Article

The Acute Influence of Running-Induced Fatigue on the Performance and Biomechanics of a Countermovement Jump

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Abstract: Lower limb kinematics and kinetics during the landing phase of jumping might change because of localized muscle fatigue. This study aimed to investigate the acute influence of running-induced fatigue on the performance and lower limb kinematics and kinetics of a countermovement jump. A running-induced fatigue protocol was applied to fifteen male subjects. Participants were asked to perform three successful countermovement jumps before and after fatigue. Kinematic and kinetic data were collected to compare any fatigue influences. Wilcoxon signed-rank tests and paired-sample *t*-tests were used to analyze the data. Running-induced fatigue did not significantly change vertical jump height and peak vertical ground reaction forces (GRF) during the push-off and landing phases. Lower limb biomechanics significantly changed, especially kinematic parameters. During the push-off phase, fatigue resulted in an increased ankle peak inversion angle, knee minimal flexion angle, knee peak abduction angle, and hip peak flexion moment. In addition, the range of motion (ROM) of the ankle and knee joints in the frontal plane was also increased. Certain parameters decreased as a result of fatigue, such as the ankle peak internal rotation angle, hip peak abduction angle, the ROM of the ankle joint in the sagittal plane, and ROM of the hip joint in the frontal plane. During the landing phase, the peak inversion angle and peak external rotation angle of the ankle joint, peak abduction angle of the knee and hip joint, ROM of the ankle joint in the horizontal plane, ROM of the ankle and knee joint in the frontal plane were all increased as a result of fatigue. The knee peak flexion moment and hip peak extension moment, however, were decreased. Under fatigue conditions, lower limb kinetics and kinematics were changed during both the push-off and landing phases. More attention should be focused on the landing phase and the last period of the push-off phase due to potentially higher risks of injury. The findings of the current study may be beneficial to athletes and coaches in preventing jumping related injuries.

Keywords: running-induced fatigue; joint angle; joint moment; jump height; countermovement jump

1. Introduction

Jumping is a fundamental physiological motion, which is used frequently in various sports. In addition, analysis of jumping performance can evaluate lower limb strength as well as bilateral

strength asymmetry [1]. The ability to jump is highly related to the performance of sports, including volleyball, basketball, and high jump. Flight time is a commonly used method to calculate the vertical jump height using simple computation. Vertical jump height calculated from flight time, however, has been overestimated by 0.025 m compared to takeoff velocity [2]. Vertical jump height is also associated with different jump types. Compared to the squat jump, the countermovement jump can increase the vertical jump height more effectively [3,4]. Squat depth is another factor that influences maximum vertical jump height achieved. In the experiment of Domire et al. [5], results indicated that jump height did not change if the subjects jumped from a preferred or deep position, whereas a computer simulation model demonstrated an increased jump height with increased squat depth. Practice to adapt the deeper squat position might assist athletes in developing a larger range of motion, and thereby, improve jumping performance. The effect of different stretching protocols on vertical jumping performance is varied. Static stretching before a vertical jump appears to reduce the jump height, while dynamic stretching contributes to a greater height obtained [6]. Knudson et al. also found that stretching could decrease vertical jump performance, although the finding was not significant [7]. Metatarsal strapping also appears to be another effective method to improve vertical jump performance [8].

Biomechanical parameters are different using the countermovement jump in jumpers with different abilities. Good performers have demonstrated greater jump heights, and the joint moments, joint power, and joint work of the three lower limb joints were increased [9]. Biomechanical assessments of jump-landings were used to compare any differences between healthy athletes and athletes with patellar tendinopathy [10,11]. The findings revealed that basketball athletes with patellar tendinopathy displayed lower loading rates during stop-jump landing tasks [10]. During the push-off phase, the triceps surae muscles, which include the gastrocnemius (GAS) and soleus (SOL) are the main contributors to vertical support and propulsion [12]. The reduction in strength in the triceps surae muscles can influence ankle power generation and change gait patterns [13]. The Achilles tendon, as an energy provider, that plantarflexes the foot, propels the body forward as well as controls the behavior of triceps surae [14]. When faced with rigorous cyclic loading, the Achilles tendon is subjected to a greater risk of injury and fatigue-induced damage may contribute to tendon failure [15].

