J. Phys. Ther. Sci. 28: 3371–3375, 2016

The Journal of Physical Therapy Science

Original Article

Effect of short-term fatigue, induced by high-intensity exercise, on the profile of the ground reaction force during single-leg anterior drop-jumps

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Abstract. [Purpose] Fatigue may be an important contributing factor to non-contact anterior cruciate ligament injuries in sports. The purpose of this study was to evaluate the effects of controlled lower limb fatigue, induced by a short-term, high-intensity exercise protocol, on the profile of the ground reaction force during landings from single-leg anterior drop-jumps. [Subjects and Methods] Twelve healthy males, 18 to 24 years old, performed single-leg anterior drop-jumps, from a 20 cm height, under two conditions, 'fatigue' and 'non-fatigue'. Short-term fatigue was induced by high-intensity interval cycling on an ergometer. Effects of fatigue on peak vertical ground reaction force, time-to-peak of the vertical ground reaction force, and loading rate were evaluated by paired t-test. [Results] Fatigue shortened the time-to-peak duration of the vertical ground reaction force by 10% (non-fatigue, 44.0 ± 16.8 ms; fatigue, 39.6 ± 15.8 ms). Fatigue also yielded a 3.6% lowering in peak vertical ground reaction force and 9.4% increase in loading rate, although these effects were not significant. [Conclusion] The effects of fatigue in reducing time-to-peak of the vertical ground reaction force during single-leg anterior drop-jumps may increase the risk for non-contact anterior cruciate ligament injury in males.

Key words: Fatigue, Ground reaction force, Single-leg drop-jump

(This article was submitted Jun. 25, 2016, and was accepted Aug. 11, 2016)

INTRODUCTION

Knee injuries are common in sports activities, with the anterior cruciate ligament (ACL) being particularly vulnerable to non-contact injuries due to multiple risk factors that include the anatomical alignment and structure of the knee, the biomechanical role of the ACL, genetics, and hormonal factors[1, 2]. The ground reaction force (GRF) is an important biomechanical variable to evaluate mechanisms of knee injury during sport activities, with the vertical component of the GRF (VGRF) providing information on the magnitude and direction of impact forces that must be effectively controlled within the tolerance of the joints of the lower limb[3–6]. The magnitude and direction of the VGRF during landing from a jump affect the magnitude of the knee valgus moment and of the anterior tibial shear force, which directly influence the magnitude and direction of mechanical stress on the ACL[7–10]. A high magnitude VGRF applied at a high loading rate over a short ground contact phase, combined with an increase in knee abduction angle and moment, has been shown to increase the risk for ACL injury in female athletes[11]. An *in vivo* study provided evidence that, during single-leg landings from a vertical drop jump,

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Fig. 1. Sequential photographs of landing from a single-leg anterior vertical drop-jump

peak ACL strain was attained at peak VGRF[12]).

Fatigue is an important contributing factor to lower limb injuries, including non-contact ACL injuries. Epidemiological researches have attributed the higher incidence rate of knee injuries sustained in the second half of soccer and rugby games, as well as during later games in the season, to fatigue[13]), which alters lower limb biomechanics and, therefore, strain on the ACL[14–16]). However, the effects of fatigue on lower limb biomechanics have not been systematically evaluated using a controlled fatigue model. Moreover, the effects of fatigue specifically on peak VGRF, the time interval between initial foot contact (IC) and time-to-peak (i.e., the landing phase), and the resulting loading rate on the lower limb (peak VGRF divided by the duration of landing phase) have yet to be clarified. Therefore, the purpose of this study was to evaluate the effects of lower limb fatigue, induced by high-intensity exercise, on the VGRF profile during single-leg landing from anterior vertical drop-jumps. We hypothesized that lower limb fatigue would influence all three components of the VGRF, namely its peak, time-to-peak and loading rate, in a way that would increase the risk for ACL injury.

SUBJECTS AND METHODS

This study was approved by the institutional review board of Tokyo Medical and Dental University, and all participants provided signed informed consent. The study was performed in full accordance with the ethical standards in the Helsinki Declaration.

Healthy males were recruited among collegiate athletes at our institution, using the following inclusion criteria: ≥18 years of age; regular physical activity (Tegner activity scores[17]) of>4); and no history of injuries or surgery to the lower extremities or lumbar region. Twelve healthy males were enrolled into our study. Relevant characteristics of our study group, reported as the mean (standard deviation (SD) and range) were as follows: age, 20.8 (1.6, 18–24) years; height, 171.1 (8.3, 155–189) cm; mass, 67.7 (9.4, 57–88.8) kg; and body mass index, 23.1 (2.9, 20.1–31.1) kg/m^2. All participants wore identical athletic attire for the testing sessions: spandex shirts, shorts and athletic footwear with no air cushioning.

