Journal of
Exercise Science and Medicine

Winter & Spring 2019, Volume 11, Number 1

Research Paper:

Effect of Fatigue on Ground Reaction Force Variables During Single-leg Landing in Athletes With the History of Anterior Cruciate Ligament Injury

Komeil Dashti Rostami[1,2], Mohammad Hossein Alizadeh[3*], Hooman Minoonejad[4], Hamidreza Yazdi[5]

1. PhD. Student, Department of Health and Sports Medicine, Faculty of Physical Education and Sport Sciences, University of Tehran, Tehran, Iran.
2. Assistant Professor, Department of Biomechanics, Faculty of Physical Education and Sport Sciences, University of Mazandaran, Babolsar, Iran.
3. Professor, Department of Health and Sports Medicine, Faculty of Physical Education and Sport Sciences, University of Tehran, Tehran, Iran.
4. Associate Professor, Department of Health and Sports Medicine, Faculty of Physical Education and Sport Sciences, University of Tehran, Tehran, Iran.
5. Associate Professor, Neuromusculoskeletal Research Center, Iran University of Medical Sciences, Tehran, Iran.

Use your device to scan
and read the article online

Citation Dashti Rostami K, Alizadeh MH, Minoonejad H, Yazdi H. Effect of Fatigue on Ground Reaction Force Variables During Single-leg Landing in Athletes With the History of Anterior Cruciate Ligament Injury. Journal of Exercise Science and Medicine (JESM). 2019; 11(1):13-22. http://dx.doi.org/10.32598/JESM.11.1.2

http://dx.doi.org/10.32598/JESM.11.1.2

Article info:
Received: 06 April 2017
Accepted: 03 Aug 2017
Available Online: 01 Jan 2019

ABSTRACT

Introduction: Since people experience fatigue after anterior cruciate ligament injury during exercises, it is important to understand how fatigue affects the biomechanical movement patterns. Therefore, this study aimed to investigate the effect of fatigue on ground reaction force variables during single-leg landing in athletes with a history of an anterior cruciate ligament sprain.

Methods: it was a case-control study conducted in the University Laboratory. The sample consisted of 36 male athletes who were divided into three groups: 12 people with Anterior Cruciate Ligament Reconstruction (ACLR), 12 people with Anterior Cruciate Ligament Deficiency (ACLD), and 12 people as the control group. Fatigue was induced via the repetitive sets of double-leg squats (n=8), which were interspersed with the sets of countermovement jumps (n=2) and single-leg landings (n=3) until squats were no longer possible. A 2×2 repeated-measures multivariate analysis of variance was used to detect the main effects of group (ACLD, ACLR, control) and fatigue state (prefatigue, postfatigue) on the ground reaction forces variables.

Results: The results showed a significant decrease in the peak vertical force and internal-external ground reaction force in the ACLD group after fatigue. Regardless of the fatigue state, the peak vertical ground reaction force in ACLD and ACLR groups was significantly lower than that in the control group.

Conclusion: The athletes with the ACL injury, regardless of the selective treatment type, use compensatory strategies to reduce the contact forces on the lower extremity, compared with healthy athletes.

Keywords:

Injury, Fatigue, Anterior cruciate ligament, Ground reaction force, Knee joint

*** Corresponding Author:**
Mohammad Hossein Alizadeh, PhD.
Address: *Department of Health and Sports Medicine, Faculty of Physical Education and Sport Sciences, University of Tehran, Tehran, Iran.*
Tel: *+98 (912) 3489807*
E-mail: *mhalizadeh47@yahoo.com*

Introduction

The knee joint is one of the most prevalent parts of the body that gets injured because of its complex anatomy and the functional demands imposed on it. The annual incidence of Anterior Cruciate Ligament (ACL) tear caused by exercise is 2 to 5 per 10000 people. However, in some countries, almost 50% of ACL injuries are treated without surgery. Therefore, the annual prevalence of injury is probably higher than that reported [1, 2]. Epidemiologic research shows that almost 70% of ACL injuries are non-contact and usually occur when the athlete is doing pivoting, rotating, cutting, jump-landing, and sudden acceleration decrease maneuvers [1-4].

Numerous research studies have been conducted to determine the risk factors of the ACL injury. In general, the risk factors of the ACL injury include environmental factors, such as playing grounds and friction between the shoes and surface [5]; athlete's anatomical situation, such as slit stenosis between femoral condyles [6, 7]; hormonal levels, such as the increased levels of estrogen in women [8]; and athlete's neuromuscular-mechanical factors, such as muscle reaction time, muscle strength, the kinematics and kinetics of joints, and neuromuscular fatigue [6, 9]. Since neuromuscular-mechanical factors are modifiable, most research has been focused on these factors.

Fatigue is a phenomenon that is often recognized as a risk factor of the ACL injury in sports. It is defined as a decrease in the ability of the muscles to generate power and is a common and natural phenomenon in high-intensity sports [10]. According to the available literature, lower extremity fatigue can increase the risk factors of the ACL injury in athletes [5-9, 11, 12].