Biomechanical changes in the lower limbs are related to lower limb injuries. Foot pronation has been proposed as a strong contributory factor for injuries [16,17]. Increased foot pronation alters the biomechanical parameters in the ankle joint, including motion, moment, and power [18]. After mid stance running, the static foot pronation of recreational runners is increased, which might indicate increased lower limb joint loading [19]. Fatigue is an important risk factor to consider in the prevention of injuries. Various fatigue protocols have been used to explore the changes in lower limb biomechanics when fatigue occurs. The influence of fatigue on running biomechanics has focused on plantar pressure [20], ground reaction forces (GRF) [21], kinematics, and kinetics of the lower limbs [22,23]. The effect of fatigue on hopping and jumping has mainly considered the landing phase [24–26]. The kinematics of the hip and knee joints did not significantly change following hip extensor fatigue since increased gluteus maximus recruitment was observed to compensate for the decrease in hip extensor strength [27]. During fatigue of the knee flexor and extensor muscles, participants were asked to perform cutting movements after jump landings from different heights. Kim et al. [28] found that the shock absorption provided by the knee joint decreased, while the ankle joint contribution increased. Knee extensor fatigue resulted in lower vertical jump height, a reduction in impulse, and jumping-landing kinematic changes in both male and female groups, especially under severe fatigue conditions [29].

Previous studies have investigated lower limb biomechanical changes induced by fatigue, and their research has mainly focused on the landing phase. Most fatigue protocols previously have investigated localized muscle fatigue. Therefore, the purpose of this study was to determine the influence of running-induced fatigue on performance characteristics and biomechanics of an entire countermovement jump. We hypothesized that running-induced fatigue would lead to a reduction in jump height and changes in lower limb kinematics and kinetics.

2. Materials and Methods

2.1. Design

Each participant in our study visited the laboratory for one day only. The experimental protocol was divided into three parts: pre-fatigue, fatigue protocol, and post-fatigue (Figure 1). During pre-fatigue and post-fatigue, the lower limb kinematics and kinetics of the participants were collected. A running-induced fatigue protocol was conducted between the pre- and post-fatigue conditions. There were no intervals between the fatigue protocol and post-fatigue. This study complied with the reporting guidelines of the Equator network.
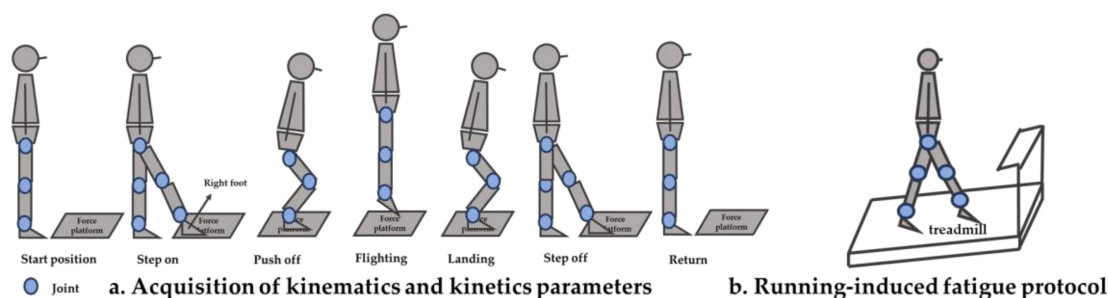

Figure 1. Illustration of the entire experiment. Sequence: (**a**) pre-fatigue, (**b**) fatigue protocol, (**a**) post-fatigue.

