

# Fatigue alters lower extremity kinematics during a single-leg stop-jump task

Anne Benjaminse · Ayako Habu · Timothy C. Sell ·  
John P. Abt · Freddie H. Fu · Joseph B. Myers ·  
Scott M. Lephart

Received: 11 June 2007 / Accepted: 3 October 2007  
© Springer-Verlag 2007

**Abstract** To examine the kinematic characteristics of the hip and knee during a single-leg stop-jump task before and after exercise-to-fatigue, and to determine if the fatigue response is gender-dependent. Lower extremity kinematic measurements were taken of male and female subjects while they performed a sports functional task before and after fatigue developed from exhaustive running. Thirty healthy, physically active subjects (15 males and 15 females) Knee and hip joint kinematics were calculated utilizing three-dimensional video analysis. Each subject performed five single-leg stop-jumps before and after an exercise-to-fatigue bout. All subjects underwent a fatigue protocol using the modified Astrand protocol. Fatigue was verified using the Rating of Perceived Exertion along with the subject's heart rate. All data were analyzed using two factor (test × gender) repeated measures ANOVA ( $P < 0.05$ ). Both males and females demonstrated significantly less maximal knee valgus ( $P = 0.038$ ) and decreased knee flexion at initial contact ( $P = 0.009$ ) post-fatigue. No significant differences were identified in hip joint angles between sessions or between sexes. The results show that fatigue developed from exhaustive running alters lower extremity kinematics during a single-leg stop-jump task. The more neutral position in the frontal plane might be an

effort to protect the knee. The decrease in knee flexion at initial contact may be an attempt to increase knee stability following fatigue. Our results did not reveal any gender differences in this specific task.

**Keywords** Anterior cruciate ligament · Fatigue · Injury · Kinematics · Neuromuscular control · Stop-jump

## Introduction

The majority of anterior cruciate ligament (ACL) injuries occur during sports participation and are a result of a noncontact mechanism of injury [1, 2]. These injuries typically occur during a sharp deceleration task such as landing from a jump, a quick stop, or a cutting maneuver [1]. A more detailed examination of the underlying mechanism to ACL injury is crucial in an attempt to try to reduce the amount of injuries. Researchers have investigated the potential risk factors for noncontact ACL injuries and they can be categorized into two different areas: non-modifiable (anatomical and hormonal) and modifiable (neuromuscular and biomechanical) [3]. The majority of research into noncontact ACL injury risk factors has focused on the neuromuscular and biomechanical risk factors because of their potential for modification. Despite such efforts to prevent noncontact ACL injuries by modifying landing strategies, the incidence remains high [4]. Key factors associated with ACL injuries still need to be explored. Another potential modifiable factor is neuromuscular fatigue. However, the role of fatigue on neuromuscular control has not been sufficiently studied.

Fatigue is an extrinsic factor affecting the musculo-skeletal and neurological systems [5]. It seems to create an environment that increases the risk of noncontact ACL

---

A. Benjaminse · A. Habu · T. C. Sell (✉) ·  
J. P. Abt · F. H. Fu · J. B. Myers · S. M. Lephart  
Neuromuscular Research Laboratory,  
Department of Sports Medicine and Nutrition,  
School of Health and Rehabilitation Sciences,  
University of Pittsburgh, 3200 South Water Street,  
Pittsburgh, PA 15203, USA  
e-mail: selltc@upmc.edu

A. Benjaminse  
e-mail: anb87@pitt.edu

injuries by altering lower extremity landing strategies. It has been reported that most athletic injuries occur in the later stages of activities and competition [6–12] indicating that vigorous exercise and fatigue may influence dynamic knee stability. Fatigue has been reported to result in decreased motor control performance [13, 14], increased knee joint laxity [14–16], decreased balance skill [13] and decreased proprioception [16–20]. These effects indicate a decreased capacity for controlling body movement after fatigue and may indicate fatigue as a contributor to non-contact ACL injuries [6, 17, 21]. Fatigue may have a cumulative, unfavorable effect, especially in latter stages of competition, on neuromuscular control and may potentially result in hazardous movement strategies [22]. Fatigue or resistance to fatigue could potentially be a modifiable risk factor that could improve the lower extremity alignment throughout movement.

Previous studies looking at fatigue and the effect on kinematic and kinetic characteristics found that subjects land with significantly increased peak proximal tibial anterior shear forces, increased valgus moments and decreased knee flexion angles during landings of stop-jump tasks [5]. Others investigated the influence of isolated quadriceps and hamstrings fatigue on landing motion [21]. They found that fatigue of the hamstrings resulted in decreased peak impact knee flexion moments, increased internal tibial rotation at peak knee flexion and decreased peak ankle dorsiflexion. Whereas quadriceps fatigue did result in increased peak ankle dorsiflexion moments, decreased peak knee extension moments, delayed peak knee flexion and delayed subtalar peak inversion moments [21]. More recently, others found that fatigue resulted in increased initial and peak knee abduction and internal rotation motions and peak knee internal rotation, adduction, and abduction moments, with the latter being more pronounced in females [22].

