©Journal of Sports Science and Medicine (2018) **17**, 640-649
http://www.jssm.org

Research article

Effects of Exercise-Induced Fatigue on Lower Extremity Joint Mechanics, Stiffness, and Energy Absorption during Landings

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Abstract

The aim of this study was to determine the effects of two fatigue protocols on lower-limb joint mechanics, stiffness and energy absorption during drop landings. Fifteen male athletes completed landing tasks before and after two fatigue protocols (constant speed running [R-FP] and repeated shuttle sprint plus vertical jump [SJ-FP]). Sagittal plane lower-limb kinematics and ground reaction forces were recorded. Compared with R-FP, SJ-FP required significantly less intervention time to produce a fatigue state. The ranges of motion (RoM) of the hip were significantly greater when the athletes were fatigued for both protocols. Knee RoM significantly increased after SJ-FP but not after R-FP ($p > 0.05$), whereas the RoM of the ankle was significantly greater after R-FP but lower after SJ-FP. When fatigued, the first peak knee extension moment was significantly greater in R-FP but lower in SJ-FP; the second peak ankle plantar flexion moment was lower, regardless of protocols. After fatigue, vertical, hip, and knee stiffness was lower, and more energy was absorbed at the hip and knee for both protocols. Hip and knee extensors played a crucial role in altering movement control strategies to maintain similar impact forces and to dissipate more energy through a flexed landing posture when fatigued compared to when non-fatigued. Furthermore, SJ-FP seems to be a more efficient method to induce fatigue due to less intervention time than R-FP.

Key words: Landing, exercise-induced fatigue, joint mechanics, stiffness, energy absorption.

Introduction

The lower extremity, particularly at the ankle and knee joints, is vulnerable to injuries during movements involving repetitive landings. One major reason is that during those landing activities, e.g., landings after a basketball layup, a volleyball block jump or a gymnastics somersault, the lower extremity is exposed to vertical ground reaction forces (GRFs) amounting to 3.5–11 times body weight (BW) (Puddle and Maulder, 2013). The lower extremity plays a crucial role in attenuating these impacts (Kim et al., 2017). Consequently, related overuse damages, e.g., stress fracture (James et al., 2006), patellar tendinopathy (Rosen et al., 2015) and internal derangement of the knee joint (Granata et al., 2002; Tsai et al., 2016), often result from the accumulation of these repeated high impacts (Macdermid et al., 2017).

Adjustments in the landing patterns of the lower limbs, e.g., changes in leg geometry and joint torque or stiffness, can be beneficial for mediating the magnitude of the impact forces, joint loading and energy dissipation (Rowley and Richards, 2015; Yeow et al., 2011). For instance, DeVita et al. (1992) reported a redistribution of joint energy absorption in the lower extremity during a soft landing with a greater peak knee flexion compared with a stiff landing. However, these altered landing strategies are negatively affected by neuromuscular fatigue associated with prolonged exercise and, such fatigue may place athletes at a higher risk of landing-related injury (Murdock and Hubley-Kozey, 2012; Tamura et al., 2016). Brazen et al. (2010) observed a greater peak GRF after fatigue, whereas Cortes et al. (2014) reported a more erect landing posture after fatigue; both were considered as risk factors for anterior cruciate ligament injury. Moreover, studies on the effects of fatigue during landing activities have demonstrated different responses in both GRF characteristics and lower extremity control strategies (James et al., 2010; Nikooyan and Zadpoor, 2012). While Coventry et al. (2006) illustrated an increase in knee flexion after fatigue, a study reported no significant differences in knee flexion in women in post fatigue conditions (Kernozek et al., 2008), or even decreased knee flexion, as mentioned previously (Cortes et al., 2014). Collectively, numerous studies have shown that neuromuscular fatigue can affect the landing strategy of the lower extremity, mostly in a detrimental manner (Madigan and Pidcoe, 2003; Murdock and Hubley-Kozey, 2012). Multifactorial causes underlie these different responses, and further studies beyond the analysis of the kinematic level are warranted to provide insight on the energy absorption / dissipation strategies and the underlying neuromuscular actions occurring during fatigue.

Developing reliable fatigue protocols is a key aspect in understanding the effects of fatigue on landing biomechanics. The components for designing a fatigue protocol in a laboratory setting include consistent fatigue levels, valid fatigue models and standardized landing styles (Barberwestin and Noyes, 2017; Ferraz et al., 2017). Studies have followed both short- and long-term fatigue protocols. The short-term protocols included consecutive vertical jumps (Chappell et al., 2005), short-distance sprints and shuttle runs (Sanna and O'Connor, 2008) and approximately 50% 1 repetition maximum pedal exercise of the lower limbs (Gehring et al., 2009). The long-term protocols mainly induced fatigue through long-term treadmill running (Dierks et al., 2010; Koblbauer et al., 2014). Moreover, a recent study reported that fatigue protocols involved combinations of forward sprints, lateral shuffles, pivoting and backward running (Webster et al., 2016). Various fatigue protocols have been established to more accurately

Received: 21 March 2018 / Accepted: 15 October 2018 / Published (online): 20 November 2018

mimic athletic activities occurring in real sports scenarios. Nevertheless, evidence is still limited regarding whether biomechanical changes in the lower extremity are related to the type, site, or severity of fatigue (Barberwestin and Noyes, 2017). Furthermore, inconsistent results in the shock attenuation of the lower extremity were found in various exercise-induced fatigue protocols (Coventry et al., 2006). As previously summarized, no scientific consensus has been reached regarding the effects of fatigue on specific biomechanical features, such as kinematics, kinetics, stiffness and energy dissipation. The lack of consensus is largely because of insufficient comparisons between different fatigue protocols.

Therefore, this study quantified the effects of two typical exercise-induced fatigue protocols (constant speed running [R-FP] and repeated shuttle sprint plus vertical jump [SJ-FP]) on joint mechanics, stiffness and energy absorption in the sagittal plane of the lower extremity during double-leg drop landings. We hypothesized that both fatigue protocols would alter GRFs, joint mechanics, stiffness and energy absorption. Specifically, participants would have more GRFs and joint range of motion, and less vertical stiffness and joint stiffness, as well as more energy absorption after fatigue. Moreover, aforementioned biomechanical variables would be more pronounced in SJ-FP than R-FP.

Methods

Participants

Considering the intensity of a series of fatigue tests, fifteen collegiate male medium distance runners (age: 20.9 ± 0.8 years; height: 1.76 ± 0.04 m; weight: 68.9 ± 5.5 kg), with an average of 4.2 ±1.1 years of experience in track and field events were recruited to participate in the study. All athletes had no history of musculoskeletal injuries to the lower extremity in the previous 6 months and did not engage in strenuous exercise for 24 hours before the study. A post-hoc power analysis was performed to indicate the statistical power. It revealed that a sample size of 15 was sufficient to minimize the probability of Type II error for our variables of interest (Faul et al., 2007). Each participant signed an informed consent form before the experiments. The study was approved by the Institutional Review Board of Shanghai University of Sports.

Instrumentation

Kinematics were collected using a 16-camera infrared three-dimensional (3D) motion capture system (Vicon T40, Oxford Metrics, UK) at a sampling rate of 240 Hz. Thirty-six infrared retroreflective markers, each with a diameter of 14.0 mm, were attached bilaterally to both lower extremities to define hip, knee and ankle joints according to the plug-in gait marker set (Figure 1). GRFs were measured with two 90 × 60 × 10-cm 3D force plates (9287C, Kistler Corporation, Switzerland) at a sampling rate of 1200 Hz. The 3D kinematic and force plate data were synchronized using the Vicon system. The maximum vertical jump height of each participant was acquired with a Quattro Jump force plate (9290BD, Kistler Corporation, Switzerland), which was also used to monitor the vertical jump height during the procedure of inducing fatigue. A heart rate (HR) transmitter belt monitor (SS020674000, Suunto Oy, Finland) was attached to each participant's chest to continuously monitor their HR during the entire fatigue procedure. The intervention time was recorded by a stopwatch (ZSD-013, sienoc, USA).