2.2. Subjects

Prior to the study, the sample size was calculated using G*Power (effect size = 0.8, α level = 0.05, power value = 0.9, trails: two). Fifteen male participants were recruited from students at Ningbo University, and their information is presented in Table 1. They had a mean (SD) age of 23.93 (0.80) years. Their mean (SD) height, mass, and body mass index (BMI) were 176.70 (2.75) cm, 73.93 (4.76) kg, and 23.35 (1.22), respectively. Individuals were free of any foot deformities, which had been examined by an experienced physician before conducting tests. Subjects with lower limb injuries or surgeries within the previous six months were excluded. All the included subjects exercised more than three hours per week and were defined as physically active. Furthermore, they all had normal foot arches with 253.2 ± 1.82 mm foot length and 87.4 ± 1.35 cm leg length. Foot posture index (FPI) was assessed and scored from −2 to 2 for each item with 6 items in total [30]. The subjects with FPI scores between −5 and 5 were included in this study, which demonstrated normal foot postures [19]. The entire selection process of the participants is outlined in Figure 2. All participants used their right legs in a ball kicking task, and as a result, the right leg was deemed to be the dominant leg. Before the test, all participants provided informed consent and were provided with details and objectives of this study. Ethical approval for the study protocol was obtained from the Human Ethics Committee of Ningbo University.
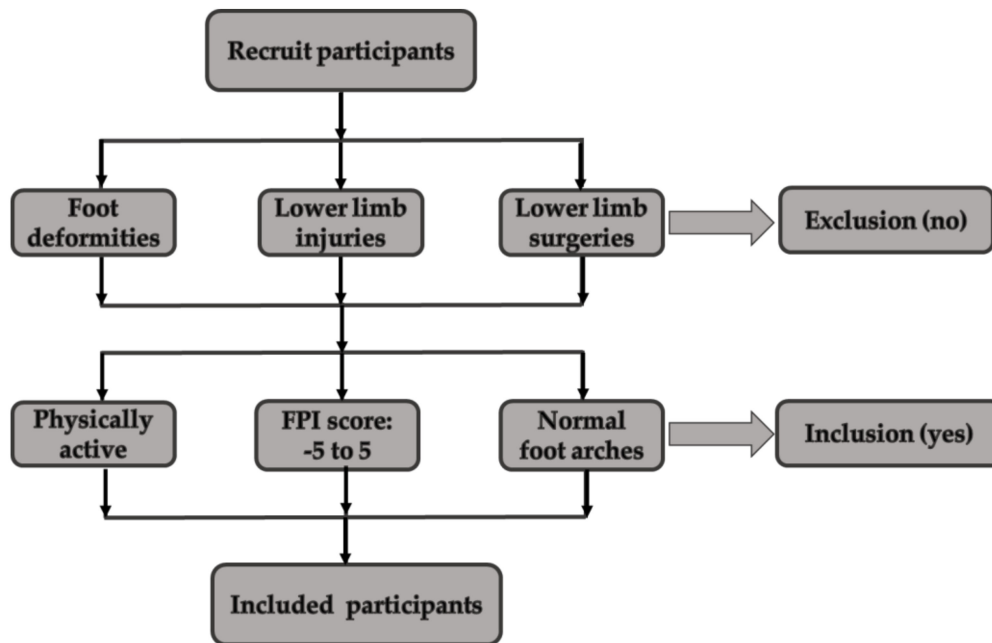
Figure 2. Flow chart of participant selection. Note: FPI-foot posture index.

Figure 2 illustrates how the participants were selected. The descriptive features of the subjects are presented in Table 1.

Table 1. Descriptive characteristics of participants.

Variables	Mean	SD
Age (year)	23.93	0.80
Weight (kg)	73.93	4.76
Height (cm)	176.70	2.75
BMI	23.35	1.22
Foot length (mm)	253.2	1.82
Leg length (cm)	87.4	1.35

Notes: BMI: body mass index; SD: standard deviation.

2.3. Experimental Procedures

Before formal experimentation, the weight and height of each subject were measured using a stadiometer and a calibrated weighing scale. Assigned shoes were provided to reduce measurement error. The experimental protocol was divided into three parts: pre-fatigue, fatigue, and post-fatigue. During the pre-fatigue and post-fatigue phases, the kinetics and kinematics of the lower limbs were captured synchronously. An eight-camera infrared Vicon motion capture system (Oxford metric Ltd., Oxford, UK) and a Kistler Force Platform (Model9281B, Winterthur, Switzerland) were used to collect the kinematics and kinetic data with sampling frequencies of 200 Hz and 1000 Hz, respectively. To track the motion of participants, twenty-one reflective markers, and six rigid marker clusters were attached with adhesive tape, which is illustrated in Figure 3 [31]. Reflective markers were bilaterally placed on the lower limbs and pelvis, which included the anterior superior iliac spines, iliac crests, greater trochanters, lateral and medial femoral epicondyles, lateral and medial malleolus, distal interphalangeal joint of the second toe, the first and fifth metatarsal heads, and the final marker was placed on the joint space between the fifth lumbar and the first sacral spinous. In addition, six marker clusters were bilaterally placed on the mid-thigh, mid-shank, and heel counter of the shoes with a self-adhering bandage. All these preparations were done by the same experienced researcher. Before data collection, the force platform was zero-leveled, and the definition of contact on the force platform was a value

of vertical GRF surpassing 20 N. In both pre-fatigue and post-fatigue phases, all subjects were asked to perform three successive trials. While performing the countermovement jump, participants were informed to stand in a position facing the force platform. When the researcher gave the instruction to start, the participants used their right foot to step on the force platform with his left foot following. Subjects then performed the countermovement jump with the hands placed on the hip. When the subjects completed the jumps, they stepped off the force platform and maintained an upright position. If the left foot touched the force platform, the trial was not analyzed.

Figure 3. The placement of reflective markers and rigid clusters.

2.4. Running-Induced Fatigue Protocol

After collecting kinematic and kinetic data of the lower limb under the pre-fatigue condition, participants were informed to start a running-induced protocol [32,33]. The 15-point Borg scale was used to rate perceived exertion, and a Polar H10 was used to monitor heart rate. At the beginning of the protocol, subjects ran on the treadmill at a speed of 6 km/h. Every two minutes, the speed was increased by 1 km/h. Subjects started to run as soon as the treadmill speed facilitated the running pace for the subjects. When the subjects scored 13 (somewhat hard) on the Borg scale, the speed of the treadmill was not allowed to increase. When the subjects graded 17 (very hard) or reached 90% of maximum heart rate, a further 2-minutes of running was noted for each participant. Following the additional two minutes of running, the subjects were assumed to have reached volitional exhaustion.