Considering the current knowledge regarding the effects of fatigue on the noncontact ACL injury mechanism, we decided to examine the kinematic characteristics of the hip and knee joints during a single-leg stop-jump task before and after exercise-to-fatigue, and to examine if fatigue affects each gender equally.

Our main purpose of this study was to examine the kinematic characteristics of the hip and knee joint during a single-leg stop-jump task before and after exercise-to-fatigue. The secondary purpose was to examine if the joint kinematics changes following exercise-to-fatigue are different between males and females. We hypothesized that fatigue developed from exhaustive running would result in: (1) increased internal hip rotation angle, (2) increased hip adduction angle, (3) increased knee valgus angle and (4) decreased knee flexion angle during a single-leg stop-jump task in both genders. We also hypothesized that females

would exhibit increased alterations post-fatigue in knee and hip joint kinematics compared to males: (1) greater hip internal rotation changes compared to males, (2) greater hip adduction changes compared to male, (3) greater knee valgus changes compared to males and (4) greater knee flexion angle changes compared to males.

## Materials and methods

### Subjects

Thirty (15 males and 15 females) healthy and physically active subjects between the ages of 18–30 years old were recruited for this study. The term “physically active” was defined as individuals performing aerobic exercise for a minimum of 30 min a day, three times a week. All subjects were recreational athletes. Subject demographics are presented in Table 1. Written informed consent according to the University’s Institutional Review Board was obtained from the subjects prior to participation in the study.

### Data collection

Subjects wore their own clothes and shoes for the testing session. A Polar Tempo Heart Rate Monitor™ (U.S. model A3, Polar Electro Inc., Woodbury, NY) was attached to the subject according to the manufacturer’s instructions prior to data collection. Anthropometric data including height, weight, and lower extremity linear (anterior superior iliac spine width, thigh length, lower leg length, malleolus height, knee diameter, ankle diameter, foot breadth, and foot length) and circumferential (mid-thigh and mid-calf) measurements were obtained. Reflective markers, with a diameter of 0.025 m, were positioned on anatomical landmarks of each lower extremity as follows: posterior heel, lateral malleolus, second metatarsal head, lateral femoral condyle, anterior superior iliac spine and sacrum. Four additional markers were attached to wands (distance of 0.09 m from the skin) and placed at the lateral side of the mid-thigh and mid-calf [23]. A three-dimensional optical capture system (Vicon Motion Systems, Inc., Centennial,

**Table 1** Subject demographics

	Age (years) Mean ± SD	Height (cm) Mean ± SD	Mass (kg) Mean ± SD
Males	22.7 ± 1.6	180.3 ± 7.7	80.0 ± 10.5
Females	22.1 ± 1.7	169.1 ± 6.6	60.7 ± 7.4

CO) was used to collect coordinate data of the lower extremities during the single-leg stop-jump task. Six high speed (120 Hz) optical cameras (Pulnix Industrial Product Division, Sunnyvale, CA) encircled two force plates. A static calibration trial was conducted prior to data collection (pre- and post-fatigue). Based on the data collected from the camera recordings, the anatomical hip and knee joint angles were calculated to examine clinically applicable angles and were based on studies by Chao [24] and Grood and Suntay [25]. All of the kinematic calculations were performed in the Kinematic module of the Vicon Motus software package (Vicon Motion Systems, Inc., Centennial, CO) and were based on the work of Vaughan et al. [23].

Kistler force plates (Kistler Instrument Corporation, Amherst, NY) embedded within adaptable flooring and instrumented with the Motus System were used for identification of four dependent variables (hip internal–external rotation, hip abduction–adduction, knee valgus–varus and knee flexion–extension) at initial contact. Initial contact was defined as the subject touching the force plate with 5% of his or her body weight.

The stop-jump task consisted of a single-leg standing jump onto a force plate followed immediately by a maximal effort vertical jump. This type of task was chosen as this is a high demanding task that requires a sudden deceleration that replicates a task frequently performed in basketball, volleyball and team handball. Noncontact ACL injuries frequently occur during this kind of task [1, 26]. Also, it is suggested that even during double-legged movements the weight during noncontact ACL injuries is for 65–100% on one leg (with 8 out of 12 being 100%) [26]. Other research has indicated that the hip plays an important role in the kinetic chain of the lower extremity [27, 28] and might therefore play an important role in the gender differences in ACL injury rate. We therefore decided to include the knee and hip in our motion analyses.