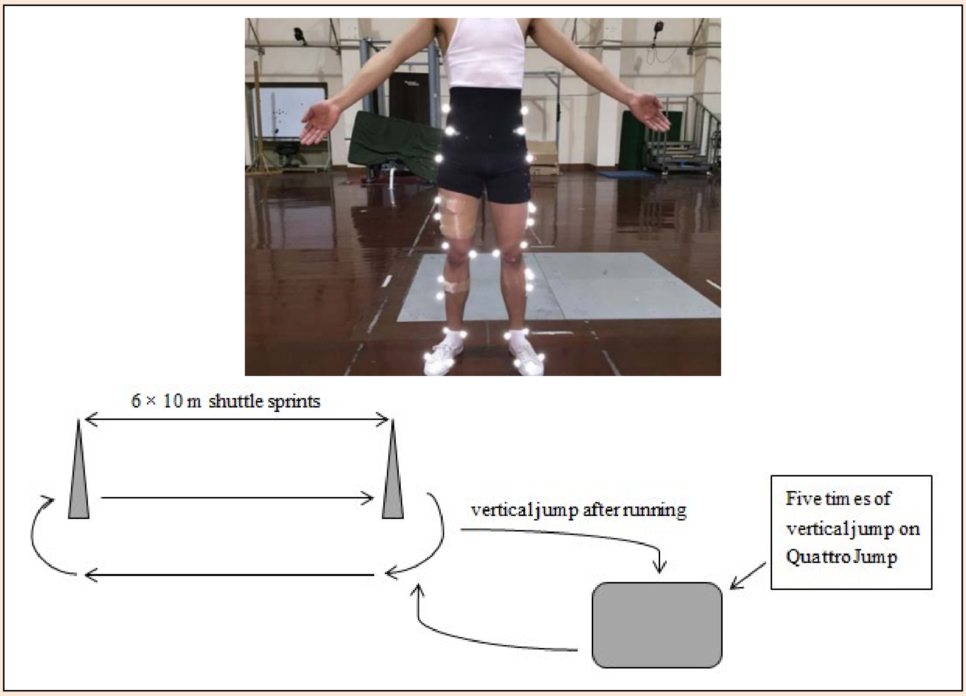

Figure 1. Marker set used in this study (upper). Scheme of the exercise-induced fatigue protocol with shuttle sprint and vertical jump (lower).

Experimental protocol

The participants visited the laboratory on two separate days and completed bipedal drop landing (DL) tasks for one of the two exercise-induced fatigue protocols at each visit. A 1-week break period was required between visits to ensure that fatigue was eliminated, and the two protocols would not affect each other (Yeow et al., 2009). The order of the two protocols was randomized using a random number allocation table (Zhang et al., 2000).

At each visit, the participants were asked to complete the DL tasks from a height of 60 cm (Zhang et al., 2000). A successful trial required the participants to step off with either leg from a landing platform without jumping up or losing their balance and to land as naturally as possible with a toe-heel landing. Furthermore, the participants were instructed to perform the landing tasks with their arms on their hips to reduce the influence of swinging during landing. Before given practice trials to become familiar with the DLs, participants wore a spandex outfit with non-cushioning shoes (WD-2A; Warrior, Shanghai, China). After a regular warm-up routine and practice trials, five successful trials were acquired for analysis. The DL tests were performed before and after conducting the exercise-induced fatigue protocols.

Exercise-induced fatigue protocol with constant speed running (R-FP)

The participants were required to run on a treadmill at 4 m/s until they could not continue running (Garcia-Perez et al., 2013). They were considered to have achieved fatigue, and intervention was terminated when the following two criteria were met: 1) The HR of the participants reached 90% of their age-calculated maximum HR (maximum HR estimated as 220 − age) (Ramos-Campo et al., 2017) and 2) the participants could not continue running (Quammen et al., 2012).

Exercise-induced fatigue protocol with shuttle sprint + vertical jump (SJ-FP)

Before executing the SJ-FP, the maximal height of the vertical jump for each participant was recorded. The fatigue protocol comprised five consecutive vertical jumps, followed by a series set of 6 × 10-m shuttle sprints (Figure 1) (Tsai et al., 2009). The participants were required to repeat the aforementioned sequence at least five times with their maximal effort. They were considered to have reached a fatigued state, and the intervention was terminated when the following occurred: 1) the participants could not reach 70% of the maximal vertical jump height for all five jumps and 2) The HR of the participants reached 90% of their age-calculated maximum HR (maximum HR estimated as 220 − age) (Ramos-Campo et al., 2017).

During the procedure of either fatigue-induced intervention, the highest HR or intervention time was recorded. The rated perceived exertion (RPE) for each participant was acquired immediately after the intervention (Chow and Etnier, 2017).

Data processing

Data for the dominant leg, defined as the preferred kicking leg (Yeow et al., 2009), were processed. The 3D coordinates of the reflective markers were filtered through a Butterworth fourth-order, low-pass filter at a cut-off frequency of 7 Hz with V3D software (4.0.75.12, C-Motion Inc., USA) (Fu et al., 2017). The GRF data were filtered at a cut-off frequency of 100 Hz. The initial contact was defined as the time at which the GRF exceeded 10 N (Lee et al., 2013). The landing period in this study was defined as the time interval from the initial contact to the occurrence of the maximum knee flexion (Hoch et al., 2015; Zhang et al., 2000). The absolute total landing time (from initial contact to maximum knee flexion) was calculated. The RoM in degrees for hip (RoM_H), knee (RoM_K) and ankle (RoM_A) were determined by calculating the differences between the maximum and minimum angles of the three joints during the landing period.

The impact force shortly after the ground contact, normally within the initial 20% of the landing period, typically included two peaks (Figure 2) (Nordin et al., 2017). Accordingly, the main variables of the GRF included: 1) the first peak of the vertical GRF (vGRF1) and the absolute (t_vGRF1) and relative time (T_vGRF1) from contact to vGRF1, and 2) the second peak of the vertical GRF (vGRF2) and the absolute (t_vGRF2) and relative time (T_vGRF2) from contact to vGRF2. The vGRF was normalized to body weight (BW) and the relative time was normalized by total landing time (% of landing time).

Three-dimensional net joint moments were calculated by combining the kinematic and force plate data with anthropometric data by Dempster (1955) in inverse dynamics equations. Values for each joint moment were normalized to body mass and are presented as internal (muscle) moments. Hip, knee, and ankle joint centers were calculated by the coordinates from a static calibration trial with local coordinate systems for each segment in participants. Hip-joint center was defined as 25% of the distance from the ipsilateral to the contralateral greater trochanter marker. Knee-joint center was located midway of a line between the lateral and medial femoral condyles markers. Ankle-joint center was located midway of a line between the lateral and medial malleoli markers. Representative curves and peaks of the hip (M_H), knee (M_K) and ankle (M_A) joint moments during DL are presented in Figure 2. Based on the study of Zhang et al. (2000) the main variables of the joint moment included 1) two typical peaks of the first (M_{H1} and M_{A1}) and second (M_{H2} and M_{A2}) moments in both hip and ankle joint moment – time curves as well as the absolute (t_M_{H1}, t_M_{A1}, t_M_{H2} and t_M_{A2}) and relative time (T_M_{H1}, T_M_{A1}, T_M_{H2} and T_M_{A2}) from contact to M_{H1}, M_{A1}, M_{H2} and M_{A2}, and 2) three typical peaks (M_{K1}, M_{K2} and M_{K3}) in the knee joint moment – time curve as well as the absolute (t_M_{K1}, t_M_{K2} and t_M_{K3}) and relative time (T_M_{K1}, T_M_{K2} and T_M_{K3}) from contact to M_{K1}, M_{K2} and M_{K3}.