Ground Reaction Force (GRF) is an important kinetic parameter in the biomechanical studies of the lower extremity. This parameter has been considered in many experimental studies as an approximate index of external loading experienced by the human body [13]. In healthy individuals, the heightened posterior GRF during exercises increases ACL loading by enhancing the quadriceps muscle contraction. The posterior GRF causes the flexion torque in the knees; this torque needs to be balanced with the extension torque produced by the quadriceps muscles. Quadriceps muscle contraction increases the anterior shearing force at the end of proximal tibia via the patellar tendon. The greater the posterior GRF, the higher the quadriceps muscle force that increases the ACL loading [14-17]. The results of Cerulli et al. study showed that the maximum strain applied to the ACL would occur at the peak of the vertical contact GRF, immediately after the initial contact of the foot with the ground [15]. Also, Yu et al. showed that the peak vertical and posterior contact GRF would occur simultaneously [18].

Regarding the effects of fatigue on GRF, the results of Madigan et al. (2003) and Timothy et al. (2014) have demonstrated a significant decrease in the vertical GRF, after fatigue [19]. A decrease in the maximum values of GRF is often justified by the articular kinematics changes, such as femur and knee flexion angles when the foot contacts with the ground during landing [20, 21]. On the other hand, the results of Boham et al. (2013) showed that the fatigue would increase the GRF in all directions, but it mostly affects the anterior-posterior GRF component. The anterior-posterior GRF aimed to prevent the proximal tibia anterior shear force. Fatigue can be a dominant risk factor for ACL injury [22].

An increase in the vertical GRF during landing disturbs the knee joint and potentially increases the risk of ACL injury. At the initial contact, The body is unable to absorb contact forces using active structures (such as muscles), thus, the risk of injury is exacerbated at this point. The risk of ACL injury increases after fatigue because fatigue reduces the neuromuscular function and leads the passive structures (such as ligaments and articular capsules) to absorb the shock. These changes eventually put the person at the risk of injury after an exhausting activity [22, 23].

The literature review shows conflicting results for the effects of fatigue on GRF. To the best of our knowledge, little information is available about the effects of fatigue on the GRF variables in athletes with a history of ACL injury. Undoubtedly, more knowledge on knee joint control during functional activities is necessary for the better design of rehabilitation programs. Therefore, the present research aimed to investigate the effect of fatigue on lower extremity kinetic indices, including the peak vertical, mediolateral and anteroposterior GRF, the time to peak vertical force, and the loading rate of vertical force in athletes with a history of an ACL tear that underwent surgical and non-surgical treatment.

Materials and Methods

Study Participants

It was a case-control study. The study population comprised male athletes aged 18 to 30 years, who had suffered

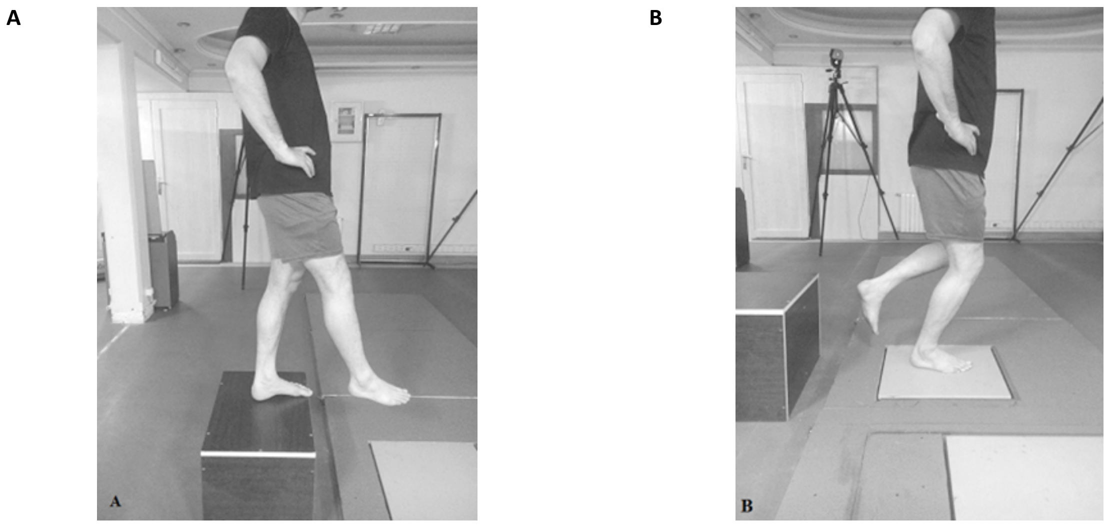

Figure 1. Single-leg vertical top landing

A. Preparation phase; B. Landing phase

from ACL tear over the past 3 years, and received both surgical and non-surgical treatments. Thirty-six athletes were selected from the population, as the study sample: 12 athletes with Anterior Cruciate Ligament Reconstruction (ACLR), 12 athletes with Anterior Cruciate Ligament Deficiency (ACLD), and 12 healthy athletes. Considering the statistical power of 0.80 and the alpha value of 0.05, the sample size was estimated by using STATA software. Also, the mean and standard deviation of the main research variable (GRF) in the study population and sample were regarded for the repeated measures research design [4, 24].