Subjects were asked to land on the force plate following the maximal effort vertical jump. Subjects started the single-leg jump at a distance equal to 40% of their height from the edge of the force plate on their preferred leg. The preferred leg was defined as the leg that the subject was most comfortable completing the task with. Subjects were instructed in the proper technique (proper start position, single-leg landing on the force plate, maximum effort vertical jump) and provided practice trials to familiarize themselves with the task. Five acceptable trials were collected for pre- and post-fatigue sessions on the preferred leg. An acceptable trial was defined as landing on the force plate with the foot completely on the force plate without losing balance (i.e. touching nonjumping leg or ground prior to jump), prior to the maximal effort vertical jump. When the subject failed to jump single-legged and/or lost his or her balance, the trial was considered as invalid, and

the subject performed another trial. Post-exercise procedures were completed immediately after the fatigue protocol and were identical to the pre-test measures.

All subjects underwent a fatigue protocol using the modified Astrand protocol [29, 30] in conjunction with Borg's 15-category rating of perceived exertion (RPE) [31], in addition their heart rate was monitored to establish the threshold of exercise intensity. The equation of the estimated maximal heart rate ( $HR_{max}$ ) was determined by subtracting subject's age from 220 (Estimated  $HR_{max} = 220 - \text{age}$ ) [32]. The heart rate difference between the end of the fatigue protocol and the initiation of the post-fatigue test, and the time between the end of the fatigue protocol and the last post-fatigue trial were also averaged. The fatigue developed in this protocol is defined as fatigue developed from exhaustive running, as the subjects gave their maximal effort and ran until exhaustion.

After proper explanation, each subject was instructed to start walking for 3 min as a warm-up on a Wellness Treadmill WTM410 (model no. 945-240, Biodex Medical System Inc., Shirley, NY), at a speed of 2 mph (0% grade). As soon as the 3-min warm-up session was completed, the speed was increased to 5–8 mph for 3 min (0% grade) according to the subjects' comfortable running pace. After 3 min at 0% grade running, the grade was increased 2.5% every 2 min throughout the session until the termination of the fatigue protocol (i.e., subject could not run anymore at maximum effort). During the test the subject was verbally encouraged to continue running until exhausted. Mean running speed was  $6.3 \pm 0.62$  mph in males and  $5.8 \pm 0.43$  mph in females. The running speed set at the beginning remained constant throughout the fatigue protocol. Immediately following the termination of the fatigue protocol all subjects performed the same single-leg stop-jump task as before running. The time between the end of the fatigue protocol and the initiation of the post-fatigue test, and the time between the end of the fatigue protocol and the last trial were averaged (Table 3).

#### Data reduction

The kinematic variables of knee and hip joints were calculated using Motus Software video analysis system (Version 7.2.3; Vicon Motion Systems, Inc., Centennial, CO) based on Vaughan et al. [23]. Raw three-dimensional coordinate data from single-leg stop-jump were filtered using a fourth order zero lag Butterworth digital filter with an optimal cut-off frequency [33]. All kinematic data was normalized to the static calibration trial that was collected prior to each set of jumps (pre- and post-fatigue). Hip and knee joint kinematics (hip internal–external rotation, hip

adduction–abduction, knee valgus–varus, and knee flexion–extension) were evaluated at initial contact and at the maximum value of each variable respectively. For both test sessions, the first three successful trials were digitized and averaged for each subject from the initial contact onto the force plate to the second landing. Vertical jump height was measured using the sacral marker (change in percent body height with respect to the static trial) and was expressed as percent body height.

#### Data analysis

The knee and hip joint kinematic measurements (hip internal–external rotation, hip abduction–adduction, knee valgus–varus, and knee flexion–extension) were used for data analysis. All data were analyzed using two factor (test  $\times$  gender) repeated measures ANOVA on the knee and hip variables. The independent variables in each analysis were gender and fatigue condition. The alpha level for all statistical analysis was set at  $P < 0.05$ .

