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Fatigue alters the biomechanical contribution of lower extremity joints during a stretch-shortening cycle task

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Purpose: This study aimed to explore the effect of fatigue on the biomechanical contribution of the lower extremity joints during a typical stretch-shortening cycle (SSC) task. *Methods:* 15 male athletes completed drop jump (DJ) under pre- and post-fatigue. Vicon motion capture system and 3D Kistler force plates were used to collect kinematics and ground reaction force data simultaneously. *Results:* Under fatigue condition, 1) the DJ height decreased; the touchdown angle of knee and ankle reduced and the range of motion increased; 2) the maximum push-off moment and power of knee was reduced; 3) the stiffness of knee, ankle, and legs was reduced; 4) the energy generation and the net energy of the ankle decreased; 5) the energy contribution of knee decreased during the eccentric phase. *Conclusions:* Fatigue altered biomechanical contribution of the lower extremity joints by changing the movement pattern during DJ. The control ability of the knee and ankle were decreased. Eventually, the jump performance was reduced. In addition, the decrease of stiffness as well as the energy contribution of these joints can be used as sensitive indices to evaluate the performance of DJ after fatigue.

Key words: *stretch-shortening cycle, drop jump, fatigue, stiffness, joint work*

1. Introduction

The stretch-shortening cycle (SSC) is one of the most common movement forms of the lower extremity, particularly during running, jumping and hopping [15], [17]. It contains three fundamental phases: a pre-activation of the muscles before contacting with the ground, a short and fast eccentric phase and an immediate transition between stretch (eccentric phase), and shortening (concentric phase). SSC is a natural pattern of muscle activation that stores elastic energy during the eccentric phase of a preactivated muscle and partly reuses the stored energy during the subsequent concentric phase [17]. During an SSC procedure, a person can recruit additional muscle fibres, mobilise fast muscle motor units and produce great explosive force compared with the isolated concentric phase [15]. Therefore, SSC exercise is regularly used by athletes and coaches as a means of enhancing performance [27], strength and power of lower limbs and neuromuscular coordination and control ability [15].

However, during training or competition, athletes are required to perform numerous SSC movements, such as running and jumping, which leads to neuromuscular fatigue [17]. Fatigue due to such movements is commonly defined as any exercise-induced reduction in muscle performance (produce to power and force) irrespective of task completion [12]. From a biomechanical perspective, fatigue can affect impact forces [3], leg geometry [23] and joint torque or stiff-

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ness [7], moreover, it can change the landing strategy of the lower extremity and decrease the control ability of the musculoskeletal system [6]. Hence, it places athletes at a high risk of injury [8].

At present, most studies focus on exploring the effect of fatigue on lower extremity biomechanics and performance at the impact phase during SSC movements in terms of kinematics, ground reaction forces (GRF) and electromyography (EMG). For instance, Weinhandl et al. [29] reported that fatigue significantly increases knee extension and ankle plantar flexion at initial contact during repetitive drop jumps (DJ) without any significant changes in peak vertical GRF (vGRF). Prieske et al. [22] showed that a fatigue protocol produces significant decreases in 1) biceps femoris and tibialis anterior activities during the pre-activation phase and 2) vastus lateralis, biceps femoris, tibialis anterior, gastrocnemius medialis and soleus activities during the braking (eccentric) phase of the DJ. Schmitz et al. [24] reported the contribution of knee flexor and extensor strength during the initial landing phase of DJ. Overall, a limited number of studies have examined the lower extremity biomechanics for the whole total landing phase (from initial contact to take off) during an SSC task, especially for the push-off (concentric) phase.

Meanwhile, stiffness is considered to be one of the most important factors of musculoskeletal system performance during SSC actions [4]. Previous studies have shown that change in lower extremity stiffness occurs in response to initial contact of the ground [16]. In terms of SSC performance, a certain level of stiffness is required for the following purposes: 1) utilizing stored elastic energy in the musculoskeletal system efficiently during the eccentric phase of movement [13] and 2) preventing the collapse of the lower extremity, releasing energy maximally and completing joint work [1]. Moreover, neuromuscular control strategies and how these strategies potentially affect injury risks can be further understood by examining joint energetics during an SSC movement [25]. Therefore, stiffness and the energetic characteristics are essential to the evaluation of SSC performance. Further studies beyond the analysis of the kinematic level may contribute some new understanding on stiffness and energy absorption/dissipation strategies and the underlying neuromuscular SSC actions occurring during fatigue.