The inclusion criteria for both groups of ACL injury (ACLR and ACLD) were as follows: the passing of 18-36 months since ACL reconstruction or conservative treatment, the age ranged 18-30 years, the completion of the rehabilitation period, and returning to moderate-to-high exercise activity. Also, the exclusion criteria for both groups (ACLR and ACLD) were as follows: lower extremity surgery other than ACL reconstruction; lower extremity injury after ACL reconstruction; bilateral injury; the injury of other knee ligaments, including medial cruciate ligament, lateral cruciate ligament, and posterior cruciate ligament; and other injuries in the lower extremity (patellofemoral pain syndrome, ankle sprains, etc.) The participants in the control group had no history of a knee injury and were matched with the participants of both injured groups in terms of age range and the level of physical activity [24-26].

Athletes with a history of ACL tear were selected concerning the inclusion and exclusion criteria and with the permission of the orthopedic surgeon. The ethical permission of the research was obtained from the Research Ethics Committee of the Sport Sciences Research Institute of Iran. After writing the informed consent by all participants, their demographic information (age, athletic background, athletic field, and the time passed since the injury or ACL surgery) was recorded in the data collection form.

Study Intervention

In this research, a functional fatigue protocol was used to induce fatigue in the participants; the protocol had been applied in previous research studies [26-28]. First, the procedure was described to the participants, then, the baseline measurements (before fatigue) were performed. Next, the participants warmed up for 10 to 15 minutes. Thereafter, they performed the fatigue protocol that included the repetitive sets of eight 90-degree knee flexion squats, two vertical jumps with maximum power, and three single-leg landings from a 30-cm height box on the force plate device. The repetitive sets were performed until the participants could no longer perform five consecutive squats with 90-degree knee angles. The number of squats that the participants could perform was unlimited. Borg scale was used to measure the level of fatigue in the participants; this mental scale ranges from 6 (no perceived pressure) to 20 (maximum perceived pressure) for fatigue grading [23]. In the present study, the single-leg drop landing technique was used to investigate the GRF variables (Figure 1). The participants were asked to stand on top of a box at a height of 30 cm and perform the vertical single-leg drop landing on the force plate device.

In the present study, the force plate (AMTI, USA, 2000 Hz) was used to collect data on GRF and its variables, including the maximum value of the vertical, anteroposterior and mediolateral GRF components, the time to peak vertical force, and vertical loading rate. The data were also extracted by the motion analysis system (Cortex software), and Excel 2013 was used to analyze the force data. The sampling frequency of 2000 Hz was selected. To filter the raw data, the low-pass Butterworth filter technique with the shear frequency of 20 was employed; the shear frequency was determined using residual analysis technique [29]. The components of the peak GRF were normalized via dividing over participants' weight and were expressed as a ratio of the body weight (%BW). Then, the mean values of the three successful landings before and after fatigue were used to calculate the time to peak force that is the time interval between the contact of the first leg with the force plate and the peak time of vertical GRF during landing.

Statistical Analysis

Descriptive and inferential statistical methods were used to analyze the collected data. The Shapiro-Wilk test was used to investigate the normalization of data (because of the higher accuracy of this test, compared with the Kolmogorov-Smirnov test). The main effects, including fatigue (before and after fatigue), group (ACLR, ACLD, and control), and fatigue-group interaction were investigated using repeated measures Multivariate Analysis of Variance (MANOVA).

Next, the paired samples univariate t-test, One-Way Analysis of Variance (ANOVA), and Tukey posthoc test were used to determine the within- and between-groups differences. The effect size index was also calculated for significant within- and between-groups differences. It is worth noting that data analysis was performed at the significance level of 95% and the alpha level of less than or equal to 0.05. All the statistical analyses were performed in SPSS V. 20.

Results

Table 1 presents the mean and standard deviation of the demographic characteristics of the study sample. According to Table 2, the results of repeated measures MANOVA shows a significant group effect. This result shows a significant difference in GRF between the study groups, but the effect of fatigue and fatigue-group interaction is not significant. Therefore, fatigue did not significantly affect the GRF. The insignificant interaction effect of fatigue in the group showed a significant difference between the groups, regardless of fatigue state (before and after fatigue). Afterward, the dependent t-test and the one-way ANOVA were used for within- and between-group comparisons (Figures 2-6).