#### Results

There were no gender differences for subject demographics (age,  $P = 0.85$ ; height,  $P = 0.59$ ; mass,  $P = 0.09$ ), mean running speed ( $P = 0.36$ ), maximal heart rate ( $P = 0.15$ ), heart rate at the last averaged trial ( $P = 0.74$ ), or percent maximal heart rate ( $P = 0.43$ ). Overall, the jump height as a measure of performance did decrease from  $17.71 \pm 4.53$  pre-fatigue to  $16.70 \pm 4.01$  post-fatigue (% body height). For males, the jump height pre-fatigue was  $20.16 \pm 4.52$  compared to  $18.08 \pm 4.19$  post-fatigue. For females however, the jump height did not change after the fatigue protocol:  $15.26 \pm 3.06$  pre-fatigue compared to  $15.32 \pm 3.42$  post-fatigue (Table 2). Information about the fatigue developed from high-intensity running is listed in Table 3. The average time to fatigue was  $14:00 \pm 2:34$  min in males, and  $11:43 \pm 1:50$  min in females ( $P = 0.18$ ). The mean elapsed time between the termination of fatigue and the beginning of the first post-fatigue jump was  $1:13 \pm 0:18$  min in males and  $1:10 \pm 0:15$  min in females ( $P = 0.61$ ). Male and female subjects completed the post-fatigue jump trials in  $1:52 \pm 0:23$  and  $1:49 \pm 0:17$  min ( $P = 0.20$ ) respectively after termination of fatigue protocol. The heart rate was also recorded after each post-fatigue single-leg stop-jump.

The pre-fatigue session and post-fatigue session mean test scores for the dependent measures of hip internal–external rotation angles, hip adduction–abduction angles, knee valgus–varus angles, and knee flexion–extension angles for both genders are presented in Table 4. There

**Table 2** Maximal height of jumping (% body height)

	Mean $\pm$ SD
Pre-fatigue	
Males	20.16** $\pm$ 4.52
Females	15.26** $\pm$ 3.06
Total	17.71* $\pm$ 4.53
Post-fatigue	
Males	18.08** $\pm$ 4.19
Females	15.32** $\pm$ 3.42
Total	16.70 $\pm$ 4.01

\* Statistical significance at  $P < 0.05$  (pre–post)

\*\* Statistical significant gender difference at  $P < 0.05$

**Table 3** Fatigue information

	Males Mean $\pm$ SD	Females Mean $\pm$ SD	<i>P</i> value
Time to fatigue (min)	14:00 $\pm$ 2:34	11:43 $\pm$ 1:50	0.182
Time 1 <sup>a</sup> (min)	1:13 $\pm$ 0:18	1:10 $\pm$ 0:15	0.614
Time 2 <sup>b</sup> (min)	1:52 $\pm$ 0:23	1:49 $\pm$ 0:17	0.203
Max HR (bpm)	193 $\pm$ 9.5	188 $\pm$ 6.2	0.153
HR at the end (bpm)	156 $\pm$ 13.6	148 $\pm$ 10.9	0.742
% Max HR	80.8 $\pm$ 5.9	78.5 $\pm$ 5.2	0.431

<sup>a</sup> Time 1 is the time between termination of fatigue and the start of the post-fatigue jump trials

<sup>b</sup> Time 2 is the time between termination of fatigue and the completion of the post-fatigue jump trials

were no significant differences for any of the hip kinematic variables the between pre-fatigue session and post-fatigue session or between genders. Post-fatigue, both males and females showed significantly less maximal knee valgus angles ( $P = 0.038$ ) and knee flexion angles ( $P = 0.009$ ) at initial contact. No gender difference existed in the other knee valgus–varus variables or in the knee flexion–extension variables between males and females either in the pre- and post-fatigue sessions.

#### Discussion

We were interested in the effect of fatigue developed from exhaustive running on lower extremity kinematics during landing due to reports of athletic injuries occurring in different sports in the later stages of activities and competition [6, 7]. In addition, since research studies have reported that female athletes are sustaining noncontact ACL injuries more frequently than their male counterparts [1, 34–36], we were interested in whether fatigue developed from exhaustive running would change lower

