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Comparison of the effect of acute and delayed fatigue on the time to stability of female gymnasts with and without dynamic knee valgus during drop-landing task

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Abstract

Background: Drop landing is one of the tasks performed in many sports skills. Lower limb injuries have the highest prevalence in sports where jump landing is repeated frequently. One of the most common landing injuries is an anterior cruciate ligament (ACL) tear, which increases knee valgus and may contribute to an increased risk of ACL injury in athletes. In this situation, fatigue is one of the components that can affect various parameters of the landing task.

Aim: The purpose of this study was to investigate and compare the acute and delayed effects of fatigue on the time to stability (TTS) of female gymnasts with and without dynamic knee valgus (DKV) during the landing task.

Materials and Methods: In this semi-experimental study with a pretest-posttest design, 42 female gymnasts were selected through purposive and available sampling and divided into two groups of 21: a control group without DKV and an experimental group with DKV. The TTS in these individuals was measured before, after, and 24 hours after the fatigue protocol using the Kistler force plate device. The data was analyzed using SPSS software and statistical methods of analysis of covariance with repeated measures at a significance level of $P \geq 0.05$.

Results: According to the findings of this study, it showed that there is a significant difference in the variable of TTS in three time periods (before, after, 24 hours after fatigue) in the control and experimental groups (P= 0.026).

Conclusion: The results of the present study showed that plyometrics on the TTS are significantly different between people with DKV and without DKV, and people with DKV are necessarily at a greater risk of injury during landing tasks.

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1. Introduction

Anterior cruciate ligament (ACL) injuries are the most common ligament injury of the knee, accounting for between 100,000 and 200,000 injuries among athletes per year [1]. ACL injuries occur via contact and non-contact mechanisms, with the former being more common in males and the latter being more common in females [2].

Numerous studies have attempted to determine risk factors for ACL rupture, including hormonal, biomechanical, and sport- and gender-specific factors [3]. We investigated the biomechanical mechanisms contributing to ACL injury and considered differences between males and females [2]. Poor core stability, landing with a heel strike, weak hip abduction strength, and increased knee valgus may contribute to an increased risk of ACL injury in athletes [4].

Various factors are thought to contribute to ACL injury incidence. Perhaps the most widely considered risk factor is DKV, which places significant tensile forces on the ACL, especially during landing and cutting [5, 6]. Knee valgus may occur secondary to many factors, including but not limited to weak hip abductor strength, poor hip musculature control, increased femoral anteversion/medial tibial torsion, wider pelvis, increased midfoot mobility, and larger Q-angle. Anatomically speaking, females have wider hips, which predisposes them to larger Q-angles and subsequent higher risk of ACL injury than males [4, 7].

Females who participate in gymnastics, soccer, or basketball appear to be at the highest risk of experiencing a non-contact ACL injury [8]. The subject of landings in gymnastics is important due to the accompanying injuries. Landings in gymnastics are a crucial element that is incorporated in every routine in each artistic gymnastics event. Gymnastics landings should be both proper in terms of judge scores and safe for the athlete [9]. The risks of landing injuries are associated with loads that affect the musculoskeletal system [10]. With regard to landings, the main load is focused on the lower limbs and the trunk. In high-performance sports, where jumping is the primary technique, there is a tendency to transfer larger forces acting on the knee and spine, which can contribute to serious injuries. The higher the ground reaction forces (GRF) during landings, the higher the risk of injury, especially of the ACL [11, 12].

Through previous studies, it has been found that knee ACL injuries mainly occur in the last stage of the game [13, 14]. Fatigue is an important cause of non-contact ACL injury [15]. Fatigue is one of the main factors in increasing the rate of injury in the lower extremities, especially in the knee joint [16]. In this regard, studies have investigated the effect of fatigue on the biomechanics of various sports movements, including landing from a height. Jump-landing movements are performed in many sports [17]. Muscle fatigue would lead to muscle activation delay after fatigue, and this would result in decreased motor control and increased knee laxity [14].