The variables for the stiffness of the lower extremity included: 1) vertical stiffness (k_{vert}) = F_{max} /Δy (Granata et al., 2002), where F_{max} is the maximum vGRF, and Δy is the maximum vertical displacement of the center of mass based on the pelvis and greater trochanter anatomical landmarks; 2) average joint stiffness (k_{joint}) = ΔM/RoM (Butler and Davis, 2003), where ΔM is the change in hip, knee, and ankle joint moments during the landing period (from the

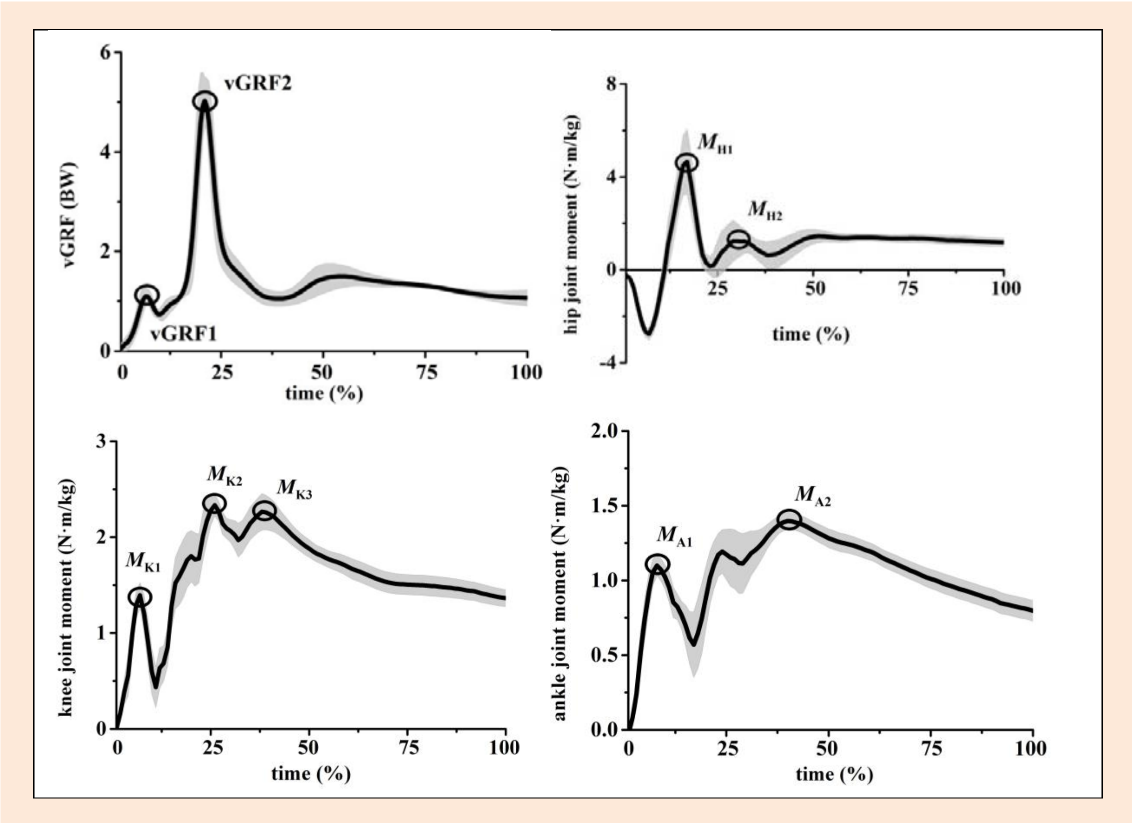

Figure 2. vGRF – time curve and hip, knee, and ankle joint moment – time curves during a DL task from a 60-cm height. vGRF = vertical ground reaction force; vGRF1, vGRF2 = the first and second peaks of the vertical ground reaction forces; M_{H1}, M_{H2} = two typical peaks in the hip joint moment – time curve; M_{K1}, M_{K2}, and M_{K3} = three typical peaks in the knee joint moment – time curve; M_{A1}, M_{A2} = two typical peaks in the ankle joint moment – time curve.

initial contact to the maximum knee flexion), and the RoM is the joint range of motion.

Joint energy in this study refers to the magnitude of the joint work during the landing period, i.e., time integral of joint power by using the following equation (Yeow et al., 2009):

$$Energy = \int_{t_2}^{t_1} P_j(t) \cdot dt$$

where P_j is the joint power computed as the product of the joint moment and joint angular velocity, and t_1 and t_2 are the time interval from the initial contact to the occurrence of the maximum knee flexion. The net amount of work of the three joints during the landing period is negative, indicating energy absorption (EA) through eccentric muscle contractions.

Statistical analysis

Paired *t*-tests were performed to determine the effects of fatigue protocols on intervention time, the maximal HR and RPE. A 2 × 2 repeated-measures ANOVA was used to quantify the effects of fatigue (pre- and post fatigue) and fatigue protocols (R-FP and SJ-FP) on each variable of the joint RoM, joint mechanics, stiffness and joint energy. When a significant interaction effect was found for an ANOVA, paired *t*-tests were used as *post hoc* tests to identify potential protocol effects before or after fatigue and fatigue effects for each protocol (21.0, SPSS Inc., USA). The observed effect size (η^2) values were reported to ANOVAs results and effect size (Cohen's *d*) values were reported to paired *t*-tests results. The level of significance was set at $p < 0.05$.

Results

Fatigue-induced intervention

Compared with R-FP, SJ-FP required significantly less intervention time to produce a fatigue state (SJ-FP: 4.3 ± 0.98 vs. R-FP: 18.8 ± 5.7 min, p < 0.01, Cohen's *d* = 3.55). No significant differences were observed in the maximal HR (SJ-FP: 184.7 ± 6.3 vs. R-FP: 189.4 ± 6.9 bpm, p > 0.05) and RPE scale (SJ-FP: 16.7 ± 1.4 vs. R-FP: 16.3 ± 1.3, p > 0.05) between SJ-FP and R-FP.

Joint mechanics

Significant fatigue × protocol interaction effects were observed for RoM_K (p = 0.01, η^2 =0.21) and RoM_A (p < 0.01, η^2 = 0.25) (Figure 3). Specifically, RoM_K significantly increased in SJ-FP (p < 0.01, Cohen's *d* = 0.75), but not in R-FP (p > 0.05) after fatigue. RoM_A significantly decreased in R-FP (p = 0.049, Cohen's *d* = 0.43) but increased in SJ-FP (p = 0.013, Cohen's *d* = 0.26) after fatigue. A significant main effect of fatigue was observed for the RoM_H, which increased by 13.5% (p < 0.01, η^2 = 0.44) during landings after fatigue (Table 1). However, no significant differences were observed for either the vertical peak GRF (vGRF1 and vGRF2) or the absolute occurrence time (*t*_vGRF1 and *t*_vGRF2) between the pre- and post-fatigue tests (p > 0.05) (Table 1). For the joint moment, significant fatigue ×

protocol interaction effects were noted for M_{K1} ($p = 0.027$, $\eta^2 = 0.16$), t_M_{H2} ($p = 0.027$, $\eta^2 = 0.16$) and t_M_{A2} ($p = 0.048$, $\eta^2 = 0.13$) (Figure 3). Specifically, M_{K1} increased in R-FP ($p = 0.035$, Cohen's $d = 0.29$) but decreased in SJ-FP ($p = 0.031$, Cohen's $d = 0.72$) after fatigue. t_M_{H2} did not change in R-FP ($p > 0.05$) but increased in SJ-FP ($p = 0.025$, Cohen's $d = 0.34$) , whereas t_M_{A2} decreased in R-FP ($p = 0.028$, Cohen's $d = 0.30$) but increased in SJ-FP ($p < 0.01$, Cohen's $d = 0.46$). A significant main effect of fatigue was observed for M_{A2}, which decreased by 13.3% ($p = 0.015$, $\eta^2 = 0.19$) during landings after fatigue (Table 2). A significant main effect of fatigue was observed for the absolute total landing time and relative time of each peak. Specifically, total landing time increased in both protocols after fatigue ($p < 0.01$, $\eta^2 = 0.19$), and T_vGRF1 ($p = 0.04$, $\eta^2 = 0.19$), and T_vGRF2 ($p = 0.02$, $\eta^2 = 0.22$), and relative time of each joint moment peak decreased in both protocols after fatigue ($p < 0.05$, $\eta^2 = 0.18 \sim 0.44$) (Table 3). All interaction and main effects not discussed were non-significant ($p > 0.05$).