**Table 4** Hip and knee kinematics pre- and post-fatigue

	Group	Pre-fatigue	Post-fatigue
<b>Hip kinematics</b>			
Hip internal–external rotation at initial contact (deg)	Males	$-2.6 \pm 8.5$	$-4.4 \pm 8.2$
	Females	$-3.2 \pm 5.2$	$-3.6 \pm 3.4$
	Total	$-2.9 \pm 7.0$	$-4.0 \pm 6.2$
Maximum hip internal–external rotation (deg)	Males	$3.4 \pm 6.0$	$1.1 \pm 5.5$
	Females	$3.2 \pm 5.3$	$2.3 \pm 3.8$
	Total	$3.3 \pm 5.5$	$1.7 \pm 4.7$
Hip adduction–abduction at initial contact (deg)	Males	$7.1 \pm 4.7$	$6.2 \pm 6.7$
	Females	$4.7 \pm 4.3$	$5.9 \pm 4.3$
	Total	$5.9 \pm 4.6$	$6.0 \pm 5.5$
Maximum hip adduction–abduction (deg)	Males	$12.2 \pm 4.7$	$11.9 \pm 5.2$
	Females	$9.7 \pm 4.3$	$10.7 \pm 4.3$
	Total	$11.0 \pm 4.6$	$11.3 \pm 4.7$
<b>Knee kinematics</b>			
Knee valgus–varus angles initial contact (deg)	Males	$-0.4 \pm 3.0$	$-0.9 \pm 2.2$
	Females	$3.1 \pm 1.9$	$3.0 \pm 1.9$
	Total	$1.36 \pm 3.0$	$1.0 \pm 2.8$
Maximal knee valgus–varus (deg)	Males	$1.5 \pm 3.6$	$0.8 \pm 3.5$
	Females	$5.5 \pm 2.5$	$4.6 \pm 2.3$
	Total*	$3.5 \pm 3.7$	$2.7 \pm 3.5$
Knee flexion angles at initial contact (deg)	Males	$12.2 \pm 5.1$	$10.6 \pm 4.9$
	Females	$14.9 \pm 5.3$	$12.3 \pm 6.6$
	Total*	$13.6 \pm 5.3$	$11.5 \pm 5.8$
Maximal knee flexion (deg)	Males	$51.2 \pm 6.8$	$51.3 \pm 7.4$
	Females	$49.0 \pm 7.3$	$48.5 \pm 8.0$
	Total	$50.1 \pm 7.0$	$49.9 \pm 7.7$

Hip internal rotation (+), hip external rotation (–), hip abduction (+), hip adduction (–), knee valgus (+), knee varus (–)

\* Statistically significant at  $P < 0.05$

extremity kinematics and if the effect of fatigue would be more pronounced in females than in males. The first purpose of this research study was therefore to investigate the influence of fatigue on hip and knee joint kinematics in healthy, active males and females. Secondly, we wanted to determine if fatigue affects both genders differently in terms of joint kinematics, in order to hopefully provide more insight in why females are more prone to noncontact ACL injuries.

Females did not demonstrate a significant difference in jump height pre- versus post-fatigue, however males did show a decrease in jump height after the fatigue protocol. Although the decrease in jump height in males was statistically significant, we feel that this has minimal clinical implications as the difference was only  $\sim 2\%$  of their body height.

In the current study, it was hypothesized that fatigue would result in altered movement patterns during a single-

leg stop-jump task in both genders, with more change post-fatigue in females. Our first hypothesis was partially fulfilled in that there was a significant decrease in the maximal knee valgus angle and knee flexion angle at initial contact between pre- and post-fatigue in both males and females. There were no significant pre- and post-fatigue differences in other variables analyzed.

The result of this study did not support our hypothesis that fatigue developed from exhaustive running would result in an increased knee valgus angle. However, both males and females showed more neutral knee position (less valgus angle) in the post-fatigue condition. The maximal knee valgus angle was decreased in both groups post-fatigue (females  $4.6 \pm 2.3^\circ$ , males  $0.8 \pm 3.5^\circ$ ,  $P = 0.038$ ). Even though both females and males were still in knee valgus, this result suggests that both groups tended to bring the knee in more neutral position in the frontal plane in post-fatigue condition. This might be a protective effort as studies have suggested that an increase in knee varus or valgus moment tends to increase the stress on the ACL [37–40].

Previous cadaveric studies have shown that a decreased knee flexion angle can increase ACL strain [40–44]. The results of this study did support our hypothesis that the subjects would land with less knee flexion. The decrease in knee flexion at initial contact was significant in both genders ( $P = 0.009$ ). Both females and males landed with less knee flexion post-fatigue ( $12.3 \pm 6.6^\circ$  for females and  $10.6 \pm 4.9^\circ$  for males). This type of landing may increase ACL strain and support evidence suggesting that more injuries occur at the later stages of a competition. Although the decrease was small, this may be an attempt to increase knee stability following fatigue, because decreased knee flexion prevents valgus and landing with the knee less flexed does not require as much eccentric muscular strength. With less knee flexion, subjects could rely more on the bony architecture and noncontractile tissues surrounding the knee, like the tightened collateral ligaments. Muscle fibers have a decreased capacity to absorb energy when fatigued [45], but although this might be a position requiring less “energy”, the subject may be at greater risk for injury due to the increased strain in the ACL. The decreased knee flexion angle combined with previous research demonstrating increased anterior tibial translation with fatigue [14] may increase the risk of ACL injury during the latter stages of competition.