Participants completed two testing sessions, one under *non-fatigue* condition and one under *fatigue* condition, with testing sessions successively held on one day. For the non-fatigue session, participants completed a 5-minute warm-up comprised of stationary bicycling without resistance and light stretches and then performed three successful single-leg anterior vertical drop-jumps. Drop-jumps were performed in standardized fashion. Participants stood on a 20 cm high step (RBK-BO001, Reebok, USA), placed 60 cm from the center of a 5 cm high force platform. Participants then assumed a single-leg stance on their dominant leg, with arms crossed and hands tucked under their upper arms (Fig. 1). Anterior drop-jumps were performed by limiting the amount of upward motion. Participants were instructed to land, as naturally as possible, only on their dominant leg and in the center of the force platform. Atrial was deemed unacceptable if part of the sole of the foot fell outside the force plate at landing, the foot moved or slid after landing, or the sole of the opposite foot touched the force plate or floor. Failed trials were determined visually, and feedback on landing performance was withheld. Participants were required to complete three successful trials for analysis.

For the fatigue session, participants again completed a brief warm-up, followed by high-intensity interval exercise on a cycle ergometer (POWERMAX V3, KONAMI Sports & Life, Japan). The high-intensity interval exercise was designed to induce lower limb muscle fatigue in a short period of time[18–21]). The exercise consisted of six, 30 s, bouts of maximum velocity pedaling, repeated at 5-min intervals. Pedaling resistance was set at 7.5% of each participant's body weight. Participants had to complete at least 50% of the protocol to induce sufficient fatigue. The mean power and peak velocity of pedaling was calculated for every bout. After a 5-minutes rest at sitting on a chair, participants performed the standardized vertical drop-jumps.

The GRF using the force plate (260AA6, Kistler Instrumente AG) was analyzed using the IFS-4 J/3 J software (DKH Co. Ltd.)[22]). The peak vertical GRF (VGRF), time-to-peak VGRF and loading rate were calculated. The peak VGRF was normalized by body mass (%). The time-to-peak VGRF was defined as the interval between initial contact (IC) and peak VGRF[12]), where IC was defined as the moment when the VGRF exceeded 10 N. The loading rate was obtained by dividing the peak VGRF by the time-to-peak VGRF[23, 24]).

The intraclass correlation coefficients (ICC), model (1, 3), was calculated to confirm the reliability of the calculated

Table 1. Comparison of the mean power and peak velocity of pedaling between the first bout and last bout, including the percentage change in values

Variable	First	Last	%Change
Mean power (W)	597 ± 100	456 ± 62	23 ± 8%**
Peak velocity (rpm)	159 ± 16	132 ± 19	16 ± 11%**

All data are reported as the mean ± SD. **p<0.001

Table 2. Intra-rater reliability for measured variables of the vertical ground reaction force

Variable	ICC (95% CI)
Non-fatigue landings	
Peak VGRF (% BW)	0.951 (0.874–0.985)
Time to peak VGRF (ms)	0.967 (0.914–0.990)
Loading rate (% BW ms^{-1})	0.983 (0.956–0.995)
Fatigue-landings	
Peak VGRF (% BW)	0.952 (0.876–0.985)
Time to peak VGRF (ms)	0.963 (0.904–0.988)
Loading rate (% BW ms^{-1})	0.967 (0.914–0.989)

ICC: intraclass correlation coefficients (model, 1, 3); CI: confidence interval

Table 3. Comparison of the mean ± SD time to peak of the VGRF, peak VGRF and loading rate for landings under fatigue and non-fatigue conditions

Variable	Non-fatigue	Fatigue
Peak VGRF (% BW)	394.6 ± 81.4	380.5 ± 87.6
Time to peak VGRF (ms)	44.0 ± 16.8	39.6 ± 15.8*
Loading rate (% BW ms^{-1})	11.7 ± 8.3	12.8 ± 9.3

*p<0.01

variables for the three trials per participant Differences in the three GRF variables for the fatigue and non-fatigue conditions were evaluated using paired t-test, with an α-level of 0.05. Paired t-test analysis was also used to compare differences in mean power and peak velocity of pedaling between the first and last bout.

RESULTS

Effects of the high-intensity exercise on the mean power and pedaling velocity are summarized in Table 1. Three of twelve participants could not complete six bouts of pedaling. Both of mean power and peak velocity were reduced in all participants. All coefficients were high with ICC ranging from 0.951 to 0.983 (Table 2).

Time to peak VGRF decreased 10.0% (p<0.05) under the condition of fatigue (Table 3). Fatigue also yielded a 3.6% lowering in peak magnitude of the VGRF and a 9.4% increase in loading rate, although these effects did not reach statistical significance (Table 3).

DISCUSSION

During weight-bearing sport activities, several factors can increase ACL strain and, therefore, the risk for non-contact ACL injury: anterior tibial shear forces, which increase axial loading near full knee extension[25)]; tibiofemoral compression force; and combined moments of knee abduction and internal rotation[14)]. *In vivo* research has also shown peak ACL strain to correspond to the peak VGRF magnitude[12)]. Considering that lower limb fatigue can alter the profile of the VGRF, fatigue is considered to be an important risk factor for ACL injury[14–16)]. With regards to landing from vertical jumps, short-term fatigue has been shown to: increase anterior tibial shear force[15)]; increase hip extension and internal rotation at initial contact[16)]; increase peak knee abduction and internal rotation[16, 26)]; and decrease the end-point flexion angle at the hip and knee[26)].