The delay of knee muscle activity has been identified as a major risk factor for knee instability and the risk of cruciate ligament injury [13, 14, 16, 18]. Although previous studies have suggested that lower-extremity muscle fatigue is a risk factor for ACL injury [19, 20, 21, 22, 23], the precise impact of fatigue on injury risk to the ACL is still unknown.

Many sports injuries occur during landing [19]. In fact, the ground reaction force during landing sometimes reaches up to five times the weight of the body, which can be considered a risk factor in this regard [24]. In a study, it was reported that 63% of lower limb injuries were seen in jump-landing competitions. It was finally concluded that successful landing after jumping requires strength, stability, and balance to prevent injury [25].

Preventing joint damage and achieving quick stability after landing is one of the important factors in preventing various injuries. TTS (Time to Stabilization) is the amount of time which takes for a person to return to a stable state after a jump. TTS is an indicator of dynamic stability that measures stability during jump-landing motion. It is defined as the ability of individuals to maintain balance and minimize postural fluctuations during the transition from a dynamic to a static state. Therefore, it is a fully functional test [26]. Increased levels of fatigue with increasing the DKV may put athletes at greater risk for ACL injury [27]. Exercise fatigue increases DKV in young athletes. Female athletes and older individuals also reported the greatest impact [28].

To our knowledge, no study has examined how fatigue affects TTS of female gymnasts with and without DKV during landing, despite its importance for various sports movements. As a result, the aim of the present study was to investigate the acute and delayed effect of fatigue on the TTS during the drop-landing task.

2. Materials and Methods

2.1. Participants

In this study, 42 female gymnasts were divided into two groups, including the control group without DKV (n=21) and the experimental group with DKV (n=21). Participants were physically active females who practiced gymnastics three to five times a week for at least three years. None of the participants had a medical history of injury or neuromuscular disorder within the preceding two years [29]. These individuals participated in this study voluntarily. They were requested to abstain from physical exercises involving the lower limbs 24 hours prior to testing. The number of samples was calculated using G. power and based on Deborah's study [30], considering $\alpha= 0.05$, $\beta= 0.20$, SD= 0.80. The subjects also had a dominant right lower limb, which was determined using the selective leg method for shooting the ball [31].

2.2. Design and Procedures

Before performing the fatigue protocol, the subjects performed stretching and warm-up movements for 10 min. They were also asked to perform three repetitions of jump-landing movements as well as landing from a 40 cm platform several times to meet the conditions and method of execution and get acquainted with the test. The landing test from a height of 40 cm on the force plate device was performed by the subjects before performing the fatigue protocol. In this situation, the subject left her bare foot from a 40 cm platform that was placed at a distance of 20 cm from the force plate and landed with a single leg in the center of the force plate. As soon as she sat down, she placed her hands on her hips, held her head up, and looked straight ahead, trying to maintain her balance. The subject maintained this position until complete stability and immobilization of the body.

2.3. Fatigue protocol

For fatigue, the subjects used a plyometric exercise program. These exercises included running and jumping. Running comprised high-speed running at a distance of 10 m in the form of sweeping and jumping, such as double-leg jumping and landing, single-leg jumping and landing, vertical jumping, jumping over obstacles, tuck jumping, and single-leg jumping between lines. The exercises were performed in three sets of 10 m, with 30 sec of rest between each set [32]. This program was performed three times, and there was a two-minute break between each set.

2.4. Measurements
Immediately after the subject reached exhaustion, she performed a descent from a height as a pre-test on the force plate device. Twenty-four hours later, the descent motion on the force plate was measured again. In each measurement of the subject, three landing movements were recorded and analyzed. Component TTS information was measured using a Kistler force plate device made in the Netherlands with a sampling frequency of 1000 Hz. After collecting the data, a low-pass Butterworth filter with zero phase difference of four times and a cut-off frequency of 20 Hz was used to reduce data noise. The force information was normalized to the weight of the subject. Then, the TTS parameter was calculated.