Also, although less knee flexion does not require as much eccentric strength of the quadriceps, the mechanism seen in this study in the decrease in knee flexion and valgus angles may not be present anymore in an extreme level of fatigue towards the end of a game, as this position probably required more muscle activity from the hip abductors, especially the gluteus medius. It can be expected that more



detrimental loading patterns, including more knee valgus, will be seen during a higher level of exhaustion.

The second hypothesis was not supported by our results and likely resulted from the combination of the small sample size for gender comparisons (15 males and 15 females) and small effect size for gender differences. If males and females did adopt different landing strategies as a result of fatigue for this study, the low power of the gender results prohibits robust conclusions. Therefore future research in this area is needed to further explore if fatigue affects gender differently.

In this study, we did not see compensation in the hip joint for the loss in knee flexion. As hip joint motion did not change significantly and ankle kinematics were not assessed, we could say that our subjects landed with a stiffer landing and energy of the lower extremity was therefore not dissipated as efficiently in the fatigued condition. Knee joint flexion decreased and no compensatory response to absorb the mechanical energy of the impact was seen. This suggests that the subjects landed in a more dangerous position and the probability of ACL injury may be increased [46].

Several fatigue protocols have been discussed in the literature. An isokinetic dynamometer has been used to induce fatigue for the local muscles [14, 15, 47] and whole lower extremity [13]. Rodacki et al. induced a fatigue by repeating vertical jumping until subjects no longer achieved 70% of their maximal jump height [6]. Nyland et al. used a general lower extremity fatigue protocol using uphill treadmill walking [48]. They terminated the protocol when subjects could no longer continue [48]. In the current study fatigue was induced by having subjects run on a treadmill using the modified Astrand protocol [29, 30] in conjunction with RPE. The protocol utilized a standard RPE and heart rate to maximize accuracy and minimize errors of fatigue status [49]. We selected this fatigue protocol because running would create a similar condition as actual sports activities, and the inclination would induce even more fatigue localized in the lower extremity. Because of the nature of the sports in regard to repetitive movement and running, not only whole body aerobic fatigue, but also local muscle fatigue will occur during the athletic event. A focus of the current research was to induce a fatigue pattern that simulates the fatigue as seen in these real athletic events. The termination of fatigue was at the time when the subject was no longer able to continue the protocol. Although Chappell et al. [5] used a different fatigue protocol compared to ours (unlimited repetitions of five consecutive vertical jumps followed by a 30-m sprint), our results are similar to theirs in that fatigued recreational athletes demonstrated altered motor control strategies. It appears as though fatigue developed from exhaustive running alters

the strategies to maintain joint stability and supports the hypothesis of more injuries occurring at the later stages of athletic competition.

The average time to reach fatigue status for this protocol was  $14:00 \pm 2:34$  min in males and  $11:43 \pm 1:50$  min in females. This average time may potentially simulate the fatigue experienced in the middle or later stages of competition when research reports have indicated that many injuries occur [6, 7]. Furthermore, we measured the time between termination of fatigue and the post-fatigue jump tasks. We tested the post-fatigue jumps immediately after the termination of fatigue, and the last jump task was collected within 2 min after the termination of the fatigue protocol (Table 3). HR was also recorded (Table 3). These measurements assure that the subjects were still in the state of fatigue during the post-fatigue stop-jump tasks.

### Limitations

Since no EMG measurements were taken we cannot exactly comment on the muscular contribution to the observed kinematic changes. The decrease in knee flexion at initial contact could however very likely be a result of quadriceps fatigue, making eccentric contraction difficult. As maximum knee valgus decreased, it would also be interesting to compare the firing patterns of hip musculature pre-and post-fatigue. Future research is therefore needed to investigate the influence of fatigue on muscle firing patterns, which is important to know in an attempt to integrate neuromuscular and biomechanical findings with the noncontact ACL injury mechanism. Also, ankle kinematics was not assessed and it is therefore difficult to thoroughly analyze the work distribution of the entire lower extremity. For future research it is recommended to include analysis of ankle motion [22]. Although the effect of fatigue on lower extremity kinematics was our primary objective, limitations to the current study also included a small sample size for gender comparisons. Furthermore, the generalization of the study results is limited to the specific fatigue protocol utilized in this study. The results from this study do not hold true for all forms of exercise to fatigue.

### Conclusion

Our results revealed that both males and females used a stiff landing strategy following fatigue by landing with less maximal knee valgus and less knee flexion at initial contact of the single-leg stop-jump, without changing the hip joint angles. The decrease in knee valgus angle might be a protective effort as an increase in knee varus or valgus

moment tends to increase the stress on the ACL. The decrease in knee flexion at initial contact may be an attempt to increase knee stability while relying on the static structures of the knee more than the dynamic structures following fatigue. Our results did not reveal any gender differences in this specific task.