Our findings contribute to this body of knowledge with evidence of an effect of fatigue in reducing the time-to-peak VGR (p<0.05) while concomitantly increasing loading rate. The duration of the time-to-peak phase in our task extends from toe-contact (IC) to heel contact. This time interval can be shortened by an increase in angular velocity of dorsiflexion, likely resulting from fatigue of the ankle plantarflexors. During landing, the plantarflexors produce an internal plantarflexion moment that resists the external dorsiflexion moment produced by the GRF. With fatigue, the plantarflexors are unable to generate the same magnitude of force as in their non-fatigue state, resulting in a lowering of the internal plantarflexion moment available during landing and a resultant an increase in angular velocity of dorsiflexion. Coventry et al.[27)] have also reported that the range of ankle dorsiflexion, from IC to peak VGRF, also decreases with fatigue. We postulate that these mechanisms, namely decreased range of dorsiflexion, increased angular velocity of dorsiflexion, and decreased the flexion angle of the hip and knee[26)] contributed to the shorter time-to-peak VGRF with fatigue. This finding would be consistent with the previously published findings of Shimokochi et al.[28)] who demonstrated a lowering in the activation of the gastrocnemius muscle and plantarflexor moment, in combination with an increase in the moment of ankle dorsiflexion, decreased plantarflexion angle at IC and decreased time-to-peak VGRF in subjects instructed to land on heel with body as upright as possible, compared to land on forefoot with forward lean of the body. Although non-significant, our identified effects of fatigue in lowering peak VGRF agree with the findings of Kernozek et al.29), Weinhandl et al.30), Coventry et al.27), and James et al.31), but not with the findings of an increase in peak VGRF with fatigue reported by Dominguese et al.19) and Brazen et al.32). In our study, we predict that the decrease in peak VGRF was caused by fatigue of the knee extensors after the high-intensity exercise. Pearcey et al., in fact, have reported a lowering in maximum voluntary contraction force, voluntary activation and twitch force of the knee extensor following repeated maximal intensity intermittent-sprints on a bicycle ergometer33). Moreover, Kellis et al. demonstrated an association between knee extensor fatigue and lower peak VGRF during landing from vertical drop-jumps34).

Different short-term fatiguing protocols have been used in research. Chappell et al. evaluated the effects of fatigue by having participants complete unlimited cycles of 5 consecutive vertical jumps followed by a 30 m sprint6). Borotikar et al. used repetitive squatting and randomly ordered jump sequences, until performance of squats was no longer possible16). However, as different fatigue protocols yield different effects on lower limb biomechanics31), there is no consensus on which fatigue protocol which would produce the largest effects on lower limb biomechanics and, therefore, increase the risk for ACL injury35). This is highlighted by James et al.'s evaluation of the effects of two short-term fatigue protocols on the knee angle at IC when landing from drop-jumps, repeated squatting or cycling to fatigue31). In their evaluation, James et al. reported a greater increase in knee flexion angle at IC after the cycling protocol, indicative that cycling may be more effective than repeated squatting to induce short-term lower limb fatigue. High-intensity interval exercise on a bicycle ergometer, as we used in our study, has been previously used as a fatigue protocol in research31, 35–37).

With regards to mechanism of non-contact ACL injury, Cowling and Steele38) reported that synchronization between peak activation of the semimembranosus muscle and peak tibiofemoral shear force may provide a protective effect on the ACL during landing from jump. As both the GRF and muscle forces contribute to the tibiofemoral joint shear forces during landing, the decrease in time-to-peak VGRF after fatigue will decrease the latency between IC and time-to-peak magnitude of the anterior tibiofemoral joint shear force. Therefore, fatigue might induce a delay between peak anterior tibiofemoral shear force and peak activation of the semimembranosus muscle, which would increase the risk for ACL injury. As we did not include measures of joint angles, muscle activity and muscle force in our study, future research will be needed to validate our interpretation of the importance of synchronization between peak anterior tibiofemoral shear force and peak semimembranosus activity to the risk for ACL injury when landing from jumps.

In conclusion, we demonstrated that lower limb fatigue, induced by high-intensity interval exercise, shortens time from IC to peak VGRF during landing from single-leg, anterior vertical drop-jumps in males. Although only the effects on the magnitude of peak force reached statistical significance in our study group of 12 participants, we consider the identified effects on time-to-peak to be an important variable which could explain the increased risk for anterior cruciate ligament injury with fatigue. Monitoring of fatigue, in combination with including endurance training, could reduce the incidence of sport-related, non-contact, ACL injuries.

ACKNOWLEDGEMENTS

I acknowledge the contributions of Mr. Kenji Hirohata, Mr. Takehiro Ohmi, and Mr. Shunsuke Ohji in data acquisition and analysis, and the contributions of Mr. Shinya Kaji in data acquisition.

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