Stiffness

Significant main effects of fatigue were observed for k_{vert} and Δy (Figure 4). Specifically, k_{vert} decreased by 15.3% (18.70 ± 6.02 BW/m vs. 15.64 ± 5.01 BW/m; $p < 0.01$, $\eta^2 = 0.29$) and Δy increased by 17.1% (0.35 ± 0.02 m vs. 0.41 ± 0.02 m; $p < 0.01$, $\eta^2 = 0.31$) after fatigue. Hip and knee stiffness decreased by 18.4 % (0.29 ± 0.03 Nm/kg/° vs. 0.24 ± 0.02 Nm/kg/°; $p < 0.01$, $\eta^2 = 0.27$) and 15.7% (0.05 ± 0.003 Nm/kg/° vs. 0.041 ± 0.002 Nm/kg/°; $p < 0.01$, $\eta^2 = 0.33$) during landings after fatigue (Figure 4). No significant differences were observed for ankle stiffness between the pre- and post-fatigue tests ($p > 0.05$). There was neither significant group by fatigue interaction, nor main effects of protocol with respect to vertical and joint stiffness ($p > 0.05$).

Joint energetics

A significant main effect of fatigue was observed on the joint EA. Specifically, hip (0.88 ± 0.08 J/kg vs. 1.05 ± 0.10 J/kg; $p < 0.01$, $\eta^2 = 0.27$) and knee (1.87 ± 0.07 J/kg vs. 1.95 ± 0.07 J/kg; $p < 0.01$, $\eta^2 = 0.33$) joints absorbed more energy during landings after fatigue (Figure 4). No significant differences were observed for the energy absorbed by the ankle joint between the pre- and post- fatigue tests ($p > 0.05$).

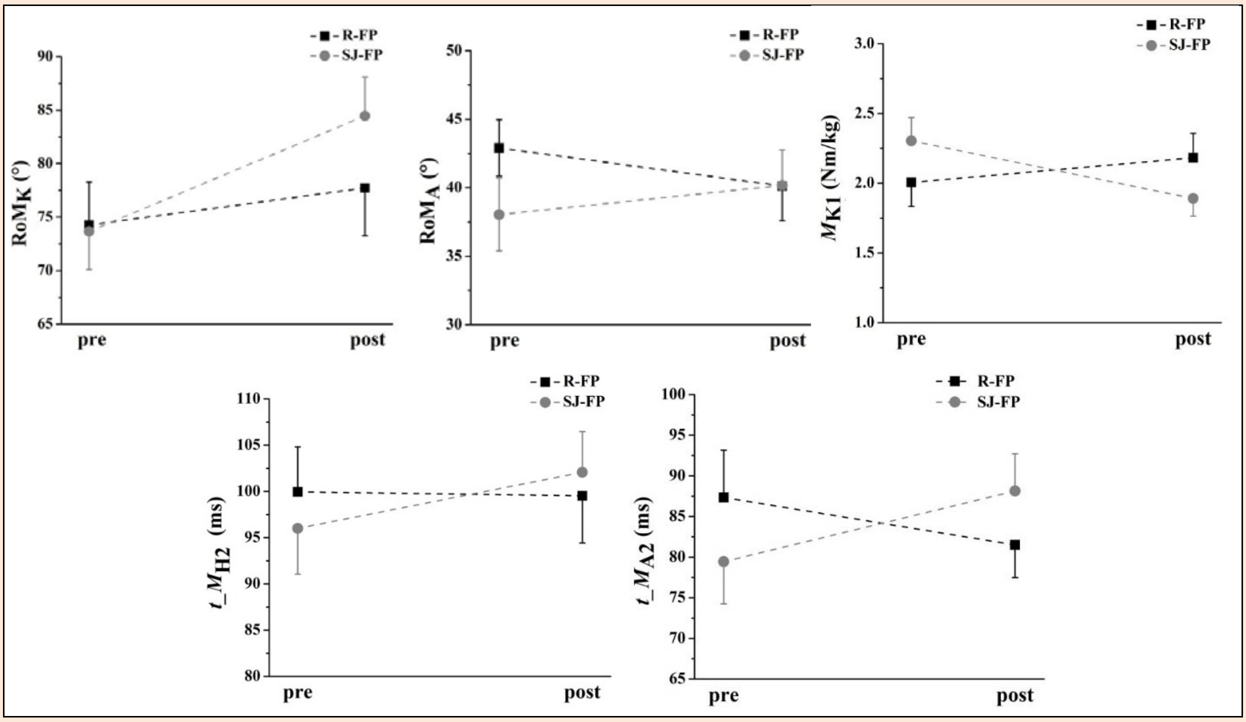

Figure 3. Significant fatigue × protocol interaction effects for RoM$_K$ and RoM$_A$ (upper), M_{K1} (middle), t_M_{H2} and t_M_{A2} (lower). R-FP = fatigue protocol with constant speed running; SJ-FP = fatigue protocol with shuttle sprint plus vertical jump; pre = pre-fatigue; post = post-fatigue.

Table 1. Comparison of the RoM, peak vGRF (vGRF1 and vGRF2), and absolute occurrence time (t_vGRF1 and t_vGRF2) (mean ± SD) in the sagittal plane during landings between pre- and post-fatigue conditions.

Protocols	Fatigue	RoMH (°) *	RoMK (°) *†	RoMA (°) *†	vGRF1 (BW)	t_vGRF1 (ms)	vGRF2 (BW)	t_vGRF2 (ms)
R-FP	pre	48.5 ± 17.9	73.8 ± 14.9	44.2 ± 9.0	1.2 ± 0.5	12.2 ± 1.8	5.8 ± 0.9	33.6 ± 6.5
	post	53.7 ± 17.5	78.9 ± 15.9	40.2 ± 9.5	1.1 ± 0.4	12.7 ± 2.6	5.8 ± 1.0	32.7 ± 7.5
SJ-FP	pre	50.4 ± 14.2	73.6 ± 13.4	37.9 ± 9.8	1.2 ± 0.5	11.9 ± 3.8	6.0 ± 0.8	33.3 ± 8.8
	post	58.6 ± 15.8	83.7 ± 13.5	40.4 ± 9.6	1.4 ± 0.3	11.6 ± 3.5	5.9 ± 0.9	29.9 ± 10.4

* Significant differences between pre- and post-fatigue conditions, with $p < 0.05$. † Significant fatigue × protocol interaction effects, with $p < 0.05$. R-FP = fatigue protocol with constant speed running; SJ-FP = fatigue protocol with shuttle sprint plus vertical jump; pre = pre-fatigue; post = post-fatigue; RoM$_H$ = the range of motion of the hip; RoM$_K$ = the range of motion of the knee; RoM$_A$ = the range of motion of the ankle; vGRF1, vGRF2 = the first and second peaks of the vertical ground reaction forces; t_vGRF1, t_vGRF2 = the absolute time from contact to vGRF1, vGRF2; BW = body weight.