2.5. Data Processing

The entire countermovement jump in this study was separated into three parts, including push-off, flight, and landing phases. Marker trajectories were processed by Visual 3-D software (version 3.26, C-Motion Inc., Germantown, MD, USA) and were smoothed using a low-pass filter with a 10 Hz cutoff frequency. The joint angles were calculated using an inverse kinematics algorithm, which was conducted in Visual 3D. The calculation of joint moments was based on the calculated joint angles and collected GRF, and an inverse dynamics algorithm was used to acquire the joint moments. The kinematics and kinetics of the lower limbs in the push-off and landing phases were analyzed, respectively, and the data for each phase were normalized to 100 frames. The vertical GRF were normalized to body weight (BW). Kinematic variables of interest included peak joint angles as well as the range of motion (ROM) of the ankle, knee, hip joints in three planes. Kinetic variables included peak values for vertical GRF and peak joint moments of the ankle, knee, and hip joints, which were normalized to the body mass of each participant. As for the flight phase, jump height was calculated by the flight time to evaluate the jump performance according to Equation (1) [34,35].

$$jump\ height(m)\ =\ \frac{9.80 m \cdot s^{-2} \times flight\ time(s)^2}{8} \tag{1}$$

2.6. Statistical Analysis

Shapiro–Wilks tests were conducted to examine whether the variables obeyed normal distribution. Some parameters were not normally distributed; therefore, Wilcoxon signed-rank tests were carried out to evaluate the differences between pre- and post-fatigue. The differences between the other variables between the two conditions were assessed by Paired sample *t*-tests. Mean and standard deviations (SD) were used to describe the variables. All statistical analyses were performed using SPSS (version 25, SPSS, Chicago, IL, USA), with the significance level set at a *p*-value 0.05. Effect sizes (ES) (Cohen's d) were calculated by G*Power, and an ES between 0.2 and 0.5 was defined as small. Medium class referred to an ES between 0.5 and 0.8, and an ES beyond 0.8 was defined as large [36].

3. Results

3.1. Jump Height

The jump heights for the pre- and post-fatigue conditions were 280.0(35.4) mm and 271.7(54.4) mm. No significant differences in jump height were observed between the two conditions ($p = 0.368$, ES = 0.22).

3.2. Kinematics

3.2.1. Joint Angles during the Push-Off Phase

As shown in Table 2, differences were found between the pre-fatigue and post-fatigue conditions. As for the ankle joint, the ROM in the sagittal plane of the pre-fatigue condition was significantly different from that of the post-fatigue condition ($p = 0.010$, ES = 0.60). In the frontal plane, the peak inversion angle and ROM were significantly larger when fatigue occurred ($p = 0.004$, ES = 0.64; $p = 0.005$, ES = 0.39). In the horizontal plane, the peak internal rotation angle before fatigue was larger than the angle after fatigue ($p = 0.003$, ES = 0.44). In the knee joint, significant differences were observed in the sagittal and frontal planes. The maximal joint angle in the sagittal plane, the minimal joint angle, and ROM in the frontal plane were increased under fatigue conditions ($p = 0.026$, ES = 0.73; $p = 0.036$, ES = 0.64; $p = 0.001$, ES = 1.37). In the hip joint, the differences were only found in the frontal plane with a decreased minimal joint ankle and ROM following fatigue ($p = 0.005$, ES = 0.43; $p = 0.002$, ES = 1.04).

3.2.2. Joint Angles during Landing Phase

Peak joint angles and ROM are presented in Table 3. The majority of the parameters which significantly changed were larger under fatigue conditions, such as the peak inversion angle and ROM of the ankle joint in the frontal plane ($p = 0.003$, ES = 0.65; $p = 0.001$, ES = 0.87), the peak external rotation angle and ROM of the angle joint in the horizontal plane ($p = 0.004$, ES = 0.52; $p = 0.005$, ES = 0.62), the peak abduction angle and ROM of the knee joint in the frontal plane ($p = 0.032$, ES = 0.64; $p = 0.000$, ES = 1.60), but the peak abduction angle of the hip joint was smaller when fatigue occurred ($p = 0.025$, ES = 0.39).

Table 2. Peak joint angles and range of motion (ROM) of pre-fatigue and post-fatigue during the push-off phase.