Therefore, the purpose of this study was to determine the effect of fatigue on the biomechanical contribution of the lower extremity joints during DJ task. We hypothesised that, after fatigue, 1) the maximum jump height of DJ decreased at increased joint angle and 2) the joint and leg stiffness reduced when joint energy absorption, release and contribution changed.

2. Materials and methods

Participants

A total of 15 collegiate male athletes (age: 20.9 ± 0.8 years; height: 175.5 ± 4.2 cm; mass: 68.9 ± 5.5 kg) with an average of 4.2 ± 1.1 years of experience in track and field events volunteered to participate in this study. The sample size was determined through a G-power statistical calculation with a power level of 80% and an α level of 0.05. All the participants reported no history of lower extremity injury within the previous six months and no vigorous exercise within 24 h before the experiment. Prior to the study, participants were familiarized with the experimental protocol. Informed written consent, approved by the Institutional Review Board of Shanghai University of Sports, was obtained from each participant.

Experimental protocol

Participants were required to complete a warm-up protocol consisting of 5 minutes of treadmill running at 8 km/h followed by 3 min of static stretching exercise. Then, they performed three separated vertical jumps with hands akimbo on the Quattro Jump force plate (9290BD, Kistler Corporation, Switzerland) with maximal effort. The highest value was recorded as the maximum vertical jump height [5], [28]. No rest interval was allowed between jumps. Participants were required to complete five trials of successful DJ. Specifically, participants were asked to stand in an upright position on the 60-cm platform with hands akimbo (for the elimination of the influence of arm movement; Fig. 1). The participants were instructed to “Step off with either leg the platform and then jump as high as possible with the shortest possible contact time”. Then, participants were required to conduct the fatigue protocol. Finally, participants were asked to complete five successful DJ again.

Fatigue protocol

On the basis of previous studies [5], [28], fatigue was induced using shuttle running and vertical jump-

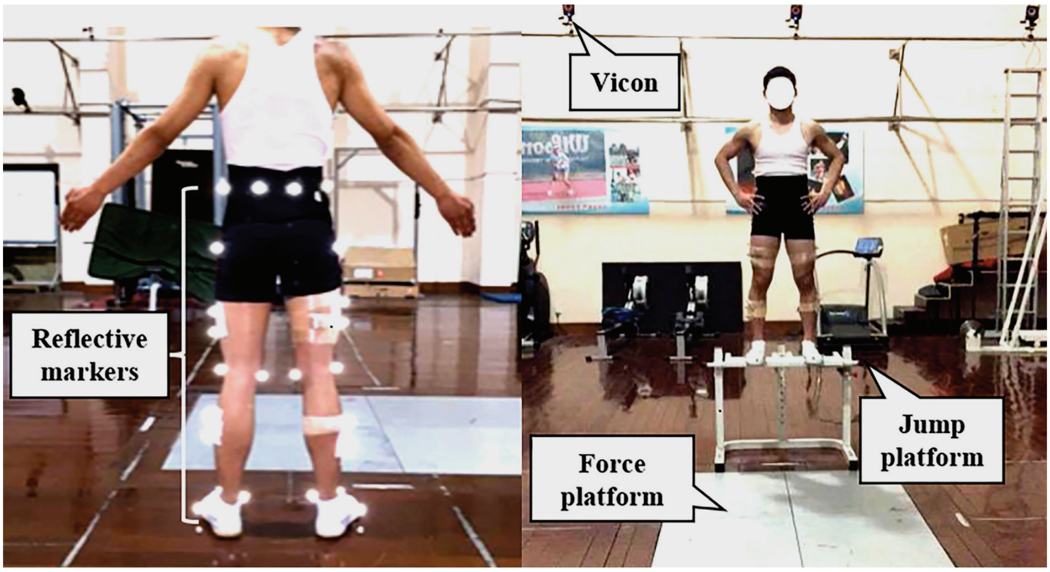

Fig. 1. Marker set used in the study (left) and the experimental setup (right)

ing protocol (Fig. 2). The participants were required to complete five consecutive vertical jumps followed by a set of shuttle running (6 × 10 m). They were required to repeat the sequence at least five times with maximal effort. They were considered to have reached a fatigued state, and the intervention was terminated when the following occurred: 1) the participants failed to reach 70% of the maximal vertical jump height for all five jumps, and 2) the heart rate (HR) of the participants, which was monitored by a HR transmitter belt monitor (SS020674000, Suunto Oy, Finland), reached 90% of their age-calculated maximum HR (maximum HR estimated as 220 − age). The rated perceived exertion for each participant was acquired immediately after the intervention.