Table 3 shows the mean variables of GRF before and after fatigue in the study groups. As can be seen, only the components of peak vertical and mediolateral GRF reduced significantly after fatigue, in the ACLD group.

Table 1. Descriptive Statistics of the demographic characteristics of the study sample

Variabels	Mean±SD			P
	ACLD	ACLR	Control	
Age (y)	24.5±2.32	23.83±5.49	24.92±2.81	0.78
Height (cm)	174.5±4.62	175.25±4.78	175±5.23	0.77
Mass (kg)	75.25±7.13	76.45±5.93	74.75±7.5	0.65
Months since surgery or initial injury	23.25±6.95	23.75±6.3	NA	

Journal of
Exercise Science and Medicine

Table 2. Repeated measures multivariate analysis of variance

Effects	P	F	Effect Size
Group	0.015*	2.51	0.31
Fatigue	0.67	0.63	0.1
Interaction	0.31	1.20	0.18

* Significant effect

Journal of
Exercise Science and Medicine

Table 3. Comparing GRF variables before and after fatigue (Within-group comparison)

Variables	Group	Mean±SD	
		Pre-fatigue	Post-fatigue
PVGRF (BW%)	ACLD	2.69±0.3	2.55±0.18 *
	ACLR	2.70±0.18	2.81±0.31
	Control	3.01±0.4	2.99±0.37
PA-PGRF (BW%)	ACLD	1.32±0.17	1.32±0.18
	ACLR	1.36±0.13	1.37±0.12
	Control	1.52±0.21	1.52±0.20
PM_LGRF (BW%)	ACLD	0.43±0.11	0.40±0.08*
	ACLR	0.51±0.09	0.48±0.08
	Control	0.52±0.1	0.51±0.08
TTP VGRF (ms)	ACLD	84.02±12.9	83.67±6119.2
	ACLR	78.30±11.9	78.71±7.31
	Control	80.96±18.7	78.8160±14.6
LR (N/ms)	ACLD	0.033±0.008	0.032±0.009
	ACLR	0.035±0.006	0.036±0.005
	Control	0.039±0.01	0.040±0.01

PVGRF: Peak Vertical Ground Reaction Force; PA-PGRF: Peak Anterior-Posterior Ground Reaction Force; PM-LGRF: Peak Mediolateral Ground Reaction Force; TTP VGRF: Time To Peak Vertical Ground Reaction Force; LR: Loading Rate; ACLD: Anterior Cruciate Ligament Deficient; ACLR: Anterior Cruciate Ligament Reconstructed; BW: Body Weight

* Significant effect

In this group, the effect size index for the within-group changes of peak vertical and mediolateral GRF was equal to 0.29 and 0.33, respectively. In the ACLR and control groups, there was no significant difference between the GRF variables before and after fatigue.

As can be seen in Table 4, there were significant differences between the ACLD and control groups in the peak vertical and anterior-posterior GRF (regardless of the fatigue state) and the peak mediolateral force after fatigue. Also, the ACLR and control groups significantly differ in the peak vertical force before fatigue. Comparing the mean of the groups, it is found that the peak vertical, anterior-posterior, and mediolateral GRF of the ACLD group and the peak vertical GRF of the ACLR group were significantly less than that of the control group. The effect size index for all the significant between-group variables was higher than 0.9.

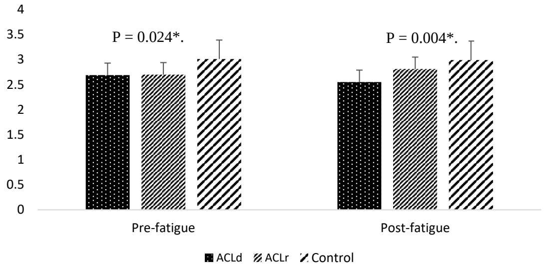

Figure 2. Comparing the peak vertical GRF before and after fatigue between study groups

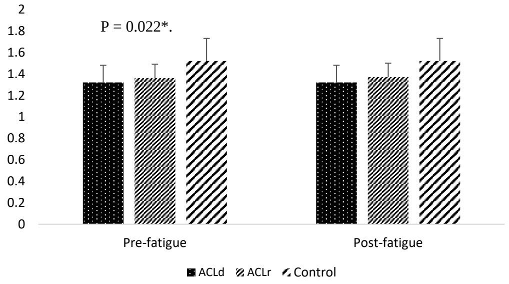

Figure 3. Comparing the peak anterior-posterior GRF before and after fatigue between study groups

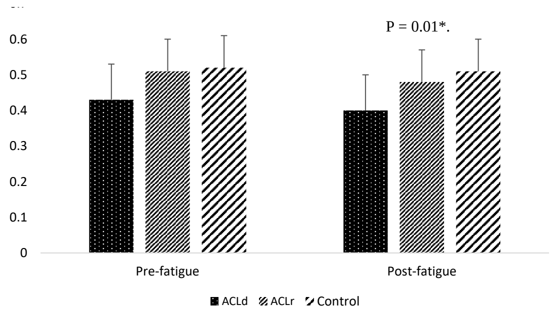

Figure 4. Comparing the peak mediolateral GRF before and after fatigue between study groups