Joint	Plane	Pre			Post		
		Max	Min	ROM	Max	Min	ROM
Ankle (°)	Sagittal	29.31 (5.17)	−22.82 (5.81)	**52.13 (3.32)** *	30.02 (6.14)	−19.98 (3.30)	**50.01 (3.73)** *
	Frontal	**7.62 (2.55)** *	−9.02 (5.97)	**16.64 (6.36)** *	**9.41 (3.03)** *	−9.63 (5.73)	**19.04 (5.79)** *
	Horizontal	**9.43 (6.69)** *	−5.57 (9.95)	15.00 (7.95)	**6.07 (8.33)** *	−6.19 (6.83)	12.26 (2.31)
Knee (°)	Sagittal	**−1.69 (2.19)** *	−97.40 (18.63)	95.70 (18.07)	**−4.44 (4.83)** *	−96.45 (26.96)	92.01 (24.53)
	Frontal	8.12 (4.15)	**−3.08 (4.66)** *	**11.20 (2.07)** *	11.12 (9.34)	**−8.30 (10.60)** *	**19.42 (8.24)** *
	Horizontal	9.48 (7.37)	−9.28 (5.11)	18.76 (5.12)	10.89 (19.15)	−8.76 (18.03)	19.65 (3.26)
Hip (°)	Sagittal	60.70 (19.42)	−1.07 (3.82)	61.77 (20.90)	60.99 (23.88)	1.08 (4.48)	59.91 (21.10)
	Frontal	3.71 (4.28)	**−9.38 (6.35)** *	**13.09 (3.13)** *	3.79 (6.10)	**−6.47 (7.18)** *	**10.26 (2.23)** *
	Horizontal	6.45 (6.07)	−7.36 (3.06)	13.81 (4.78)	8.34 (15.20)	−5.36 (16.80)	13.70 (3.89)

Notes: pre: pre-fatigue; post: post-fatigue. * indicates a significant difference between pre- and post-fatigue.

Table 3. Peak joint angles and ROM of pre-fatigue and post-fatigue during the landing phase.

Joint	Plane	Pre			Post		
		Max	Min	ROM	Max	Min	ROM
Ankle (°)	Sagittal	25.23 (6.33)	−16.58 (4.53)	41.80 (4.31)	25.83 (8.73)	−15.10 (6.50)	40.93 (4.16)
	Frontal	**7.35 (4.33)** *	−6.86 (3.29)	**14.20 (4.10)** *	**10.29 (4.67)** *	−7.45 (4.17)	**17.75 (4.03)** *
	Horizontal	9.14 (6.31)	**−3.08 (5.11)** *	**12.22 (3.87)** *	7.90 (9.68)	**−6.55 (7.88)** *	**14.45 (3.31)** *
Knee (°)	Sagittal	−1.84 (2.55)	−76.95 (27.27)	75.11 (27.84)	−3.80 (4.96)	−77.46 (35.40)	73.66 (33.08)
	Frontal	6.63 (4.85)	**−1.87 (3.89)** *	**8.49 (2.41)** *	9.32 (7.44)	**−5.75 (7.70)** *	**15.07 (5.27)** *
	Horizontal	8.66 (7.42)	−6.31 (3.85)	14.98 (4.10)	8.35 (21.74)	−7.31 (20.43)	15.66 (3.01)
Hip (°)	Sagittal	41.08 (27.17)	−4.69 (6.25)	45.77 (30.61)	43.12 (34.20)	−2.88 (5.92)	46.00 (33.65)
	Frontal	3.22 (1.97)	**−8.85 (5.45)** *	12.07 (3.68)	4.62 (4.46)	**−6.65 (5.91)** *	11.27 (1.83)
	Horizontal	5.68 (6.02)	−5.72 (4.43)	11.41 (5.13)	7.86 (15.01)	−3.63 (14.30)	11.49 (4.41)

Notes: pre: pre-fatigue; post: post-fatigue. * indicates a significant difference between pre- and post-fatigue.