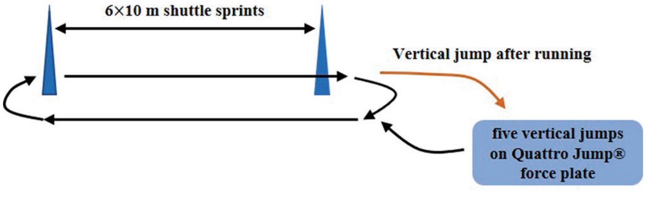

Fig. 2. Schematics of the exercise-induced fatigue protocol with shuttle sprint and vertical jump

Data acquisition and analysis

Kinematics of the lower extremity was captured with a 16-camera infrared 3D motion capture system at a sampling rate of 240 Hz (Vicon T40, Oxford Metrics, UK). Based on the Vicon Plug-in-Gait marker set, we attached 36 retroreflective markers (14.0 mm in diameter) to the bone landmarks of the pelvis and lower extremity to define the hip, knee and ankle joints. The GRF were recorded with two 90 cm × 60 cm × 10 cm force platforms (9287B, Kistler Corporation, Switzerland) embedded in the laboratory floor at a sampling rate of 1200 Hz. The 3D kinematic and force plate data were synchronised with the Vicon system.

Sagittal plane kinematic data of the dominant lower extremity, defined as preferred kicking leg [19]. The 3-dimensional trajectories of the markers were filtered using a fourth-order, zero-lag Butterworth with a 7 Hz cut-off frequency via Visual 3D (4.75.12, C-Motion Inc., USA) [11]. The main sagittal kinematic variables of the hip, knee and ankle joints during the landing phase were as follows: 1) joint flexion/ankle plantarflexion angle at initial contact (θ_0); 2) maximum flexion joint angle (θ_{flex}) and its occurrence time ($t_{\theta\text{flex}}$); 3) changes in the hip, knee and ankle joints ($\Delta\theta$), which were determined by calculating the differences between θ_0 and θ_{flex}; and it also determines the joint stiffness. 4) take-off angle, also known as the maximum extension joint angle (θ_{ext}); 5) joint range of motion (RoM), which was determined by calculating the differences between the maximum flexion and extension angles of the three joints during the entire landing period; 6) center of mass (COM) displacement (Δy), which was the maximum vertical displacement of the COM based on the pelvis and greater trochanter anatomical landmarks (a virtual landmark of the model in Visual 3D, named “CentHip”) during the eccentric phase; 7) jump height, which was determined by calculating the maximum height differences between the static and motion model of the “CentHip” landmark and 8) time for eccentric, concentric and

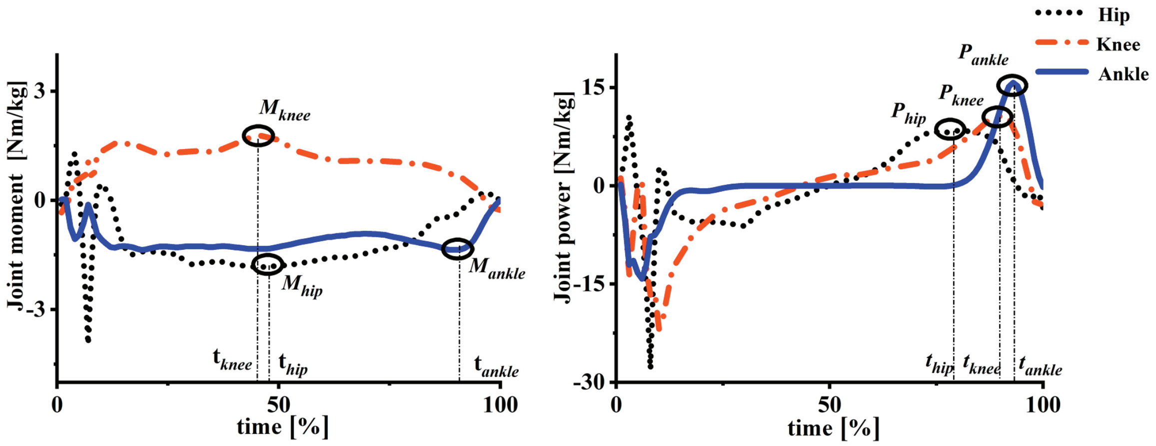

Fig. 3. Schematic of joint moment (left) and joint power (right) during the landing phase of DJ

total contact phases. The landing phase of DJ was divided into two phases, i.e., eccentric and concentric phases [18]. The eccentric phase was defined as the time interval from the instant of touchdown, which was determined as the instant vGRF exceeding a threshold of 10 N, to the maximum knee flexion angle. The concentric phase was defined as the time from the instant of maximum knee flexion angle to the instant of take-off [18].