Table 2. Comparison of the peak moment (M_H, M_K, and M_A, N·m/kg) and absolute occurrence time (t, ms) (mean ± SD) in the hip, knee, and ankle joints in the sagittal plane during landings between pre- and post-fatigue conditions.

Protocols	Fatigue	MH1	t_MH1	MH2	tMH2*†	MK1*†	tMK1	MK2	tMK2	MK3	tMK3	MA1	tMA1	MA2*	tMA2*†
R-FP	pre	8.9 ±2.2	35.6 ±11.0	2.0 ±1.0	99.9 ±18.9	2.0 ±0.7	17.3 ±3.5	2.5 ±0.5	53.7 ±16.0	2.3 ±0.5	82.8 ±34.6	1.6 ±0.5	18.4 ±5.9	1.5 ±0.4	87.3 ±22.7
	post	9.2 ±2.3	32.6 ±10.5	2.1 ±0.8	99.5 ±19.8	2.2 ±0.7	19.7 ±6.1	2.4 ±0.6	57.2 ±17.6	2.4 ±0.6	90.4 ±45.5	1.5 ±0.9	17.6 ±7.2	1.4 ±0.4	81.5 ±15.5
SJ-FP	pre	8.9 ±1.6	31.3 ±12.2	2.2 ±0.9	96.0 ±19.2	2.3 ±0.6	18.6 ±7.3	2.4 ±0.5	51.7 ±12.6	2.3 ±0.4	85.3 ±18.5	1.4 ±0.5	19.9 ±7.3	1.4 ±0.3	79.4 ±20.2
	post	8.9 ±2.3	31.7 ±11.5	2.0 ±0.5	102.1 ±17.0	1.9 ±0.5	16.2 ±3.9	2.3 ±0.5	53.6 ±10.5	2.2 ±0.5	72.8 ±30.1	1.4 ±0.6	17.9 ±6.7	1.3 ±0.3	88.1 ±17.7

* Significant differences between pre- and post-fatigue conditions, with $p < 0.05$. † Significant fatigue × protocol interaction effects, with $p < 0.05$. R-FP = fatigue protocol with constant speed running; SJ-FP = fatigue protocol with shuttle sprint plus vertical jump; pre = pre-fatigue; post = post-fatigue; M_{H1}, M_{H2} = two typical peaks in the hip joint moment – time curve; t_M_{H1}, t_M_{H2} = the absolute time of contact to M_{H1} and M_{H2}; M_{K1}, M_{K2}, and M_{K3} = three typical peaks in the knee joint moment – time curve; t_M_{K1}, t_M_{K2}, t_M_{K3} = the absolute time of contact to M_{K1}, M_{K2}, and M_{K3}; M_{A1},M_{A2} = two typical peaks in the ankle joint moment – time curve; t_M_{A1}, t_M_{A2} = the absolute time of contact to M_{A1} and M_{A2}.

Table 3. Comparison of the absolute total landing time (ms) and relative time of each peak (T, % of landing time) (mean ± SD) during landings between pre- and post-fatigue conditions.

Protocols	Fatigue	Total landing time*	T_vGRF1*	T_vGRF2*	T_MH1*	T_MH2*	T_MK1*	T_MK2*	T_MK3*	T_MA1*	T_MA2*
R-FP	pre	225.8 ± 72.7	5.9 ± 3.2	17.4 ± 9.6	18.0 ± 9.4	49.1 ± 16.8	8.4± 2.6	25.3 ± 7.0	39.7 ± 14.2	9.2± 4.2	41.1± 9.6
	post	251.3 ± 69.2	5.0 ± 2.4	14.1 ± 7.4	13.6 ± 6.4	40. 6 ±11.3	7.8 ± 2.1	22.9 ± 6.7	36.9 ± 17.5	7.1 ± 2.9	33.1 ± 8.9
SJ-FP	pre	228.3 ± 54.8	5.7 ±1.3	15.8 ± 4.8	18.3 ± 6.1	53.2 ± 10.7	10.4 ± 4.2	28.1 ± 8.4	43.9 ± 12.4	10.0 ± 3.7	39.3± 8.2
	post	255.1 ± 46.4	5.2 ± 1.3	13.5 ± 4.2	13.0 ± 4.9	41.7 ± 9.5	6.7 ± 2.4	21.2 ± 6.4	33.3 ± 9.1	7.3 ± 2.8	35.6 ± 7.1

* Significant differences between pre- and post-fatigue conditions, with $p < 0.05$. R-FP = fatigue protocol with constant speed running; SJ-FP = fatigue protocol with shuttle sprint plus vertical jump; pre = pre-fatigue; post = post-fatigue; T_vGRF1, T_vGRF2 = the relative time from contact to vGRF1, vGRF2; T_M_{H1}, T_M_{H2} = the relative time from contact to M_{H1} and M_{H2}; T_M_{K1}, T_M_{K2}, T_M_{K3} = the relative time from contact to M_{K1}, M_{K2}, and M_{K3}; T_M_{A1}, T_M_{A2} = the relative time from contact to M_{A1} and M_{A2}.

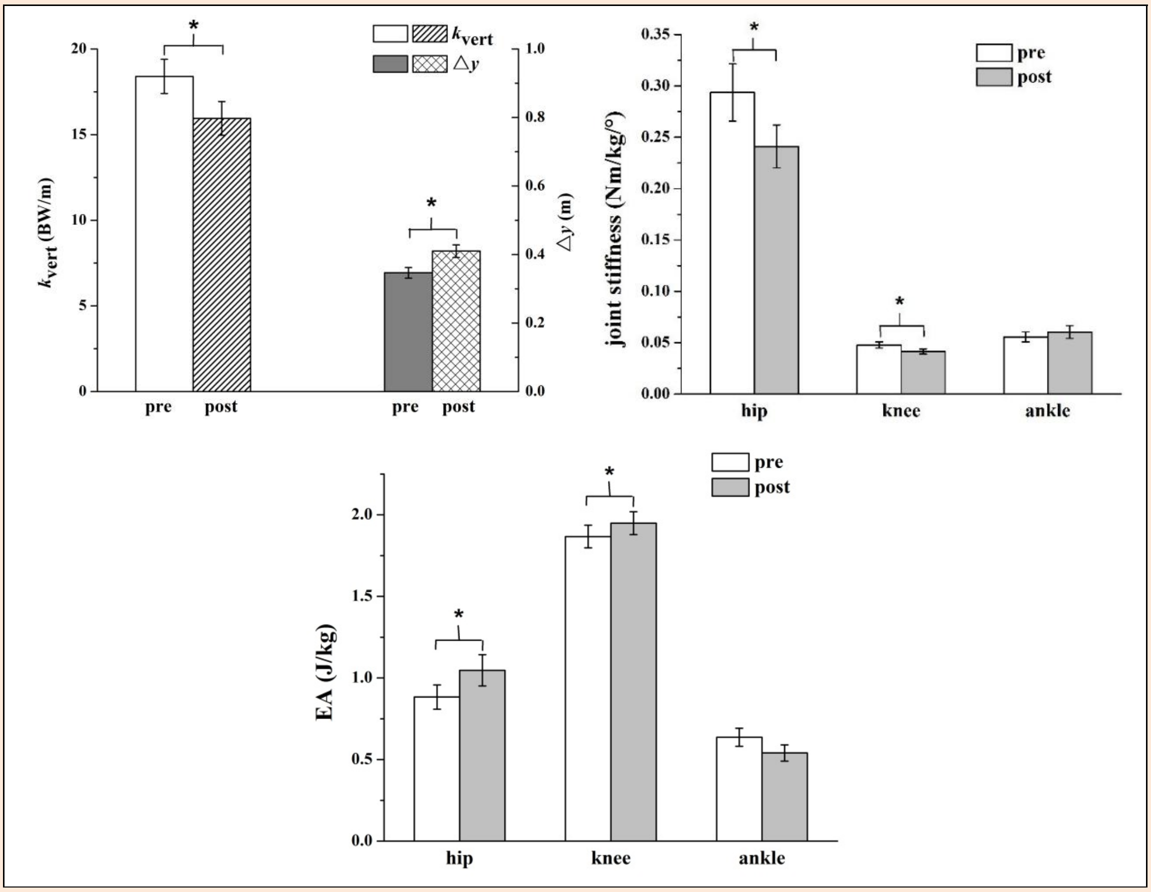

Figure 4. Comparison of k_{vert} and Δy (left upper) and joint stiffness (right upper), and the EA in the hip, knee, and ankle joints (lower) during landings between pre- and post-fatigue conditions. *Significant differences between pre- and post-fatigue conditions, $p < 0.05$. pre = pre-fatigue; post = post-fatigue; k_{vert} = vertical stiffness; Δy = the maximum vertical displacement of the center of mass; EA = energy absorption.