3.3. Kinetics

3.3.1. Joint Moments during the Push-Off Phase

The consecutive joint moments during the push-off phase are presented in Figure 4. Significant differences were only found in the sagittal plane. The peak flexion moment of the knee joint before fatigue was significantly larger ($p = 0.031$, ES = 0.87); besides, the peak flexion moment of hip joint increased under the fatigue condition ($p = 0.036$, ES = 0.54).
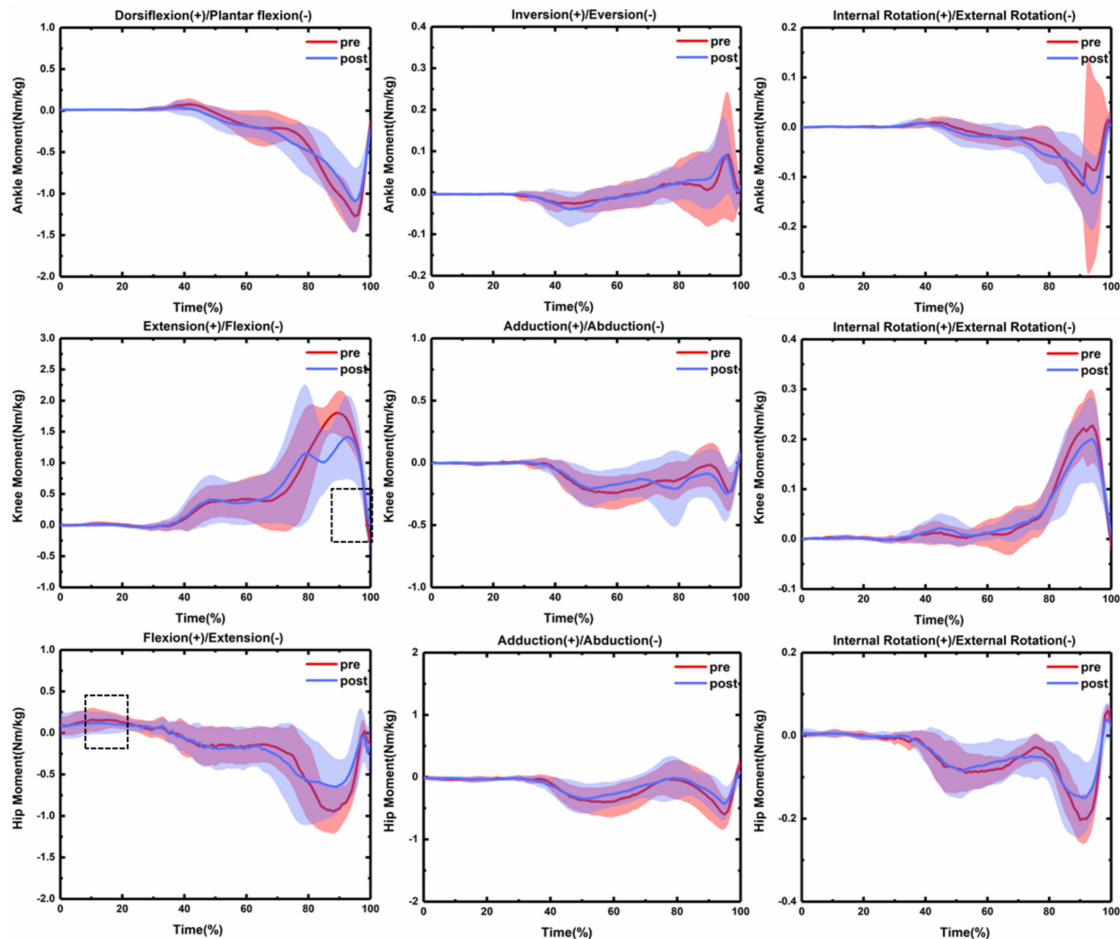

Figure 4. The joint moments between pre- (red solid lines) and post-fatigue (blue solid lines) during the push-off phase. Shaded areas mean standard deviation. Black dotted boxes indicate significant differences between the two conditions.