Sagittal plane joint moments were calculated from the kinematic, GRF and anthropometric data through an inverse dynamics approach. Joint power was defined as the product of the joint moment and joint angular velocity at each time point. Representative joint moment–time and joint power–time curves are presented in Fig. 3. The variables included 1) the maximum net joint moment ($M_{\max}$) and its occurrence time ($t_{M\max}$) and 2) the maximum joint power ($P_{\max}$) during the concentric phase of DJ and its occurrence time ($t_{P\max}$).

The variables for the stiffness of the lower extremity included: 1) leg stiffness (k_{leg}) = GRFi/Δy [18], where the GRFi was the vGRF at the transition from the eccentric to concentric action (the maximum knee flexion); 2) average joint stiffness (k_{joint}) = $\Delta M/\Delta\theta$ [4], where ΔM was the change in joint moment, and the $\Delta\theta$ was the changes in the joints angle during the eccentric period.

Joint work (W_j) was calculated by integrating the joint power curve, and W_j was negative during the eccentric phase of DJ, which presented energy absorption. However, the values were positive during the concentric phase of DJ, which presented energy release. Net energy was the sum of energy absorption and energy release. Joint energy contribution was the proportion of the work done by a certain joint in the total joint work of the hip, knee and ankle, as shown in the following equation [26]:

$$C_j = \frac{W_j}{W_{\text{hip}} + W_{\text{knee}} + W_{\text{ankle}}}.$$

Statistical analysis

The distribution of all the dependent variables was examined by using the Shapiro–Wilk test. The distribution did not differ significantly from normality. The effect of fatigue (pre-fatigue and post-fatigue) on jump height, sagittal plane kinematics (e.g., joint angle) and kinetics (e.g., joint moment, joint power, joint stiffness and joint work) was determined through paired sample *t*-tests. The significance level α was set at 0.05.

3. Results

Kinematics

The maximum DJ height significantly decreased (PRE: 52.7 ± 4.3 cm *vs*. POST: 50.4 ± 5.9 cm, $p = 0.025$) in the post-fatigue condition relative to that in the pre-fatigue condition. The Δy value (PRE: 40.9 ± 8.3 cm *vs*. POST: 44.9 ± 10.2 cm, $p = 0.043$) decreased after fatigue. Correspondingly, the time for eccentric (PRE: 263.9 ± 47.6 ms *vs*. POST: 238.4 ± 52.1 ms, $p = 0.044$), concentric (PRE: 320.3 ± 54.4 ms *vs*. POST: 299.7 ± 68.2 ms, $p = 0.045$) and total contact (PRE: 584.2 ± 97.4 ms *vs*. POST: 538.1 ± 118.3 ms, $p = 0.008$) increased significantly after fatigue. The joint angles θ_0 of knee reduced and that of ankle increased after fatigue ($p < 0.05$). No significant difference was observed in the θ_{flex} values of the three joints between the pre- and post-fatigue conditions (Table 1). However, the $t_{\theta\text{flex}}$ of the hip ($p < 0.05$), knee ($p < 0.01$) and ankle ($p < 0.05$) occurred later after fatigue.

Table 1. Comparison of the joint angle in the sagittal plane during DJ between pre- and post-fatigue conditions ($^{*}p < 0.05$, $^{**}p < 0.01$)

	Hip						Knee						Ankle					
	θ_0	θ_{flex}	$t_{\theta\text{flex}}$**	$\Delta\theta$	θ_{RoM}	θ_{ext}	θ_0*	θ_{flex}	$t_{\theta\text{flex}}$**	$\Delta\theta$*	θ_{RoM}	θ_{ext}	θ_0*	θ_{flex}	$t_{\theta\text{flex}}$*	$\Delta\theta$**	θ_{RoM}	θ_{ext}
	[°]	[°]	[ms]	[°]	[°]	[°]	[°]	[°]	[ms]	[°]	[°]	[°]	[°]	[°]	[ms]	[°]	[°]	[°]
Pre--fatigue	47.7 ± 9.8	107.3 ± 18.6	240.1 ± 62.5	59.6 ± 13.7	86.5 ± 14.5	20.7 ± 6.3	29.7 ± 6.7	109.1 ± 16.7	238.4 ± 52.1	81.0 ± 14.1	107.3 ± 18.2	3.2 ± 4.3	26.3 ± 10.8	11.8 ± 5.7	273.3 ± 63.0	37.3 ± 10.0	66.9 ± 6.1	55.6 ± 5.2
Post--fatigue	45.1 ± 9.4	109.8 ± 17.6	263.3 ± 50.5	64.7 ± 14.8	90.2 ± 15.9	19.5 ± 7.0	25.1 ± 6.5	111.9 ± 16.8	263.9 ± 47.6	86.8 ± 14.0	110.4 ± 16.8	1.4 ± 5.1	29.7 ± 8.2	11.5 ± 5.0	306.7 ± 58.9	41.1 ± 8.5	66.5 ± 7.0	55.1 ± 5.5