2.5. Data analysis
Descriptive statistics were used to calculate the mean and standard deviation of height, weight, and age. Using the Kolmogorov-Smirnov test, we examined the normality of data distribution. Covariance analysis with repeated measures was used to compare the experimental and control groups. All evaluations were conducted at the significance level of 0.05 in SPSS ver. 25.

3. Results
The study group's information, such as body weight, height, and Body Mass Index (BMI), is summarized in Table 1. The Kolmogorov-Smirnov test was used to check the normality of the data (Table 2). The result of the covariance test with repeated measurements for comparison between variable groups TTS is shown in Table 3.

Based on the findings of the present study, the analysis of the TTS in the post-fatigue state was significantly higher (P<0.05) than in the pre-fatigue state (Table 3).

Table 1. Demographic characteristics (age, height, weight, BMI) of the samples

Variable	Group	N	Mean ± SD	p- value
Age (y)	Experimental	21	1.54±23.14	0.09
	Control	21	2.26±22.46	
Height (cm)	Experimental	21	6.10±165.9	0.16
	Control	21	6.37±167.2	
Weight (kg)	Experimental	21	3.44±55.13	0.33
	Control	21	3.18±56.87	
BMI (kg/m^2)	Experimental	21	0.76±20.42	0.25
	Control	21	1.06±21.36	

Table 2. Kolmogorov-Smirnov test to check the normality of the data

Parameter	Component	Statistics	p- value
TTS (s)	Vertical	0.114	0.05

Table 3. Covariance test with repeated measures to compare between groups the variable of TTS

Variable	Total squares	Mean squares	F	p- value
TTS (s)	0.247	0.151	4.195	0.026

4. Discussion

The purpose of this study was to investigate and compare the acute and delayed effects of fatigue on the TTS of female gymnasts with and without DKV during the drop-landing task. According to the results of Table 3, the variable of TTS showed a significant difference in three time periods (before, after, and 24 hours after fatigue) between the two groups (*P*= 0.026). The results of the present study were in line with the results of Nasrabadi et al. (2020) [33]. They showed that the TTS in the post-fatigue state was significantly longer than the pre-fatigue state in active healthy young men during the landing task. Brazen et al. (2010) tested the TTS before and after the fatigue protocol and concluded that there was a significant difference between the mean TTS before and after fatigue. There was an anterior-posterior direction that was consistent with the results of the present study [34].

One of the important points in various studies is the possibility of lower limb injuries during performing landing movements from high altitude or jump-landing due to fatigue [35]. In this context, fatigue has been reported as a risk factor for lower extremity injuries such as ACL injuries [36], and the main reason is probably the biomechanical changes in movement following fatigue or compensatory mechanisms of the central nervous system [37, 38].

For example, in the field of compensatory mechanisms following fatigue, Padua et al. (2006) have pointed out that during maximal quadriceps muscle contraction, hamstring muscle contraction is necessary to maintain dynamic knee stability and prevent shear forces on the ACL. Fatigue causes early activation of the quadriceps muscle and delay in activation of the hamstring muscles. This delay in the recruitment of the hamstring muscles causes anterior displacement of the tibia, resulting in improper and uncontrollable load transfer to the knee joint and exposing the person to ACL damage [39]. In another study, the results showed that when performing the jump-landing movement, people after fatigue tend to use ankle axial strategies more and rely more on the ankle muscles than the knee muscles. This seems to reduce the stability of the knee and increase the risk of ACL injury [40].

Mejane et al. (2019) investigated biomechanical characteristics during landing missions in female recreational athletes and indicated that neuromuscular fatigue may alter knee kinematics during landing, reduce knee buffering capacity during landing, and increase the risk of non-contact cruciate ligament injury [16]. At the same time, knee valgus is one of the main causes of ACL injury during exercise [6]. Kristianslund et al. (2012) reported an increased knee abduction moment in fatigued and injured athletes [41]. After fatigue, the knee buckling torque and valgus moment increased significantly at the moment of contact with the ground, and the horizontal backward maximum GRF also increased significantly [42].