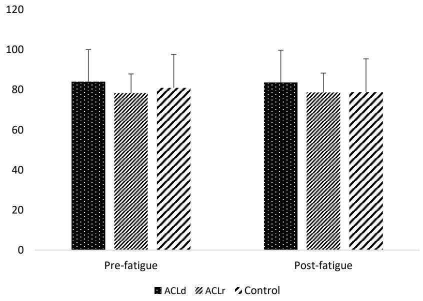

Figure 5. Comparing the time to peak vertical GRF before and after fatigue between study groups

Discussion

The ground contact mechanism of the body subjects loading to the musculoskeletal system during activities, such as running, skipping, and jump-landing. GRF is often used as an indicator of the musculoskeletal system in contact with the ground. Since the size of GRF can be 2 to 8 times of the body weight during activities, such as running and jump-landing, the human body must actively control the ground contact to minimize the potential adverse effects. Constant use of muscular forces is required to actively control the ground contact through mechanisms, such as the adjustment of body stiffness and the torsion of joint regulation. Muscles are activated before the contact (pre-landing muscle activity) and in response to the conditions experienced during landing (post-landing muscle activity). Prolonged physical activities lead to muscle fatigue, and consequently, the inability to properly control the contact. Injuries caused by running and landing, such as ACL injury, occur due to the inappropriate control of ground contact and fatigued muscles [13]. Considering the effect of fatigue as a risk factor for the variables of the GRF, the research shows inconsistent results for healthy and injured individuals. Some studies show an increase [22, 23, 30, 31], while others indicate a decrease [19, 32, 33] in peak GRF, after fatigue.

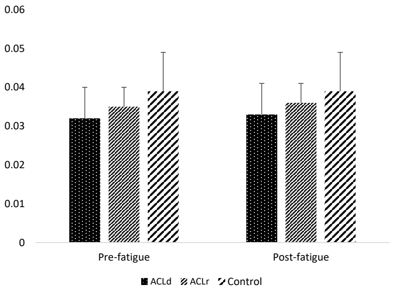

Figure 6. Comparing the loading rate of vertical GRF before and after fatigue between study groups

The results of the present study showed that the peak vertical and mediolateral GRF in the ACLD group decreased (6% and 8%, respectively) significantly after fatigue. The peak vertical and anterior-posterior GRF (regardless of the fatigue state), and the peak mediolateral GRF after fatigue in the ACLD group were significantly lower than in the control group. Also, the peak vertical GRF of the ACLR group was significantly lower than that of the control group, before fatigue. Fatigue had no significant effect on the time to peak vertical force and force loading rate.

Despite extensive research, no study has investigated the effect of fatigue on GRF variables in the athletes with the ACL tear (ACLD or ACLR). However, a significant decrease in vertical and mediolateral GRF in the ACLD group was consistent with Madigan et al. (2003), Kernozek et al. (2008), Smith et al. (2009), James et al. (2010), and Saya et al. (2016) study results. According to Madigan et al., the decrease in peak vertical GRF is associated with the efforts of individuals to change the landing strategy, thus, the contact forces would be reduced in athletes with ACL. It is suggested that a neuromuscular protective mechanism modifies the kinematic features and lower extremity stiffness to regulate the contact forces [19]. Niland et al. (1994) and James et al. (2010) believed that muscular contact mechanisms control the GRF in fatigue conditions. As a result, the potential reduction of power in the motor units leads to a decrease of stiffness, which is involved in the adaptability of textures [22, 34]. Kernozek et al. (2008), Smith et al. (2009), and Saya et al., reported a decrease in the vertical GRF after fatigue [4, 32, 33]. The increase in knee flexion angle after fatigue can probably decrease the peak vertical GRF in ACLD athletes. knee flexion, as an impor-

Table 4. Tukey test results, comparing the grf variables between study groups before and after fatigue (effect size)

Variables	Groups	P	
		Pre-fatigue	Post-fatigue
PV GRF	ACLD-ACLR	0.99	0.09
	ACLD-Control	0.04 (0.91)*	0.003 (1.62)*
	ACLR-Control	0.05 (1.06)*	0.33
PA-P GRF	ACLD-ACLR	0.78	0.76
	ACLD-Control	0.022 (1.11)*	0.02 (1.11)*
	ACLR-Control	0.1	0.1
PM-L GRF	ACLD-ACLR	0.21	0.6
	ACLD-Control	0.15	0.01 (1.37)*
	ACLR-Control	0.97	0.76

* Significant between-group difference; the effect size

Journal of
Exercise Science and Medicine

tant part of the landing stage, absorbs energy through the eccentric contraction of hamstring and quadriceps muscles and reduces the strain applied to ACL. Also, a decreased peak of mediolateral GRF after fatigue can be an attempt to reduce the knee valgus and reach a neutral state in the ACLD group.

