness modulated the external loads, allowing the musculoskeletal system to utilize stored elastic energy more efficiently [38]. Under fatigue conditions, muscular control reduced, but the changes in joint loading and balance capacity of the lower limbs post-fatigue remained unclear [39]. The experimental findings indicated a significant alteration in lower limb joint stiffness post-fatigue, with the change being more pronounced in the non-dominant leg. In addition, there was a significant increase in the joint stiffness of the hip and ankle joints post-fatigue. This result may be linked to increased lower limb stiffness post-fatigue, which was shown that higher stiffness could lead to sports injuries [15]. In the results of this study, the joint stiffness of the knee decreased post-fatigue. This may be due to the greater participation of the hip and ankle joints in the CMJ post-fatigue than the knee joint, which is a strategy to reduce the knee loadings [30; 50]. Future research on changes in lower limb stiffness should not focus solely on individual joints but instead consider the lower limbs as a continuous kinetic chain, with attention given to the interactions between all components of the chain. In addition, joint stiffness could not only be used as a performance test and rehabilitation test to predict the risk of injury but also increase understanding of changes in exercise strategies [14].

There are a few limitations that should be considered in this study. Firstly, the participants in this study were exclusively recreational male runners. Future research shall account for different athletic levels and gender differences. Secondly, parameters, such as landing angle, joint moments, stiffness, and ground loading rate alone, cannot fully determine performance stiffness and injury risk. A more comprehensive analysis shall incorporate CMJ take-off time, jump height, landing center of mass displacement, joint contact forces, and dynamic stiffness to understand the specific impact of joint stiffness distribution on performance and injury. It is also necessary to explore the relationship between the depth of reverse motion during take-off and the value of ground reaction force at the moment of touchdown in the landing stage and during the recovery period.

Combined with jump height and flight time, the changes of biomechanical load during CMJ landing stage were further explored to intuitively analyze the specific impact of running fatigue on sports injury. In addition, this study provided a pilot analysis of the lower limb motor chain during the fatigued CMJ landing phase without exploring the relationship between changes in the kinematic chain and biomechanical loads. Therefore, to gain a more comprehensive understanding of the dynamic regulatory mechanisms of the lower limb kinematic chain and the effects of fatigue on these strategies, quantitative analysis of relevant data may be required to elucidate the complex physiological adaptations during exercise. These information would provide a scientific basis for training, rehabilitation, and injury prevention.

Conclusions

This study examined the biomechanical effects of inclined running-induced fatigue on the lower limb motor chain of 20 male amateur runners during the CMJ landing. The results indicated that fatigue reduced the joint ROM during the CMJ landing, decreased the initial loading rate at touchdown, significantly reduced the time intervals between the first, second, and third peaks, and increased joint loads. These findings could serve as valuable references in optimizing sports training programs. Significant differences in joint angles, joint moments, and loads were observed between the dominant and non-dominant legs post-fatigue.

For runners, the strength training of the dominant leg and non-dominant leg should be optimized to reduce the difference. Furthermore, it was observed that during the post-fatigue landing phase of the CMJ, the contributions of the hip and ankle joints exceeded the knee joint, forming a compensatory strategy that promoted dynamic balance in the kinematic chain and reduced knee joint loading. While the knee joint plays a primary role in shock absorption and buffering, the ankle joint also contributes similarly. However, the current data needs to be more comprehensive to fully substantiate this observation. In future studies, the absorption and continuous kinetic energy of the angular impulse of the ankle joint should be further analyzed. This study provides a foundational basis for future investigations into fatigue-related injuries. The findings contribute to the broader study of fatigue performance and injury risks. Future studies should focus on joint loading under varying levels of fatigue to further elucidate the impact of fatigue on lower limb joint loading.

Conflict of Interest

No potential conflict of interest was reported by the author(s).

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