Abbreviations: θ_0 – joint flexion/ankle plantarflexion angle at initial contact; θ_{flex} – the maximum flexion/ankle plantarflexion joint angle; $t_{\theta\text{flex}}$ – the occurrence time of the maximum flexion joint angle; $\Delta\theta$ – the changes in joint angle; θ_{ext} – the maximum extension joint angle; θ_{RoM} – the joint range of motion.

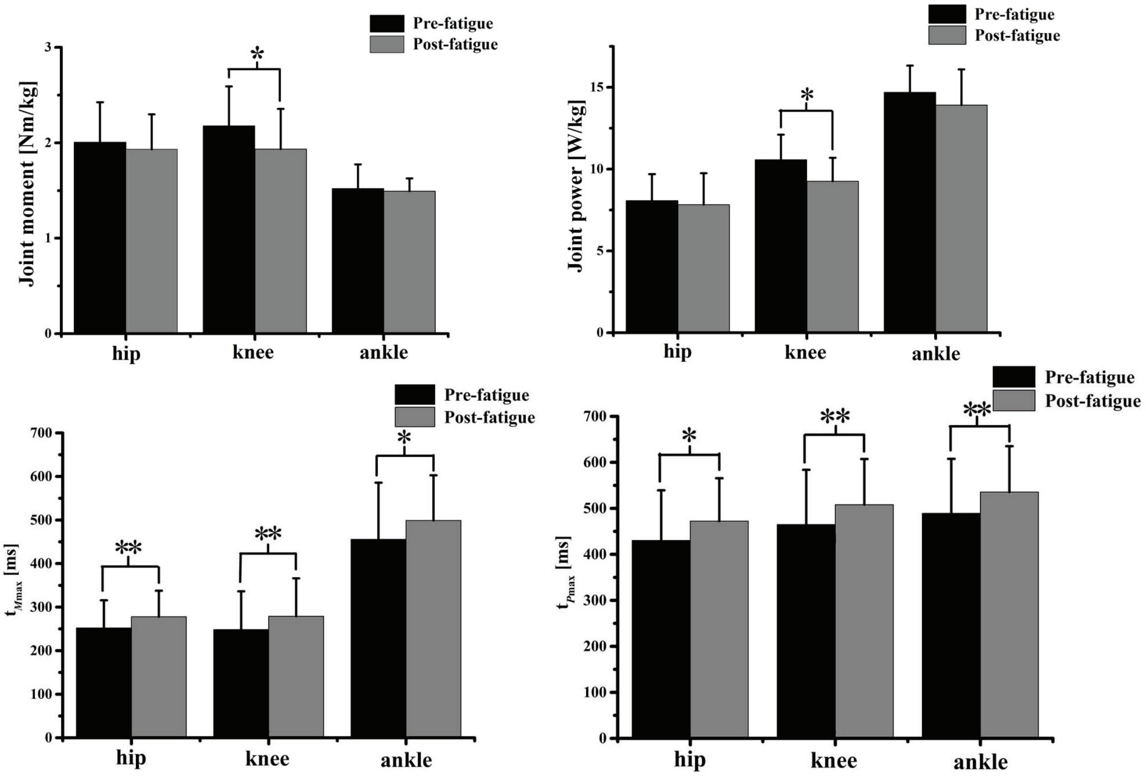

Fig. 4. Comparison of the maximum moment and power of hip, knee and ankle joints (upper) and the occurrence time for the maximum push-off moment ($t_{M_{\max}}$) and power ($t_{P_{\max}}$) (lower) during DJ between pre- and post-fatigue conditions (*$p < 0.05$, **$p < 0.01$)

Joint moment and power

After fatigue, $M_{\max}$ and $P_{\max}$ of the knee were reduced significantly ($p < 0.05$). Meanwhile, $t_{M\max}$ and $t_{P\max}$ for the three joints ($p < 0.05$) occurred later (Fig. 4).