Fatigue had no significant effect on the peak GRF in the ACLR group. This was consistent with the results of Barnet et al. (2014) and inconsistent with the results of Parsa et al. (2015) and Timothy et al. (2014). In the study of Barnet et al. (2014), fatigue did not significantly affect vertical GRF in women with ACL reconstruction [30]. Conversely, Parsa et al. (2015) reported that the soccer-specific fatigue protocol significantly increased vertical and anterior-posterior GRF [31]. The different types of applied fatigue could lead to the inconsistency of our results with the results of Parsa et al. Because of reconstruction, The response to fatigue in athletes with ACLR is similar to the response in healthy athletes.

A significant difference was observed between the ACLD and control groups in the peak vertical and anteroposterior GRF (regardless of fatigue state) and the peak mediolateral force after fatigue. The peak vertical GRF of the ACLD group was lower than that of the control group by 10% and 14% before and after fatigue, respectively. Also, the peak anteroposterior GRF of the ACLD group was lower than that of the control group by 13% before and after fatigue. Moreover, the peak mediolateral GRF of the ACDL group was lower than that of the control group by 17% before fatigue and 26% after fatigue. The peak vertical force of the ACLR group was lower than that of the control group (by 10%) before fatigue. The results of this section are consistent with the results of Radolf et al. (2001), Vairo et al. (2008), and Kristian et al. (2015). In the study of Radolf et al. (2001) and Vairo et al. (2008), the peak vertical GRF in ACLD subjects was significantly lower than in the control group [24]. Vairo et al. (2008) stated that soft landing reduced the peak vertical GRF and increased the knee flexion angle. The soft landing is an attempt to reduce the risks of further damage to a previously injured or reconstructed joint [35]. Also, Kristian et al. showed that the peak vertical GRF in the injured limbs of individuals with ACL reconstruction was lower than in the healthy limbs. These researchers attributed the difference of landing GRF to the reasonable compatibility that is based on the individual's needs and the motor experience of the affected individuals during or after rehabilitation. Changes in the sensory-motor control of individuals with ACL might justify the difference in forces.

The neuromuscular features in the injured or surgically treated limbs are different from those in healthy limbs. The participants of the ACLD and ACLR groups use compensatory strategies (such as increased hip and knee angles, decreased muscle activity, etc.) to reduce the contact forces imposed on the body. These compensatory strategies show the protective compatibility for preventing excessive strain on the injured or surgically treated ACL. Compared with the control group, the lower peak anterior-posterior GRF in the ACLD group could be an attempt to reduce the anterior shear force of the proximal tibia because research has shown a relationship between increased anterior-posterior GRF and increased proximal tibia anterior shear force [14, 22].

According to the findings of the present study, it seems that athletes with ACLD (compared with healthy athletes) use the protective strategy with a decrease of peak GRF to deal with fatigue and prevent further injury to the knee joint. Although the peak vertical GRF in the ACLR group was significantly lower than in the control group before fatigue, fatigue had no significant effect on the peak GRF in ACLR athletes. Therefore, it seems that the response of ACLR athletes to fatigue is similar to that of the healthy athletes (probably because of reconstruction). It is worth noting that the effect size index for the significant inter-group differences was higher than 0.9, which is a large effect following Cohen's scale.

Conclusion

Regardless of the fatigue state, the landing strategies in ACLR and ACLD athletes (especially ACLD athletes), compared with the healthy athletes, was such that it reduced the contact GRF to prevent further damage to the knee joint. Thus, the rehabilitation specialists are suggested to pay special attention to soft landing strategies and give the required tips to the athletes with ACL injury about soft landing during rehabilitation programs (such as increasing hip and knee angles during landing, verbal feedback, landing on the ball, and so on).

Ethical Considerations

Compliance with ethical guidelines

This study was approved by the University Institutional Review Board (Code: IR.SSRI.REC.1396.138).

Funding

This article is extracted from a PhD. thesis of first author on Sports Pathology at the Department of Health and Sports Medicine, Faculty of Physical Education and Sport Sciences, University of Tehran, Tehran.

Authors' contributions

All authors were equally contributed in preparing this article.

Conflict of interest

The authors declared no conflict of interest.

References

[1] Bahr R, Engebretsen L, Laprade R, McCrory P, Meeuwisse W. The IOC manual of sports injuries: An illustrated guide to the management of injuries in physical activity. Wiley Online Library; 2012. [Online Published] [DOI:10.1002/9781118467947]

[2] Brukner P. Brukner & Khan's clinical sports medicine. North Ryde NSW: McGraw-Hill; 2012.