Discussion

The purpose of this study was to determine the effects of two fatigue protocols (R-FP and SJ-FP) on lower extremity joint mechanics, stiffness and EA in the sagittal plane during double-leg DLs. Regardless of protocol, fatigue altered landing performance by increasing RoM_H; reducing M_{A2}, k_{vert}, and hip and knee stiffness; as well as absorbing more energy in the hip and knee. In addition, total landing time increased and relative time of vGRF and each joint moment peak decreased in both protocols after fatigue. Apart from the finding that no fatigue effect was observed on the GRFs, these results supported our first hypothesis. Furthermore, significant fatigue × protocol interaction effects were noted for RoM_K, RoM_A, M_{K1}, t_M_{H2} and t_M_{A2}. Moreover, less intervention time was observed in SJ-FP. These results partially supported our second hypothesis, i.e., fatigue changed the lower extremity biomechanics between the two protocols. Summarized as follows (↑ = increase; - = no difference; ↓ = decrease):

Measure	R-FP	SJ-FP
RoM_K	-	↑
RoM_A	↓	↑
M_{K1}	↑	↓
t_M_{H2}	-	↑
t_M_{A2}	↓	↑

Our main results indicated that the participants adopted a more flexed landing posture and total landing time increased after fatigue, which was associated with an increase in RoM_H and RoM_K (Table 1). These results were consistent with Kernozek et al.'s study (2008) showing that the male participants landed with greater hip and knee flexion during a 50-cm DL after fatigue. Similar to our findings, Orishimo et al. (2006) observed greater knee motion and the increasing tendency of RoM_H during single-leg hop landing after a fatigue protocol, consisting of two sets of 50 step-ups , which was more close to SJ-FP. One explanation for the greater joint RoM was that a soft landing, defining as the knee flexion angle greater than 90° after floor contact (Devita and Skelly, 1992), was adopted to dissipate the external impact force in a fatigue state. Furthermore, RoM_K increased more in SJ-FP not in R-FP, and ROM_A significantly increased in SJ-FP but decreased in R-FP after fatigue. Similar results were measured in James at el.'s study (2010), who reported the inconsistent knee flexion between two different protocols. Briefly, after fatigue had been induced, participants were more likely to change the control of joint movement during a preplanned neuromuscular task (Zadpoor and Nikooyan, 2012).

Coventry et al. (2006) demonstrated that major muscle groups (e.g., hip and knee extensors) played a more vital role in landing strategy after fatigue to maintain similar shock attenuation. The current evidence in this study directly showed no significant differences in the first and second peak vertical GRFs. Our results were consistent with Wikstrom et al.'s study (2004), which reported no significant difference in vGRF between isokinetic and functional fatigue protocols. Thus, it is logical to assume that to a certain extent, participants may protect themselves from impact-related injury by maintaining a similar GRF pattern after fatigue. According to our review of relevant literature, whether the aforementioned changes were induced by fatigue itself or by a proposed self-prevention strategy remained unclear (Elvin et al., 2007). Notably, previous evidence showed a significantly increased RoM_K during single-leg hop landing with unchanged impact forces when fatigued (Orishimo and Kremenic, 2006). No significant differences were observed for the absolute occurrence time (t_vGRF1 and t_vGRF2), however, the results of relative time (T_vGRF1 and T_vGRF2) revealed the time to impact force was shortened and more time was needed to dissipate the external impact force by a more flexed landing posture after fatigue. Thus, additional studies are warranted to investigate underlying mechanisms between landing movement control and impact in a fatigue state.

With regard to joint moments, most studies have focused on fatigue effects on the mean or single peak joint moment during landings (Cortes et al., 2013). However, on the basis of the literature (Zhang et al., 2000) and the typical changes in joint moment patterns in the present study, different peak joint moment values for specific joints were selected for examination during the initial landing phase. Specifically, the passive joint moment during initial landings, mainly developed by the peak impact forces (Figure 2), acted to flex the hip, knee and ankle (dorsiflex) joints at the early contact (Madigan and Pidcoe, 2003). Accordingly, the corresponding muscles promptly produced large extension (plantarflexion) moments in the hip, knee and ankle to avoid the collapse of the lower extremity (Figure 2: M_{H1}, M_{K1}, M_{K2} and M_{A1}) (Pandy and Andriacchi, 2010). Meanwhile, our findings revealed that M_{K1} increased in R-FP but decreased in SJ-FP after fatigue, possibly indicating that the control strategy of knee muscles changed differently throughout first 10% of landing where it appears M_{K1} occurs in two protocols (Murdock and Hubley-Kozey, 2012). For instance, Kernozek et al. (2008) reported a fatigue protocol consisting of a parallel squat exercise until failure caused 20% less knee extensor moment, regardless of sex during a single-leg landing. However, Coventry et al. (2006) did not observe any significant differences in the peak knee extension moment after a fatigue protocol that involved combinations of DL, jumping and squatting. Subsequently, second peak moments were observed to maintain a stable landing posture by proactively extending the lower extremity (Figure 2: M_{H2}, M_{K3} and M_{A2}). In our study, M_{A2} decreased after fatigue, regardless of protocols. This was consistent with Madigan and Pidcoe's study (2003), who reported a decrease in plantar flexion moment at ankle joint during landing after fatigue. The protocol requiered participants to complete 19 cycles of the fatigue activity, consisting of two single-leg drop landings and three single-leg squats. Although t_M_{H2} only increased in SJ-FP and t_M_{A2} decreased in R-FP but increased in SJ-FP, the relative time of each joint moment peak decreased in both protocols after fatigue. These findings indicated the fatigue affected the capacity of initiative contraction in extensor and plantarflexors, e.g., the decreased T_M_{A2} would manifest potentially earlier ankle eccentric contraction (Decker et al., 2003). The two different protocols produced different outcomes based on the neuromuscular solicitations specific to multiple tasks (Cortes et al., 2013), which might be related to the different energy systems and types of muscle fibers. These findings were in accordance with previous fatigue-related works. Collectively, our observations clearly demonstrated that fatigue would lead to adjusted movement control strategies with changed joint moment patterns in the lower extremity induced by varied protocols. Furthermore, it seems to be helpful to consider and distinguish multiple peak joint moment values during different landing phases with and without fatigue.

As previously mentioned, the participants' post fatigue landing strategies differed from their pre-fatigue strategies. In the current study, k_{vert}, considered as overall deformation of the lower extremity in response to the GRF (Butler and Davis, 2003), decreased by 15.3% after fatigue during landings. No significant differences were observed between the two protocols. Basically, it has been suggested that a certain degree of vertical stiffness is required to resist the potential collapse of the lower limb during the early phase of landing because of the large impact forces (Butler and Davis, 2003). Nevertheless, excessive joint movements tend to reduce joint stiffness and consequently reduce vertical stiffness. Specifically, our findings indicated that hip and knee stiffness decreased after fatigue, which was associated with increased $\mathrm{RoM_H}$ and $\mathrm{RoM_K}$. Briefly, hip and knee joints changed movement control strategies by reducing stiffness leading to a more flexed posture after fatigue. These findings were in accordance with previous fatigue-related works on landing biomechanics, where knee stiffness was reduced after the squat-induced fatigue protocol which is more similar to SJ-FP (Buschke et al., 2005).