Stiffness

Compared to the pre-fatigue condition, leg stiffness was lowered by 20.1% ($p = 0.032$) in the post-fatigue condition (Fig. 5). Meanwhile, knee and ankle joint stiffness was reduced by 19.0% ($p = 0.011$) and 27.6% ($p = 0.01$) after fatigue, respectively.

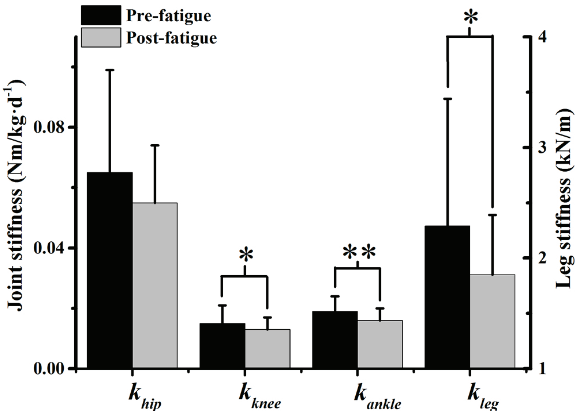

Fig. 5. Comparison of the joint stiffness and leg stiffness during DJ between pre- and post-fatigue conditions (*$p < 0.05$, **$p < 0.01$).

Joint energetics

Overall, the net energy for ankle joint was significantly reduced after fatigue ($p = 0.042$), whereas no significant changes were observed in the knee and hip joints (Fig. 6). Specifically, the energy generated by the ankle joint was reduced after fatigue ($p = 0.033$), but the energy absorbed was not reduced. During the eccentric phase, the relative energy contribution of the knee joint to the energy absorbed decreased after fatigue ($p = 0.033$) (Table 2).

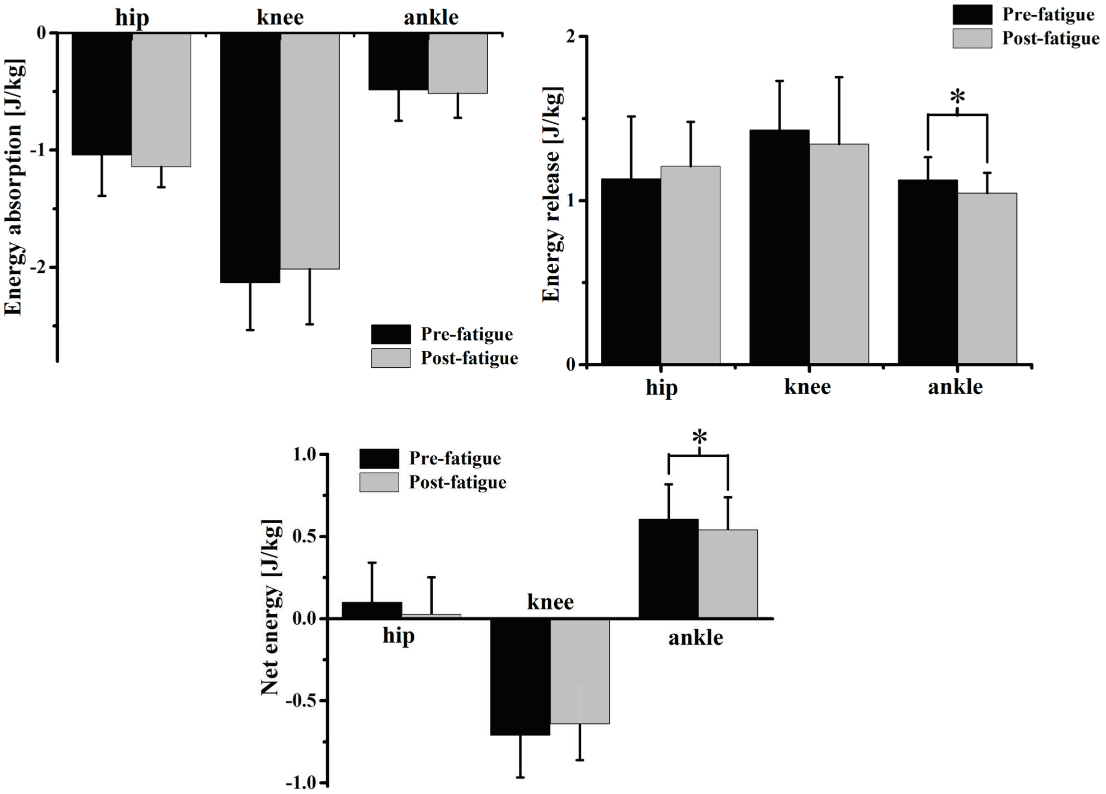

Fig. 6. Comparison of the joint work (energy absorption, energy generation and net energy) during DJ between pre- and post-fatigue conditions (*$p < 0.05$, **$p < 0.01$)