[3] Agel J, Arendt EA, Bershadsky B. Anterior cruciate ligament injury in national collegiate athletic association basketball and soccer: A 13-year review. The American Journal of Sports Medicine. 2005; 33(4):524-31. [DOI:10.1177/0363546504269937] [PMID]

[4] Smith MP, Sizer PS, James CR. Effects of fatigue on frontal plane knee motion, muscle activity, and ground reaction forces in men and women during landing. Journal of Sports Science & Medicine. 2009; 8(3):419.

[5] Griffin LY, Albohm MJ, Arendt EA, Bahr R, Beynnon BD, Demaio M, et al. Understanding and preventing noncontact anterior cruciate ligament injuries: A review of the Hunt Valley II meeting, January 2005. The American Journal of Sports Medicine. 2006; 34(9):1512-32. [DOI:10.1177/0363546506286866] [PMID]

[6] McLean SG, Beaulieu ML. Complex integrative morphological and mechanical contributions to ACL injury risk. Exercise and Sport Sciences Reviews. 2010; 38(4):192-200. [DOI:10.1097/JES.0b013e3181f450b4] [PMID]

[7] Shultz SJ, Schmitz RJ, Nguyen AD, Chaudhari AM, Padua DA, McLean SG, et al. ACL Research Retreat V: An update on ACL injury risk and prevention, March 25-27, 2010, Greensboro, NC. Journal of Athletic Training. 2010; 45(5):499-508. [DOI:10.4085/1062-6050-45.5.499] [PMID] [PMCID]

[8] Hewett TE, Myer GD, Ford KR. Anterior cruciate ligament injuries in female athletes: Part 1: Mechanisms and risk factors. The American Journal of Sports Medicine. 2006; 34(2):299-311. [DOI:10.1177/0363546505284183] [PMID]

[9] Alentorn-Geli E, Myer GD, Silvers HJ, Samitier G, Romero D, Lázaro-Haro C, et al. Prevention of non-contact anterior cruciate ligament injuries in soccer players. Part 1: Mechanisms of injury and underlying risk factors. Knee Surgery, Sports Traumatology, Arthroscopy. 2009; 17(7):705-29. [DOI:10.1007/s00167-009-0813-1] [PMID]

[10] Boyas S, Guével A. Neuromuscular fatigue in healthy muscle: Underlying factors and adaptation mechanisms. Annals of Physical and Rehabilitation Medicine. 2011; 54(2):88-108. [DOI:10.1016/j.rehab.2011.01.001] [PMID]

[11] Barry BK, Enoka RM. The neurobiology of muscle fatigue: 15 years later. Integrative and Comparative Biology. 2007; 47(4):465-73. [DOI:10.1093/icb/icm047] [PMID]

[12] Mclean SG, Samorezov JE. Fatigue-induced ACL injury risk stems from a degradation in central control. Medicine and Science In Sports And Exercise. 2009; 41(8):1661-72. [DOI:10.1249/MSS.0b013e31819ca07b] [PMID]

[13] Zadpoor AA, Nikooyan AA. 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. 2012; 226(8):579-88. [DOI:10.1177/0954411912447021] [PMID]

[14] Chappell JD, Yu B, Kirkendall DT, Garrett WE. A comparison of knee kinetics between male and female recreational athletes in stop-jump tasks. The American Journal of Sports Medicine. 2002; 30(2):261-7. [DOI:10.1177/03635465020300021901] [PMID]

[15] Cerulli G, Benoit D, Lamontagne M, Caraffa A, Liti A. In vivo anterior cruciate ligament strain behaviour during a rapid deceleration movement: Case report. Knee Surgery, Sports Traumatology, Arthroscopy. 2003; 11(5):307-11. [DOI:10.1007/s00167-003-0403-6] [PMID]

[16] Malinzak RA, Colby SM, Kirkendall DT, Yu B, Garrett WE. A comparison of knee joint motion patterns between men and women in selected athletic tasks. Clinical Biomechanics. 2001; 16(5):438-45. [DOI:10.1016/S0268-0033(01)00019-5]

[17] Sell TC, Ferris CM, Abt JP, Tsai YS, Myers JB, Fu FH, et al. Predictors of proximal tibia anterior shear force during a vertical stop-jump. Journal of Orthopaedic Research. 2007; 25(12):1589-97. [DOI:10.1002/jor.20459] [PMID]

[18] Chappell JD, Creighton RA, Giuliani C, Yu B, Garrett WE. Kinematics and electromyography of landing preparation in vertical stop-jump: Risks for noncontact anterior cruciate ligament injury. The American Journal of Sports Medicine. 2007; 35(2):235-41. [DOI:10.1177/0363546506294077] [PMID]

[19] Madigan ML, Pidcoe PE. Changes in landing biomechanics during a fatiguing landing activity. Journal of Electromyography and Kinesiology. 2003; 13(5):491-8. [DOI:10.1016/S1050-6411(03)00037-3]