The present results revealed that knee extensors were the main muscle groups for EA in landing, accounting for approximately 55% of the total EA and higher EA values were found in hip and knee joints during landings after fatigue. These findings were consistent with the research of Decker et al. (2003) in that knee extensors were the primary attenuation modulator in EA for both men and women during landings, whereas the second largest contributors to EA for men were the hip extensors. The main explanation was that the proximal muscle groups (i.e., hip and knee extensors) because of a larger volume of muscle cross-sectional area, muscle fiber length and tendon length would have a greater influence on the EA capacity than the distal muscle groups during landings (Zhang et al., 2000). Moreover, our results revealed the differences in the joint contributions for EA before and after fatigue during landings. Specifically, the EA of the hip extensors was significantly increased (+18.5%), whereas the EA of the plantarflexors was correspondingly reduced (−15.0%) after the fatigue state compared with the pre-fatigued state. These findings supported the observation from the study of DeVita and Skelly (1992), indicating the EA of the hip and the knee extensors were increased with a greater joint RoM in soft landing compared with stiff landing. Thus, impact resistance was ascribed to the increased involvement of proximal and larger muscle groups in EA. Similarly, Zhang et al. (2000) reported that hip and knee joints contributed more EA in a soft landing; the hip extensors dissipated larger amounts of energy by a more flexed hip as the landing height increased. Collectively, our results, combined with those published elsewhere, suggested that the proximal joints and extensors were the major shock and energy absorbers during landings in either pre- or post fatigue conditions, regardless of fatigue protocols used in the present study.

The present study has some limitations; and directions for future research are suggested. First, there were different results between the fatigue protocols in alterations in lower limb biomechanics, which may largely be because of the limitations of the various fatigue levels (Barberwestin and Noyes, 2017). In addition, more fatigue protocols (e.g., short or long-term and single or combined) need to be examined and documented in the future. Future research could be considered that splitting into "responder" and "nonresponder" groups to find out the biomechanical differences during landings. Finally, it was difficult to compare all the current outcomes of fatigue-induced intervention with other studies because of multifarious protocols. However, notably, less intervention time was required to reach a fatigue state by using SJ-FP than R-FP. Thus, the former protocol, i.e., SJ-FP, seems to be more efficient from a methodological perspective.

Conclusion

Fatigue altered landing biomechanical performance by generally increasing $\mathrm{RoM_H}$ and $\mathrm{RoM_K}$, reducing M_{A2}, k_{vert} and hip and knee stiffness, as well as absorbing more energy in hip and knee joints. The findings provided preliminary evidence suggesting that major muscle groups (e.g., hip and knee extensors) played a crucial role in altering movement control strategies to maintain similar impact force patterns and dissipate more energy through a flexed landing posture after fatigue. Overall, the biomechanical changes were similar between the two protocols despite different changes in certain variables, notably $\mathrm{RoM_A}$, M_{K1}, t_M_{H2} and t_M_{A2}. Nevertheless, from a methodological perspective SJ-FP appeared to be more efficient than R-FP because it required less intervention time.

Acknowledgements

This work was supported by the National Natural Science Foundation of China [grant numbers 11772201, 31701041]; The National Key Research and Development Program of China [2018YFF0300501]; the Scientific Research Program of Shanghai Municipal Science and Technology Commission [17080503300]. The reported experiments comply with the current laws of the country; in which they were performed. The authors have no conflicts of interests to declare.

References

Barberwestin, S.D. and Noyes, F.R. (2017) Effect of Fatigue Protocols on Lower Limb Neuromuscular Function and Implications for Anterior Cruciate Ligament Injury Prevention Training: A Systematic Review. *The American Journal of Sports Medicine* **45,** 1-9.

Brazen, D.M., Todd, M.K., Ambegaonkar, J.P., Wunderlich, R. and Peterson, C. (2010) The effect of fatigue on landing biomechanics in single-leg drop landings. *Clinical Journal of Sport Medicine* **20,** 286-292.

Butler, R.J. and Davis, I.M. (2003) Lower extremity stiffness: implications for performance and injury. *Clinical Biomechanics* **18,** 511-517.

Buschke, D., Hart, J. and Johnson, H. (2005) Changes In Lower Extremity Joint Stiffness With Landing After Fatigue. *Journal of Undergraduate Research* **VIII,**174.

Chappell, J.D., Herman, D.C., Knight, B.S., Kirkendall, D.T., Garrett, W.E. and Yu, B. (2005) Effect of fatigue on knee kinetics and kinematics in stop-jump tasks. *The American Journal of Sports Medicine* **33,** 1022-1029.

Chow, E.C. and Etnier, J.L. (2017) Effects of music and video on perceived exertion during high-intensity exercise. *Journal of Sport and Health Science* **6,** 81-88.

Cortes, N., Greska, E., Ambegaonkar, J.P., Kollock, R.O., Caswell, S.V. and Onate, J.A. (2014) Knee kinematics is altered post-fatigue while performing a crossover task. *Knee Surgery Sports Traumatology Arthroscopy* **22,** 2202-2208.

Cortes, N., Greska, E., Kollock, R., Ambegaonkar, J. and Onate, J.A. (2013) Changes in Lower Extremity Biomechanics Due to a Short-Term Fatigue Protocol. *Journal of Athletic Training* **48,** 306-313.

Coventry, E., O'Connor, K.M., Hart, B.A., Earl, J.E. and Ebersole, K.T. (2006) The effect of lower extremity fatigue on shock attenuation during single-leg landing. *Clinical Biomechanics* **21,** 1090-1097.

Decker, M.J., Torry, M.R., Wyland, D.J., Sterett, W.I. and Richard Steadman, J. (2003) Gender differences in lower extremity kinematics, kinetics and energy absorption during landing. *Clinical Biomechanics* **18,** 662-669.

Dempster, W.T. (1955) Space Requirements of the Seated Operator: Geometrical, Kinematic, and Mechanical Aspects of the Body with Special Reference to the Limbs. *Umr*, 55-159.

DeVita, P. and Skelly, W.A. (1992) Effect of landing stiffness on joint kinetics and energetics in the lower extremity. *Medicine and Science in Sports and Exercise* **24,** 108-115.

Dierks, T.A., Davis, I.S. and Hamill, J. (2010) The effects of running in an exerted state on lower extremity kinematics and joint timing. *Journal of Biomechanics* **43,** 2993-2998.

Elvin, N.G., Elvin, A.A., Arnoczky, S.P. and Torry, M.R. (2007) The correlation of segment accelerations and impact forces with knee angle in jump landing. *Journal of Applied Biomechanics* **23,** 203-212.

Faul, F., Erdfelder, E., Lang, A.G. and Buchner, A. (2007) G*Power 3: a flexible statistical power analysisprogram for the social, behavioral, and biomedical sciences. *Behavior Research Methods* **39,** 175-191.

Ferraz, R., van den Tillar, R. and Marques, M.C. (2017) The influence of different exercise intensities on kicking accuracy and velocity in soccer players. *Journal of Sport and Health Science* **6,** 462-467.

Fu, W., Fang, Y., Gu, Y., Huang, L., Li, L. and Liu, Y. (2017) Shoe cushioning reduces impact and muscle activation during landings from unexpected, but not self-initiated, drops. *Journal of Science and Medicine in Sport* **20,** 915-920.