**Acknowledgments** Research was funded by a grant from the National Athletic Trainers' Association Research and Education Foundation Osternig masters grant program.

## References

- Boden BP, Dean GS, Feagin JA Jr, Garrett WE Jr (2000) Mechanisms of anterior cruciate ligament injury. *Orthopedics* 23:573–578
- Noyes FR, Matthews DS, Moar PA, Grood ES (1983) The symptomatic anterior cruciate-deficient knee. Part II: the results of rehabilitation, activity modification, and counseling on functional disability. *J Bone Joint Surg Am* 65:163–174
- Harmon KG, Ireland ML (2000) Gender differences in noncontact anterior cruciate ligament injuries. *Clin Sports Med* 19:287–302
- Griffin LY, Albohm MJ, Arendt EA et al (2006) Understanding and preventing noncontact anterior cruciate ligament injuries: a review of the Hunt Valley II meeting, January 2005. *Am J Sports Med* 34:1512–1532
- Chappell JD, Herman DC, Knight BS, Kirkendall DT, Garrett Jr WE, Yu B (2005) Effect of fatigue on knee kinetics and kinematics in stop-jump tasks. *Am J Sports Med* 33:1022–1029
- Rodacki AL, Fowler NE, Bennett SJ (2001) Multi-segment coordination: fatigue effects. *Med Sci Sports Exerc* 33:1157–1167
- Feagin JA Jr, Lambert KL, Cunningham RR et al (1987) Consideration of the anterior cruciate ligament injury in skiing. *Clin Orthop Rel Res* 216:13–18
- Gabbett TJ (2000) Incidence, site, and nature of injuries in amateur rugby league over three consecutive seasons. *Br J Sports Med* 34:98–103
- Gabbett TJ (2004) Incidence of injury in junior and senior rugby league players. *Sports Med* 34:849–859
- Molsa J, Airaksinen O, Nasman O, Torstila I (1997) Ice hockey injuries in Finland. A prospective epidemiologic study. *Am J Sports Med* 25:495–499
- Pettrone FA, Ricciardelli E (1987) Gymnastic injuries: the Virginia experience 1982–1983. *Am J Sports Med* 15:59–62
- Stuart MJ, Smith A (1995) Injuries in Junior A ice hockey. A three-year prospective study. *Am J Sports Med* 23:458–461
- Johnston RB 3rd, Howard ME, Cawley PW, Losse GM (1998) Effect of lower extremity muscular fatigue on motor control performance. *Med Sci Sports Exerc* 30:1703–1707
- Wojtys EM, Wylie BB, Huston LJ (1996) The effects of muscle fatigue on neuromuscular function and anterior tibial translation in healthy knees. *Am J Sports Med* 24:615–621
- Skinner HB, Wyatt MP, Stone ML, Hodgdon JA, Barrack RL (1986) Exercise-related knee joint laxity. *Am J Sports Med* 14:30–34
- Rozzi SL, Lephart SM, Fu FH (1999) Effects of muscular fatigue on knee joint laxity and neuromuscular characteristics of male and female athletes. *J Athl Train* 34:106–114
- Hiemstra LA, Lo IK, Fowler PJ (2001) Effect of fatigue on knee proprioception: implications for dynamic stabilization. *J Orthop Sports Phys Ther* 31:598–605
- Lattanzio PJ, Petrella RJ (1998) Knee proprioception: a review of mechanisms, measurements, and implications of muscular fatigue. *Orthopedics* 21:463–470
- Lattanzio PJ, Petrella RJ, Sproule JR, Fowler PJ (1997) Effects of fatigue on knee proprioception. *Clin J Sport Med* 7:22–27
- Miura K, Ishibashi Y, Tsuda E, Okamura Y, Otsuka H, Toh S (2004) The effect of local and general fatigue on knee proprioception. *Arthroscopy* 20:414–418
- Nyland JA, Shapiro R, Caborn DN, Nitz AJ, Malone TR (1997) The effect of quadriceps femoris, hamstring, and placebo eccentric fatigue on knee and ankle dynamics during crossover cutting. *J Orthop Sports Phys Ther* 25:171–184
- McLean SG, Felin RE, Suedekum N, Calabrese G, Passerallo A, Joy S (2007) Impact of fatigue on gender-based high-risk landing strategies. *Med Sci Sports Exerc* 39:502–514
- Vaughan C, Davis BL, O'Connor JC (1999) *Dynamics of Human Gait*. 2nd edn. Kiboho, Cape Town
- Chao EY (1980) Justification of triaxial goniometer for the measurement of joint rotation. *J Biomech* 13:989–1006
- Grood ES, Suntay WJ (1983) A joint coordinate system for the clinical description of three-dimensional motions: application to the knee. *J Biomech Eng* 105:136–144
- Olsen OE, Myklebust G, Engebretsen L, Bahr R (2004) Injury mechanisms for anterior cruciate ligament injuries in team handball: a systematic video analysis. *Am J Sports Med* 32:1002–1012
- McLean SG, Huang X, van den Bogert AJ (2005) Association between lower extremity posture at contact and peak knee valgus moment during sidestepping: implications for ACL injury. *Clin Biomech (Bristol, Avon)* 20:863–870
- Yu B, Lin CF, Garrett WE (2006) Lower extremity biomechanics during the landing of a stop-jump task. *Clin Biomech (Bristol, Avon)* 21:297–305
- Kang J, Chaloupka EC, Mastrangelo MA, Biren GB, Robertson RJ (2001) Physiological comparisons among three maximal treadmill exercise protocols in trained and untrained individuals. *Eur J Appl Physiol* 84:291–295
- Pollock LM, Wilmore JH, Fox SM (1978) *Health and fitness through physical activity*. Wiley, New York, p 59
- Borg GA (1982) Psychophysical bases of perceived exertion. *Med Sci Sports Exerc* 14:377–381
- Wilmore JH, Costill DL (1994) *Physiology of sport and exercise*. Human Kinetics, Champaign
- Jackson KM (1979) Fitting of mathematical functions to biomechanical data. *IEEE Trans Biomed Eng* 26:122–124
- Toth AP, Cordasco FA (2001) Anterior cruciate ligament injuries in the female athlete. *J Gender Spec Med* 4:25–34
- Arendt EA, Agel J, Dick R (1999) Anterior cruciate ligament injury patterns among collegiate men and women. *J Athl Train* 34:86–92
- Ireland ML (1999) Anterior cruciate ligament injury in female athletes: epidemiology. *J Athl Train* 34:150–154
- Arms SW, Pope MH, Johnson RJ, Fischer RA, Arvidsson I, Eriksson E (1984) The biomechanics of anterior cruciate ligament rehabilitation and reconstruction. *Am J Sports Med* 12:8–18
- Bendjaballah MZ, Shirazi-Adl A, Zukor DJ (1997) Finite element analysis of human knee joint in varus–valgus. *Clin Biomech (Bristol, Avon)* 12:139–148
- Kanamori A, Woo SL, Ma CB et al (2000) The forces in the anterior cruciate ligament and knee kinematics during a simulated pivot shift test: a human cadaveric study using robotic technology. *Arthrosc* 16:633–639
- Markolf KL, Burchfield DM, Shapiro MM, Shepard MF, Finerman GA, Slauterbeck JL (1995) Combined knee loading states that generate high anterior cruciate ligament forces. *J Orthop Res* 13:930–935