Table 2. Effect of fatigue on the relative energy contribution of the hip, knee and ankle joints to the energy absorbed and generated during DJ (%) (*$p < 0.05$)

	Hip		Knee		Ankle	
	C_{EA}	C_{EG}	C_{EA}*	C_{EG}	C_{EA}	C_{EG}
Pre-fatigue	28.2 ± 7.5	30.5 ± 7.1	58.4 ± 8.5	38.9 ± 5.8	13.5 ± 7.9	30.6 ± 5.6
Post-fatigue	30.7 ± 8.0	31.5 ± 5.5	54.9 ± 7.9	38.5 ± 5.6	14.3 ± 5.7	30.0 ± 5.9

Abbreviations: C_{EA} – the relative energy contribution of the joints to the energy absorbed; C_{ER} – the relative energy contribution of the joints to the energy generated.

4. Discussion

The aim of this study was to investigate the effect of fatigue on lower extremity joint kinematics, kinetics, stiffness and energetics during a typical SSC task. Our hypothesis was partly supported by the present results, which indicated that fatigue alters the biomechanical contribution of the lower extremity joints by reducing the θ_0 of knee, increasing the θ_0 of ankle and $\Delta\theta$ of the knee and ankle joints. Hence, M_{max} and P_{max} of the knee were reduced, and the stiffness of knee and ankle joints and leg stiffness decreased. Meanwhile, the energy absorption and net energy of the ankle joint decreased as well. Overall, the above-mentioned joint biomechanical changes finally led to the decrease of maximum DJ height after fatigue.

Apparently, fatigue has a negative effect on jump performance. The decrease in the maximum jump height was consistent with previous studies [17]. Meanwhile, the time for eccentric and concentric phase increased, which resulted in the increase in total contact time. This increase suggests a fairly longer coupling time compared with the pre-fatigue condition between eccentric and concentric phases; furthermore, the contribution of elasticity to performance is reduced at increased contact time [26]. The changes in the joint angles before and after fatigue indicated the changes in the structure of the SSC task. We found that the touchdown flexion angle of the knee reduced and plantarflexion angle increased. Similarly, Weinhandl et al. [29] reported that knee flexion angles reduced by 7.0° and plantarflexion angle increased by 10.6° at initial contact in a fatigue condition. This result may have relevance in terms of injury risk, because an increased extension may be a compensatory mechanism for the reduced capability of the knee extensors to decelerate the body and absorb the landing impact.

A number of studies have shown that upright knee joint position during the initial contact increases the anterior shearing force of proximal tibia, thereby inducing the risk of ACL injury [28]. Meanwhile, no significant change was observed in the maximum flexion angles of hip, knee and ankle joints, but significant delay was found in the occurrence time after fatigue. Hence, the eccentric phase of SSC was prolonged after fatigue, that is, the cushioned time for lower extremity increased, which may lead to the decrease of the elastic energy ability of muscles. Muscles tension and stretch reflection also decreased and finally affected jump height [30]. The induced fatigue reduced the ability of completing the SSC task in this study and affected the kinematic performance of three joints, especially the knee and ankle joints.

On the basis of the change in moment of the three lower extremity joints during the whole landing phase (Fig. 3), the maximum moment of the hip and knee joints occurred near the transformation process of the eccentric to concentric phases. However, the ankle joint occurred in the later period of concentric phases. Hence, the muscle mobilisation of SSC actions was from proximal to distal joints: hip > knee > ankle. After fatigue, the mobilisation order of overall muscle did not change, however, the maximum moment of joints decreased, and the occurrence time delayed (Fig. 4). The maximum moment of knee decreased significantly, which indicated that fatigue had the greatest effect on the knee joint. Similarly, the maximum push-off power of the three joints appeared at the later stage of the concentric phases. The hip joint was the earliest followed by the knee joint and the ankle joint. Thus, the work done by SSC actions also followed the sequence from proximal to distal joints (Fig. 3). However, in fatigue condition, the overall work order did not change. This result also showed the decrease of maximum power and the occurrence of time delay, but only the knee push-off moment and power were significantly reduced after fatigue. The hip extension, plantar flexure moment and peak power were also slightly decreased. Therefore, fatigue would reduce the output power of joints and the ability of extensor muscles during the push-off phase (the concentric phase), especially the knee extensor muscles, to exert force and work.