[20] Gerlach KE, White SC, Burton HW, Dorn JM, Leddy JJ, Horvath PJ. Kinetic changes with fatigue and relationship to injury in female runners. Medicine and Science in Sports and Exercise. 2005; 37(4):657-63. [DOI:10.1249/01.MSS.0000158994.29358.71] [PMID]

[21] Nyland JA, Shapiro R, Stine RL, Horn TS, Ireland ML. Relationship of fatigued run and rapid stop to ground reaction forces, lower extremity kinematics, and muscle activation. Journal of Orthopaedic & Sports Physical Therapy. 1994; 20(3):132-7. [DOI:10.2519/jospt.1994.20.3.132] [PMID]

[22] Boham M, DeBeliso M, Harris C, Pfeiffer R, McChesney J, Berning JM. The effects of functional fatigue on ground reaction forces of a jump, land, and cut task. International Journal of Science and Engineering Investigations. 2013; 2(21):22-8.

[23] Brazen DM, Todd MK, Ambegaonkar JP, Wunderlich R, Peterson C. The effect of fatigue on landing biomechanics in single-leg drop landings. Clinical Journal of Sport Medicine. 2010; 20(4):286-92. [DOI:10.1097/JSM.0b013e3181e8f7dc] [PMID]

[24] Rudolph K, Axe M, Snyder-Mackler L. Dynamic stability after ACL injury: Who can hop? Knee Surgery, Sports Traumatology, Arthroscopy. 2000; 8(5):262-9. [DOI:10.1007/s001670000130] [PMID]

[25] Augustsson J, Thomeé R, Karlsson J. Ability of a new hop test to determine functional deficits after anterior cruciate ligament reconstruction. Knee Surgery, Sports Traumatology, Arthroscopy. 2004; 12(5):350-6. [DOI:10.1007/s00167-004-0518-4] [PMID]

[26] Lepley LK, Thomas AC, McLean SG, Palmieri-Smith RM. Fatigue's lack of effect on thigh-muscle activity in anterior cruciate ligament-reconstructed patients during a dynamic-landing task. Journal of Sport Rehabilitation. 2013; 22(2):83-92. [DOI:10.1123/jsr.22.2.83] [PMID]

[27] Gokeler A, Eppinga P, Dijkstra P, Welling W, Padua DA, Otten E, et al. Effect of fatigue on landing performance assessed with the Landing Error Scoring System (LESS) in patients after ACL reconstruction: A pilot study. International Journal of Sports Physical Therapy. 2014; 9(3):302-11. [PMID]

[28] Webster KE, Santamaria LJ, Mcclelland JA, Feller JA. Effect of fatigue on landing biomechanics after anterior cruciate ligament reconstruction surgery. Medicine and Science in Sports and Exercise. 2012; 44(5):910-6. [DOI:10.1249/MSS.0b013e31823fe28d] [PMID]

[29] Winter DA. Biomechanics and motor control of human movement. Hoboken, New Jersey: John Wiley & Sons; 2009. [DOI:10.1002/9780470549148]

[30] Frank BS, Gilsdorf CM, Goerger BM, Prentice WE, Padua DA. Neuromuscular fatigue alters postural control and sagittal plane hip biomechanics in active females with anterior cruciate ligament reconstruction. Sports Health. 2014; 6(4):301-8. [DOI:10.1177/1941738114530950] [PMID] [PMCID]

[31] Parsa A, Daneshmandi H, Majelan AS. The ground reaction force in jump-landing maneuver after soccer specific fatigue protocol (SAFT90) in elite soccer players. Quarterly Medical Journal of Tabriz University of Medical Sciences. 2017; 39(2):19-32.

[32] Kernozek TW, Torry MR, Iwasaki M. Gender differences in lower extremity landing mechanics caused by neuromuscular fatigue. The American Journal of Sports Medicine. 2008; 36(3):554-65. [DOI:10.1177/0363546507308934] [PMID]

[33] Watanabe S, Aizawa J, Shimoda M, Enomoto M, Nakamura T, Okawa A, et al. Effect of short-term fatigue, induced by high-intensity exercise, on the profile of the ground reaction force during single-leg anterior drop-jumps. Journal of Physical Therapy Science. 2016; 28(12):3371-5. [DOI:10.1589/jpts.28.3371] [PMID] [PMCID]

[34] James CR, Scheuermann BW, Smith MP. Effects of two neuromuscular fatigue protocols on landing performance. Journal of Electromyography and Kinesiology. 2010; 20(4):667-75. [DOI:10.1016/j.jelekin.2009.10.007] [PMID]

[35] Vairo GL, Myers JB, Sell TC, Fu FH, Harner CD, Lephart SM. Neuromuscular and biomechanical landing performance subsequent to ipsilateral semitendinosus and gracilis autograft anterior cruciate ligament reconstruction. Knee Surgery, Sports Traumatology, Arthroscopy. 2008; 16(1):2-14. [DOI:10.1007/s00167-007-0427-4] [PMID]