41. Markolf KL, Mensch JS, Amstutz HC (1976) Stiffness and laxity of the knee—the contributions of the supporting structures. A quantitative in vitro study. *J Bone Joint Surg Am* 58:583–594
42. Markolf KL, Gorek JF, Kabo JM, Shapiro MS (1990) Direct measurement of resultant forces in the anterior cruciate ligament. An in vitro study performed with a new experimental technique. *J Bone Joint Surg Am* 72:557–567
43. Sakane M, Fox RJ, Woo SL, Livesay GA, Li G, Fu FH (1997) In situ forces in the anterior cruciate ligament and its bundles in response to anterior tibial loads. *J Orthop Res* 15:285–293
44. Fleming BC, Renstrom PA, Ohlen G et al (2001) The gastrocnemius muscle is an antagonist of the anterior cruciate ligament. *J Orthop Res* 19:1178–1184
45. Lepers R, Hausswirth C, Maffiuletti N, Brisswalter J, van Hoocke J (2000) Evidence of neuromuscular fatigue after prolonged cycling exercise. *Med Sci Sports Exerc* 32:1880–1886
46. Dufek JS, Bates BT (1990) The evaluation and prediction of impact forces during landings. *Med Sci Sports Exerc* 22:370–377
47. Moore BD, Drouin J, Gansneder BM, Shultz SJ (2002) The differential effects of fatigue on reflex response timing and amplitude in males and females. *J Electromyogr Kinesiol* 12:351–360
48. Nyland JA, Shapiro R, Stine RL, Horn TS, Ireland ML (1994) Relationship of fatigued run and rapid stop to ground reaction forces, lower extremity kinematics, and muscle activation. *J Orthop Sports Phys Ther* 20:132–137
49. Cerullo JF (2000) The effect of lower extremity muscle fatigue on vertical ground reaction forces and muscle activation patterns during landing. Doctoral dissertation