Landing after a jump is a common task in sports activities that requires dynamic stability [31]. Neuromuscular control plays an important role in dynamic joint stability. Neuromuscular control can be defined as the activation of dynamic limitation in the preparation and response to joint movement and loading to maintain and stabilize functional stability of the joints [43]. TTS is a measure of neuromuscular control in which force plate values are used to assess dynamic postural stability in jump-landing activities. TTS is also used to assess the effect of fatigue on proprioception and neuromuscular control. Prolonged TTS indicates that the body's response to stability is delayed and that postural control during landing after the jump is difficult [34, 43]. TTS is the amount of time it takes for a person to bring the ground reaction forces in the vertical, internal-external, and posterior-anterior directions to the normal level of standing. The ability to have a fast TTS is generally seen as a positive and protective trait [44]. Considering that no study has been done in this field so far, further studies in this field seem necessary. According to the findings of this study, it seems that female gymnasts with DKV reach stability later than before fatigue occurs.

5. Conclusions

In conclusion, our study found that greater fatigue levels were correlated with an increase in DKV, which may place athletes at a greater ACL injury risk. Also, fatigue affects the amount of TTS in gymnasts with knee valgus dynamics.

6. Limitations

There are several limitations to this study. First, we attempted to recreate a field-based test with force plate and drop-landing tests. However, this test may not represent the actual landing that occurs in gymnastics. Nonetheless, this testing and grading protocol has been used previously and demonstrated strong accuracy. Second, the fatigue protocol used in this study was not designed for gymnastics, as a valid protocol for this field was not available. Additionally, the interobserver reliability was determined to be fair, and intraobserver reliability was not measured in this study.

Conflict of interest

The authors declared no conflicts of interest.

Authors' contributions

All authors contributed to the original idea, study design.

Ethical considerations

The author has completely considered ethical issues, including informed consent, plagiarism, data fabrication, misconduct, and/or falsification, double publication and/or redundancy, submission, etc. All study participants provided written informed consent forms. Moreover, the study was approved by the Research Ethics Committee of Allameh Tabataba'i University (Code: IR.ATU.REC.1400.167).

Data availability

The dataset generated and analyzed during the current study is available from the corresponding author on reasonable request.

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References

[1] Daniel DM, Stone ML, Kaufman KR. "Fate of the ACL-injured patient: a prospective outcome study". *The American Journal of Sports Medicine*. 1994; 22(5): 632-644. https://doi.org/10.1177/036354659402200511.

[2] Arendt E, Dick R. "Knee injury patterns among men and women in collegiate basketball and soccer: NCAA data and review of literature". *The American Journal of Sports Medicine*. 1995;

23(6): 694-701. https://doi.org/10.1177/036354659502300611.

[3] Larwa J, Stoy C, Chafetz RS, Boniello M, Franklin C. “Stiff landings, core stability, and dynamic knee valgus: a systematic review on documented anterior cruciate ligament ruptures in male and female athletes”. *International Journal of Environmental Research and Public Health*, 2021; 18(7): 3826. https://doi.org/10.3390/ijerph18073826.

[4] Krosshaug T, Nakamae A, Biden BP, Engebretsen L, Smith G, Slauterbeck JR, Hewett TE, Bahr R. “Mechanisms of anterior cruciate ligament injury in basketball: video analysis of 39 cases”. *The American Journal of Sports Medicine*. 2007; 35(3): 359-367. https://doi.org/10.1177/0363546506293899.

[5] Koga H, Bahr R, Myklebus G, Engebretsen L, Grund Th, Krosshaug T. “Estimating anterior tibial translation from model-based image-matching of a noncontact anterior cruciate ligament injury in professional football: a case report”. *Clinical Journal of Sport Medicine*. 2011; 21(3): 271-274. https://doi.org/10.1097/jsm.0b013e31821899ec.

[6] Koga H, Nakamae A, Shima Y, et al. “Mechanisms for noncontact anterior cruciate ligament injuries: knee joint kinematics in 10 injury situations from female team handball and basketball”. *The American Journal of Sports Medicine*. 2010; 38(11): 2218-2225. https://doi.org/10.1177/0363546510373570.