3.3.2. Joint Moments during Landing Phase

The consecutive joint moments during the landing phase are presented in Figure 5. In the sagittal plane, the peak flexion moment of the knee joint, and the peak extension moment of the hip joint significantly decreased when fatigue occurred ($p = 0.047$, ES = 0.60; $p = 0.036$, ES = 0.44).
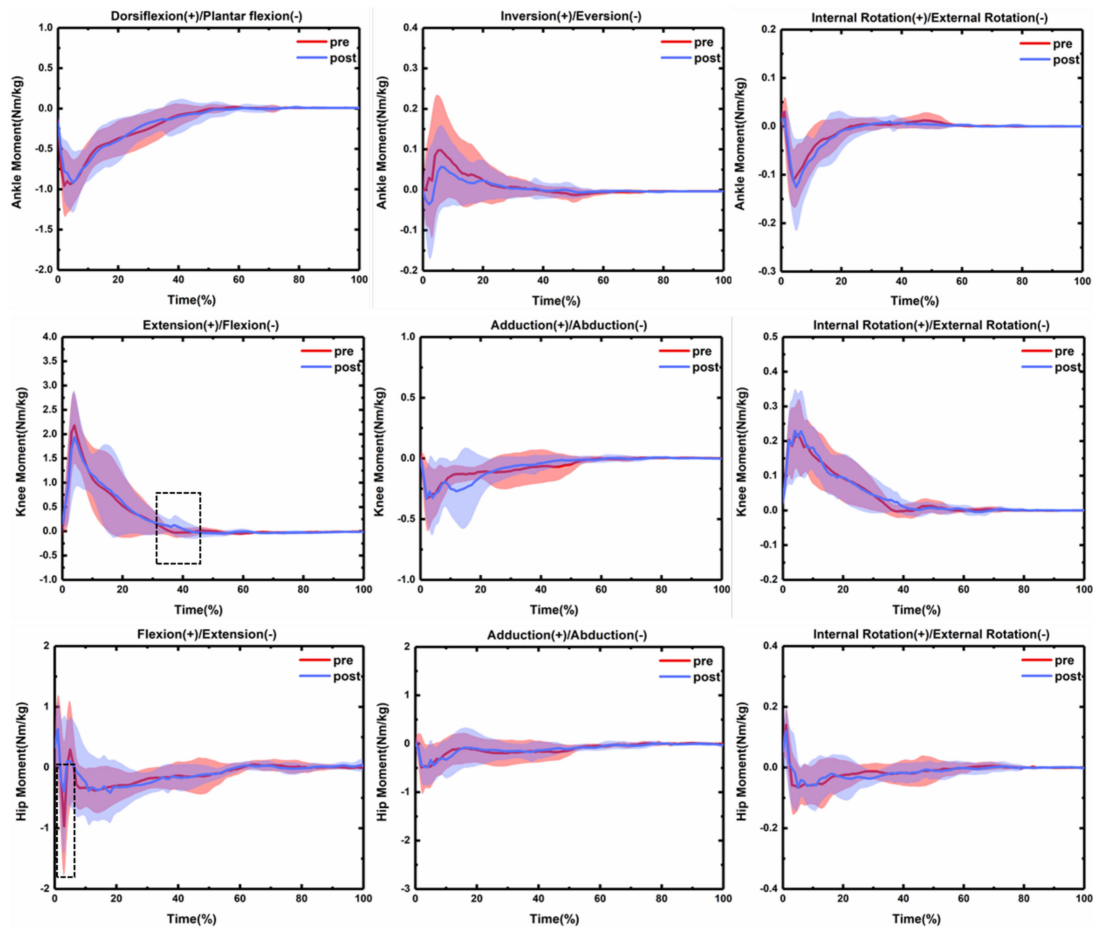
Figure 5. The joint moments between pre- (red solid lines) and post-fatigue (blue solid lines) during the landing phase. Shaded areas mean standard deviation. Black dotted boxes indicate significant differences between the two conditions.

3.3.3. Comparisons of Peak Vertical GRF

As is shown in the Table 4, no significant changes in peak vertical GRF were found between pre-fatigue and post-fatigue conditions during two phases ($p = 0.17$, ES = 0.48; $p = 0.88$, ES = 0.03).

Table 4. Peak value of vertical ground reaction forces (GRF) in the push-off phase and landing phase.

Phase	Condition	PVGRF(BW)	p	ES
Push-off	Pre	1.23 ± 0.13	0.17	0.48
	Post	1.30 ± 0.16		
Landing	Pre	2.38 ± 0.79	0.88	0.03
	Post	2.36 ± 0.50		

Notes: Pre: pre-fatigue; Post: post-fatigue; PVGRF: peak vertical GRF; *p*: *p*-value; ES: effect sizes.

4. Discussion

The purpose of this study was to investigate the influence of running-induced fatigue on performance and lower limb biomechanics of the countermovement jump. Different from our assumptions, jump height was not significantly affected by running-induced fatigue. However, the kinematics and kinetics of the lower limbs, as hypothesized, were significantly changed due to fatigue, especially the kinematic parameters.

No significant differences were found in the jump height between pre- and post-fatigue conditions. It seems that running-induced fatigue does not influence jumping performance. In previous studies,

vertical jump height has been shown to be related to fatigue levels [29]. The fatigue protocols used previously focused on the fatigue of the knee extensor. The interpretation may be that the reduced strength of the knee extensor influenced the lower vertical jump height achieved. Knee extensor fatigue influences several biomechanical variables during countermovement jumping, whereas the fatigue of the knee flexor did not alter the kinetics and kinematics of the lower extremities [37]. The biomechanical alternations in the lower limbs caused by fatigue were varied, which might partly be due to the different fatigue levels and protocols. A decrease in vertical jump height was observed using a fatigue protocol in one hundred drop jumps [38]. However, fatigue induced by running, as a long-term fatigue protocol, may not be severe enough to fatigue the localized muscles which play a vital role in jumping performance. Consecutive jumps were used as a fatigue protocol in a previous study, which focused on landing biomechanics instead of jump height and the entire jump process [26]. Further research used two different exercise-induced fatigue protocols, one of which required running at a constant speed until subjects could not continue. In that study, only the landing phase was considered [39]. Our study focused on the effects of running-induced fatigue on jump height and the entire physiological process of the countermovement jump.