In this study, the leg stiffness, considered as overall deformation of the lower extremity in response to the GRF [5], reduced after fatigue. This result was determined by the GRF and the Δy at the transition from the eccentric to concentric phase during the DJ task [18]. Our findings showed that the fatigue-related difference in joint stiffness was derived from the difference in displacement not by the GRF_i. Orishimo et al. [20] found that the leg stiffness reduced significantly after fatigue to increase range of motion, attenuate the impact and absorb more energy. However, Padua et al. [21] found the leg stiffness was unchanged after fatigue. The difference between our study and other studies can be attributed to the difference in fatigue protocols and calculation methods. At the same time, it was further speculated that there should be a reasonable range of stiffness between better performance and lower risk of injury, while higher leg stiffness optimizes muscle SSC function and effectively utilizes the storage of the elastic energy in the eccentric phase [4]. Leg stiffness reduced after fatigue may lead to decreased muscle SSC function, thus affecting performance. Moreover, the leg stiffness also depends on the joint stiffness and the geometry of the musculoskeletal system [9]. Joint and leg stiffness decreased after fatigue. The reduced joint stiffness was typically associated with increase in $\Delta\theta$. Therefore, increase in $\Delta\theta$ not only reduced the joint stiffness but also affected leg stiffness. Our results were in line with those of a previous study [10], which showed that the lower extremity adopts a soft landing strategy that increases angular displacements and the vertical displacement of the COM and reduces leg stiffness. Furthermore, in a system with multiple springs, the least stiff spring undergoes the largest displacement in response to a force and has the most influence on overall stiffness [10]. However, the stiffness of the knee and ankle joints during pre- and post-fatigue in this study were smaller than that of the hip joint. This result indirectly proved that stiffness in the ankle and knee had greater influence on leg stiffness than stiffness in the hip joint. The stiffness of the knee and ankle joint reduced significantly after fatigue.

Thus, the abovementioned effects were further expanded in the post-fatigue condition. Paying attention to the ability of the knee and ankle was then necessary to suffer the loading during training.

For the joint work, during the total landing phase, the net energy of hip and ankle joints were positive. This result indicated energy release, primarily by the ankle. The net energy of the knee joint was negative, which represented energy absorption. Only the net energy of ankle reduced significantly after fatigue (Fig. 6). Bobbert et al. [2] discovered that the net energy of the ankle reduces after fatigue, whereas that of the hip increases. The reason for the difference is that different protocols were used. During the eccentric phase, all the three joints (hip, knee and ankle), primarily the knee joint (>50%), absorbed energy followed by hip joint. The energy contribution of knee joint decreased during the eccentric phase in a post-fatigue condition. Fatigue intervention caused the changes of energy distribution in lower limb joints, and it had more obvious influence on the knee extensors, which can be the target training muscles. Thus, the muscles of knee joint should particularly be strengthened during SSC training. During the concentric phase, the joint contribution of the three joints were approximately 30–40%. The energy release of ankle joint reduced significantly after fatigue. Thus, fatigue reduced the capacity of the plantar flexor to release energy. Moreover, the ankle joint is the crucial joint for regulating performance during hopping because it greatly uses the elastic properties of the plantar flexors [14]. Therefore, from the perspective of joint work, the knee remains the main contributor to joint movement during a particular task. However, the role of the distal joint (ankle joint) in the SSC movement, especially in the concentric phase and the strength training of the corresponding small muscle groups, must be considered.

5. Conclusion

Fatigue altered the biomechanical contribution of the lower extremity joints during an SSC task by reducing joint flexion at initial contact and increasing the changes in the knee and ankle joints angles. As such, fatigue reduced the maximum net joint moment and power of the knee and decreased the stiffness of the knee, ankle joints and legs. Meanwhile, the energy generation and net energy of the ankle joint decreased as well. The findings proved that fatigue changed the movement pattern during the entire landing phase of DJ, decreased the control ability of the lower extremity, especially for the knee and ankle joints, and eventually reduced jump performance. The significant decrease in knee, ankle and leg stiffness and the energy contribution of these joints can be used as sensitive indices for the evaluation of DJ performance during fatigue.

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