[7] Hewett TE, Torg JS, Boden BP. “Video analysis of trunk and knee motion during non-contact anterior cruciate ligament injury in female athletes: Lateral trunk and knee abduction motion are combined components of the injury mechanism”. *British Journal of Sports Medicine*. 2009; 43(6): 417-422. https://doi.org/10.1136/bjsm.2009.059162.

[8] Agel J, Rockwood T, Klossner D. “Collegiate ACL injury rates across 15 sports: National collegiate athletic association injury surveillance system data update (2004-2005 through 2012-2013)”. *Clinical Journal of Sport Medicine*. 2016; 26(6): 518-523. https://doi.org/10.1097/jsm.0000000000000290.

[9] Kochanowicz A, Kochanowicz K, Niespodziuski B, Mieszkowski J, Aschenbrenner P, Bielec G, Szark-Eckardt M. “Maximal power of the lower limbs of youth gymnasts and biomechanical indicators of the forward handspring vault versus the sports result”. *Journal of Human Kinetics*. 2016; 53(1): 33-40. https://doi.org/10.1515/hukin-2016-0008.

[10] Dai B, Garrett WE, Gross MT, Padua DA, Queen RM, Yu B. “The effects of 2 landing techniques on knee kinematics, kinetics, and performance during stop-jump and side-cutting tasks”. *The American Journal of Sports Medicine*. 2015; 43(2): 466-474. https://doi.org/10.1177/0363546514555322.

[11] Leppänen M, Pasanen K, Krosshaug T, Kannus P, Vasankari T, Kujala UM, Bahr R, Perttunen J, Parkkari J. “Sagittal plane hip, knee, and ankle biomechanics and the risk of anterior cruciate ligament injury: a prospective study”. *Orthopaedic Journal of Sports Medicine*. 2017; 5(12): 2325967117745487. https://doi.org/10.1177/2325967117745487.

[12] Yu B, Garrett WE. “Mechanisms of non-contact ACL injuries”. British *Journal of Sports Medicine*. 2007; 41(suppl 1): i47-i51. https://doi.org/10.1136/bjsm.2007.037192.

[13] James CR, Scheuermann BW, Smith MP. “Effects of two neuromuscular fatigue protocols on landing performance”. *Journal of Electromyography and Kinesiology*. 2010; 20(4): 667-675. https://doi.org/10.1016/j.jelekin.2009.10.007.

[14] Rozzi SL, Lephart SM, Gear WS, Fu FH. “Knee joint laxity and neuromuscular characteristics of male and female soccer and basketball players”. *The American Journal of Sports Medicine*. 1999; 27(3): 312-319. https://doi.org/10.1177/03635465990270030801.

[15] Tamura A, Akasaka K, Otsudo T, Sawada Y, Okubo Y, Shiozawa J, Toda Y, Yamada K. “Fatigue alters landing shock attenuation during a single-leg vertical drop jump”. *Orthopaedic Journal of Sports Medicine*. 2016; 4(1): 2325967115626412. https://doi.org/10.1177/2325967115626412.

[16] Mejane J, Faubert J, Romeas T, Labbe DR, Faubert J, Romeas Th, Labbe DR. “The combined impact of a perceptual–cognitive task and neuromuscular fatigue on knee biomechanics during landing”. *The Knee*. 2019; 26(1): 52-60. https://doi.org/10.1016/j.knee.2018.10.017.

[17] Zhang X, Xia R, Dai B, Sun X, Fu W. Effects of exercise-induced fatigue on lower extremity joint mechanics, stiffness, and energy absorption during landings. Journal of sports science & medicine, 2018. 17(4): p. 640.

[18] Harato K, Morishige Y, Niki Y, Kobayashi S,

Nagura T. “Fatigue and recovery have different effects on knee biomechanics of drop vertical jump between female collegiate and recreational athletes”. *Journal of Orthopaedic Surgery and Research*. 2021; 16: 1-7. https://doi.org/10.1186/s13018-021-02893-6.