Whether during the push-off phase or the landing phase, the main changes in kinematics happened in the frontal plane. Furthermore, the knee joint angle increased, whereas the hip joint angle decreased. During the push-off phase, the sagittal-plane of motion of the ankle joint decreased following the fatigue intervention, which may be indicating that the movement of the ankle joint was limited. As the triceps surae muscles are proposed to be related to ankle power generation and gait pattern during the push-off phase, the reduction in the triceps surae muscular strength caused by fatigue might be responsible for the ankle kinematics changes in this study [13]. This change would hamper the force production of the lower limbs as well as vertical jump performance [40]. In the final period of the push-off phase, the peak inversion angle under the fatigue condition was larger than that before fatigue, and the foot was in plantar flexion. Combining these changes, the risk of ankle injuries was increased under the post-fatigue condition [41]. Furthermore, fatigue might increase the injury risk to the Achilles tendon which is crucial in propelling the body forward and plantarflexing the foot [15]. During the landing phase, almost all differences between pre- and post-fatigue were increased joint angles, except the peak abduction angle of the hip joint. As fatigue progressed, knee abduction increased during not only the push-off phase but also during the landing phase. In addition, an increased frontal-plane of motion of the knee joint also occurred. All these changes placed the individuals under a greater risk of injuries to the anterior cruciate ligament (ACL) [42]. After prolonged running, foot pronation increased which is an indicator of several running related injuries [19].

Regarding the kinetic changes under fatigue conditions, peak vertical GRF were not significantly different, the peak knee flexion moment and peak hip extension moments were decreased during the landing phase. Landing motions increased forces and moments to the lower limbs, and thus caused the collapse of the lower extremities [43]. Compared to post-fatigue, the peak hip extensor moment and peak knee flexor moment of pre-fatigue were increased, which indicated a stiffer landing [43]. Furthermore, a stiffer landing pattern might be beneficial in attenuating the high impulse loads [44]. Thus, we suspect that the landing pattern after fatigue might not be able to deal with the high impulse loads and increased risk of injuries. In the current study, the peak vertical GRF were not influenced by the intervention of running-induced fatigue. The peak extension moment of the knee joint was not significantly affected by fatigue, which agreed with a previous study [45]. Fatigue caused increased knee valgus moments, decreased knee flexion angles, and increased peak proximal tibial anterior shear forces, resulting in increased injury risk of the ACL [45]. According to previous researches, the changes in GRF during the fatigued motion were still controversial. Augustsson et al. [46] found that not only the vertical and antero-posterior horizontal but also the resultant vector of these two forces were decreased during the landing phase of single leg hopping as fatigue set in. James et al. [47] found that fatigue resulted in greater peak values of GRF and loading rate, and these changes increased the stress fracture injury risk. The type of fatigue protocols was the reason for the different changes

in GRF. Different fatigue protocols influenced neuromuscular and kinematic landing performance characteristics, while the magnitudes of GRF change remained uncertain [48].

While the results of this study interpreted the changes in lower extremities after running-induced fatigue intervention, several inherent limitations should be acknowledged. First, only males were included in this study. Therefore, the results were not appropriate to apply to female populations. Once fatigued, females use a more quadriceps-dominant strategy compared to males [49]. Second, we investigated jump height and the biomechanics of lower extremities when running-induced fatigue occurred, which might help to provide insight into the performance related characteristics of the basketball match. Further studies could use a fatigue protocol utilizing sprint performance, which may be more related to basketball matches. Furthermore, participants were limited to physically active males, and other athletes might present different lower limb biomechanical profiles. Another limitation is that the FPI values were not measured post-fatigue. FPI values have been proven to contribute to increased pronation after long distance running [19]. The changes in the FPI values post-fatigue might be a potential influencing factor to the changes in lower limb biomechanics. Finally, only the peak values of variables in three planes were analyzed, and further studies may incorporate further biomechanical analysis considering greater detail and the investigation of more variables. Further research could also consider investigation into changes in continuous values.

5. Conclusions

Injury risk to the Achilles tendon should be highlighted during the push-off phase when fatigue occurs. The final period of the push-off phase also needs greater attention because of a higher ankle injury risk compared to the pre-fatigue condition. During the landing phase, the increased valgus angle and ROM of the knee joint in the frontal plane resulted in a higher risk of ACL injuries. The results of this study should improve our understanding about the effects of running-induced fatigue on countermovement jumping. The findings also provide valuable information that will help both athletes and coaches minimize injuries.

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