Garcia-Perez, J.A., Perez-Soriano, P., Llana, S., Martinez-Nova, A. and Sanchez-Zuriaga, D. (2013) Effect of overground vs treadmill running on plantar pressure: influence of fatigue. *Gait & Posture* **38,** 929-933.

Gehring, D., Melnyk, M. and Gollhofer, A. (2009) Gender and fatigue have influence on knee joint control strategies during landing. *Clinical Biomechanics* **24,** 82-87.

Granata, K.P., Padua, D.A. and Wilson, S.E. (2002) Gender differences in active musculoskeletal stiffness. Part II. Quantification of leg stiffness during functional hopping tasks. *Journal of Electromyography and Kinesiology* **12,** 127-135.

Hoch, M.C., Farwell, K.E., Gaven, S.L. and Weinhandl, J.T. (2015) Weight-Bearing Dorsiflexion Range of Motion and Landing Biomechanics in Individuals With Chronic Ankle Instability. *Journal of Athletic Training* **50,** 833-839.

James, C.R., Dufek, J.S. and Bates, B.T. (2006) Effects of stretch shortening cycle exercise fatigue on stress fracture injury risk during landing. *Research Quarterly for Exercise and Sport* **77,** 1-13.

James, C.R., Scheuermann, B.W. and Smith, M.P. (2010) Effects of two neuromuscular fatigue protocols on landing performance. *Journal of Electromyography and Kinesiology* **20,** 667-675.

Kernozek, T.W., Torry, M.R. and Iwasaki, M. (2008) Gender differences in lower extremity landing mechanics caused by neuromuscular fatigue. *The American Journal of Sports Medicine* **36,** 554-565.

Kim, Y., Youm, C., Son, M., Kim, J. and Lee, M. (2017) The effect of knee flexor and extensor fatigue on shock absorption during cutting movements after a jump landing. *The Knee* **24,** 1342-1349.

Koblbauer, I.F., van Schooten, K.S., Verhagen, E.A. and van Dieen, J.H. (2014) Kinematic changes during running-induced fatigue and relations with core endurance in novice runners. *Journal of Science and Medicine in Sport* **17,** 419-424.

Lee, J., Lee, K. and Kim, J. (2013) Effect of shoe heel to toe drop and strike patterns in sole angle. *Footwear Science* **5,** 48-49.

Macdermid, P.W., Fink, P.W. and Stannard, S.R. (2017) Shock attenuation, spatio-temporal and physiological parameter comparisons between land treadmill and water treadmill running. *Journal of Sport and Health Science* **6,** 482-488.

Madigan, M.L. and Pidcoe, P.E. (2003) Changes in landing biomechanics during a fatiguing landing activity. *Journal of Electromyography and Kinesiology* **13,** 491-498.

Murdock, G.H. and Hubley-Kozey, C.L. (2012) Effect of a high intensity quadriceps fatigue protocol on knee joint mechanics and muscle activation during gait in young adults. *European Journal of Applied Physiology* **112,** 439-449.

Nikooyan, A.A. and Zadpoor, A.A. (2012) Effects of muscle fatigue on the ground reaction force and soft-tissue vibrations during running: a model study. *IEEE Transactions on Bio-medical Engineering* **59,** 797-804.

Nordin, A.D., Dufek, J.S. and Mercer, J.A. (2017) Three-dimensional impact kinetics with foot-strike manipulations during running. *Journal of Sport and Health Science* **6,** 489-497.

Orishimo, K.F. and Kremenic, I.J. (2006) Effect of fatigue on single-leg hop landing biomechanics. *Journal of Applied Biomechanics* **22,** 245-254.

Pandy, M.G. and Andriacchi, T.P. (2010) Muscle and joint function in human locomotion. *Annual Review of Biomedical Engineering* **12,** 401-433.

Puddle, D.L. and Maulder, P.S. (2013) Ground reaction forces and loading rates associated with parkour and traditional drop landing techniques. *Journal of Sports Science and Medicine* **12,** 122-129.

Quammen, D., Cortes, N., Van Lunen, B.L., Lucci, S., Ringleb, S.I. and Onate, J. (2012) Two different fatigue protocols and lower extremity motion patterns during a stop-jump task. *Journal of Athletic Training* **47,** 32-41.

Ramos-Campo, D.J., Rubio-Arias, J.A., Avila-Gandia, V., Marin-Pagan, C., Luque, A. and Alcaraz, P.E. (2017) Heart rate variability to assess ventilatory thresholds in professional basketball players. *Journal of Sport and Health Science* **6,** 468-473.

Rosen, A.B., Ko, J., Simpson, K.J., Kim, S.H. and Brown, C.N. (2015) Lower Extremity Kinematics During a Drop Jump in Individuals With Patellar Tendinopathy. *Orthopaedic Journal of Sports Medicine* **3,** 1-8.

Rowley, K.M. and Richards, J.G. (2015) Increasing plantarflexion angle during landing reduces vertical ground reaction forces, loading rates and the hip's contribution to support moment within participants. *Journal of Sports Science* **33,** 1922-1931.

Sanna, G. and O'Connor, K.M. (2008) Fatigue-related changes in stance leg mechanics during sidestep cutting maneuvers. *Clinical Biomechanics* **23,** 946-954.

Tamura, A., Akasaka, K., Otsudo, T., Sawada, Y., Okubo, Y., Shiozawa, J., Toda, Y. and Yamada, K. (2016) Fatigue Alters Landing Shock Attenuation During a Single-Leg Vertical Drop Jump. *Orthopaedic Journal of Sports Medicine* **4,** 1-7.

Tsai, L.C., Ko, Y.A., Hammond, K.E., Xerogeanes, J.W., Warren, G.L. and Powers, C.M. (2016) Increasing hip and knee flexion during a drop-jump task reduces tibiofemoral shear and compressive forces: implications for ACL injury prevention training. *Journal of Sports Sciences* **35,** 1-7.

Tsai, L.C., Sigward, S.M., Pollard, C.D., Fletcher, M.J. and Powers, C.M. (2009) Effects of fatigue and recovery on knee mechanics during side-step cutting. *Medicine and Science in Sports and Exercise* **41,** 1952-1957.

Webster, K.A., Pietrosimone, B.G. and Gribble, P.A. (2016) Muscle Activation During Landing Before and After Fatigue in Individuals With or Without Chronic Ankle Instability. *Journal of Athletic Training* **51,** 629-636.

Wikstrom, E.A., Powers, M.E. and Tillman, M.D. (2004) Dynamic Stabilization Time After Isokinetic and Functional Fatigue. *Journal of Athletic Training* **39,** 247-253.

Yeow, C.H., Lee, P.V. and Goh, J.C. (2009) Effect of landing height on frontal plane kinematics, kinetics and energy dissipation at lower extremity joints. *Journal of Biomechanics* **42,** 1967-1973.

Yeow, C.H., Lee, P.V. and Goh, J.C. (2011) An investigation of lower extremity energy dissipation strategies during single-leg and double-leg landing based on sagittal and fronta l plane

biomechanics. *Human Movement Science* **30,** 624-635.
Zadpoor, A.A. and Nikooyan, A.A. (2012) The effects of lower extremity muscle fatigue on the vertical ground reaction force: a meta-analysis. *Proceedings of the Institution of Mechanical Engineers. Part H, Journal of Engineering in Medicine* **226,** 579-588.
Zhang, S.N., Bates, B.T. and Dufek, J.S. (2000) Contributions of lower extremity joints to energy dissipation during landings. *Medicine and Science in Sports and Exercise* **32,** 812-819.

Key points

- Changes in lower extremity biomechanics during drop landings were found between two fatigue protocols.
- Hip and knee extensors played a crucial role in altering movement control strategies to maintain similar impact forces and to dissipate more energy when fatigued.
- The common exercise-induced fatigue protocol (repeated shuttle sprint + vertical jump) required less intervention time to reach a fatigue state than constant speed running protocol.

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