[19] Behrens M, Mau-Moeller A, Wassermann F, Plewka A, Bader R, Bruhn S. “Repetitive jumping and sprinting until exhaustion alters hamstring reflex responses and tibial translation in males and females”. *Journal of Orthopaedic Research*. 2015; 33(11): 1687-1692. https://doi.org/10.1002/jor.22935.

[20] Borotikar BS, Newcomer R, Koppes R, McLean SG. “Combined effects of fatigue and decision making on female lower limb landing postures: Central and peripheral contributions to ACL injury risk”. *Clinical Biomechanics*. 2008; 23(1): 81-92. https://doi.org/10.1016/j.clinbiomech.2007.08.008.

[21] Kernozek TW, Torry MR, van Hoof H, Cowley H, Tanner S. “Gender differences in frontal and sagittal plane biomechanics during drop landings”. *Medicine & Science in Sports & Exercise*. 2005; 37(6): 1003-1012.

[22] Mclean SG, Felin RE. Sudekum N, Calabrese G, Passerallo A, Joy S. “Impact of fatigue on gender-based high-risk landing strategies”. *Medicine and Science in Sports and Exercise*. 2007; 39(3): 502-514. https://doi.org/10.1249/mss.0b013e3180d47f0.

[23] Liederbach M, Kremenic IJ, Orishimo KF, Pappas E, Hagins M. “Comparison of landing biomechanics between male and female dancers and athletes, part 2: Influence of fatigue and implications for anterior cruciate ligament injury”. *The American Journal of Sports Medicine*. 2014. 42(5): 1089-1095. https://doi.org/10.1177/0363546514524525.

[24] Mueske N, Katzel MJ, Chaswick KP, VandenBerg C, Pace JL, Zaslow T, Edison B, O’Callahan B, Nakata HLK, Wren T. “Biomechanical symmetry during drop jump and single-leg hop landing in uninjured adolescent athletes”. *Orthopaedic Journal of Sports Medicine*. 2019; 7(3_suppl): 2325967119S00023. https://doi.org/10.1177/2325967119s00023.

[25] Zamporri J, Aguinaldo A. “The effects of a compression garment on lower body kinematics and kinetics during a drop vertical jump in female collegiate athletes”. *Orthopaedic Journal of Sports Medicine*. 2018; 6(8): 2325967118789955. https://doi.org/10.1177/2325967118789955.

[26] Gribble PA, Robinson RH. “Alterations in knee kinematics and dynamic stability associated with chronic ankle instability”. *Journal of Athletic Training*. 2009; 44(4): 350. https://doi.org/10.4085/1062-6050-44.4.350.

[27] Hunnicutt JL, Jayanthi NA, Labib SA. “Editorial Commentary: Considering fatigue when assessing athletes for dynamic knee valgus: Is this the next big step in identifying anterior cruciate ligament injury risk?”. *Arthroscopy: The Journal of Arthroscopies & Related Surgey*. 2020; 36(1): 223-224. https://doi.org/10.1016/j.arthro.2019.10.002.

[28] Fidai MS, Okoroha KR, Meldau J, Meta F, Lizzio VA, Borowsky P, Redler LH, Moutzouros V, Makhni E. “Fatigue increases dynamic knee valgus in youth athletes: results from a field-based drop-jump test”. *Arthroscopy: The Journal of Arthroscopic & Related Surgery*. 2020; 36(1): 214-222. e2. https://doi.org/10.1016/j.arthro.2019.07.018.

[29] Niespodziński B, Grad R, Kochanowics A, Mieszkowski J, Marina M, Zasada M, Kochanowicz K. “The neuromuscular characteristics of gymnasts’ jumps and landings at particular stages of sports training”. *Journal of Human Kinetics*. 2021; 78(1): 15-28. https://doi.org/10.2478/hukin-2021-0027.

[30] Knihs DA, Zimmermann HB, Dal Pupo J. “Acute and delayed effects of fatigue on ground reaction force, lower limb stiffness and coordination asymmetries during a landing task”. *Journal of Human Kinetics*. 2021; 76(1): 191-199. https://doi.org/10.2478/hukin-2021-0054.

[31] Pappas E, Sheikhzadeh A, Hagins M, Nordin M. “The effect of gender and fatigue on the biomechanics of bilateral landings from a jump: peak values”. *Journal of Sports Science & Medicine*. 2007; 6(1): 77.

[32] Chmielewski TL, George SZ, Tillman SM, Moser MW, Lentz TA, Indelicato PA, Trumble TN, Shuster JJ, Cicuttini FM, Leeuwenburgh Ch. “Low-versus high-intensity plyometric exercise during rehabilitation after anterior cruciate ligament reconstruction”. *The American Journal of Sports Medicine*. 2016; 44(3): 609-617. https://doi.org/10.1177/0363546515620583.

[33] Nasrabadi R, Sadeghi H, Yousefi M. “Effect of fatigue on some indicators of ground reaction force in young active men during drop-Landing task”. *Journal of Paramedical Sciences &*

Rehabilitation. 2020. 9(3): 62-70.

[34] Brazen DM, Todd MK, Ambegonkar JP, ATC O, Wuderlich R, Pererson C. "The effect of fatigue on landing biomechanics in single-leg drop landings". *Clinical Journal of Sport Medicine*. 2010; 20(4): 286-292. https://doi.org/10.1097/jsm.0b013e3181e8f7dc.

[35] Moir G, Sanders R, Button Ch, Galaister M. "The influence of familiarization on the reliability of force variables measured during unloaded and loaded vertical jumps". *Journal of Strength and Conditioning Research*. 2005; 19(1): 140. https://doi.org/10.1519/00124278-200502000-00024.

[36] Bourne MN, Webster KE, Hewett TE. "Is fatigue a risk factor for anterior cruciate ligament rupture?". *Sports Medicine*. 2019; 49: 1629-1635. https://doi.org/10.1007/s40279-019-01134-5.

[37] Agres AN, Chrysanthou M, Raffalt PC. "The effect of ankle bracing on kinematics in simulated sprain and drop landings: a double-blind, placebo-controlled study". *The American Journal of Sports Medicine*. 2019; 47(6): 1480-1487. https://doi.org/10.1177/0363546519837695.

[38] 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), 22-28.

[39] Padua DA, Arnold BL, Perrin DH, Gansneder BM, Carcia CR, Granata KP. "Fatigue, vertical leg stiffness, and stiffness control strategies in males and females". *Journal of Athletic Training*. 2006; 41(3): 294.

[40] Daoukas S, Malliaropoulos N, Maffulli N. "ACL biomechanical risk factors on single-leg drop-jump: a cohort study comparing football players with and without history of lower limb injury". *Muscles, Ligaments & Tendons Journal*. 2019; 9(1). https://doi.org/10.32098/mltj.01.2019.16.

[41] Kristianslund E, Krosshaug T, Van den Bogert AJ. "Effect of low pass filtering on joint moments from inverse dynamics: implications for injury prevention". *Journal of Biomechanics*. 2012; 45(4): 666-671. https://doi.org/10.1016/j.jbiomech.2011.12.011.

[42] Liu Zh, Yang Ch, Yu J, Zhao X, Wu J, Zhang Y, Li J, Gu Y. "The effect of muscles fatigue on the knee's kinetics and kinematics characteristics". *Sustainability*. 2023; 15(4): 3029. https://doi.org/10.3390/su15043029.

[43] Shaw MY, Gribble PA, Frye JL. "Ankle bracing, fatigue, and time to stabilization in collegiate volleyball athletes". *Journal of Athletic Training*. 2008; 43(2): 164-171. https://doi.org/10.4085/1062-6050-43.2.164.

[44] Webster KA, Gribble PA. "Time to stabilization of anterior cruciate ligament–reconstructed versus healthy knees in National Collegiate Athletic Association Division I female athletes". *Journal of Athletic Training*. 2010; 45(6): 580-585. https://doi.org/10.4085/1062-6050-45.6.580.