International Journal of
Physical Therapy & Rehabilitation
Research Article
Open Access
Special Issue: Various Approaches for Rehabilitation Science-Vol III

Exercise Intensity and Type of Activity Effects Landing Mechanics and Increases Anterior Cruciate Ligament (ACL) Injury Risk

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Abstract

Background: There is a high prevalence of lower extremity injuries, specifically knee ligament injuries, associated with jumping and multi-directional movement sports. Deficient landing mechanics associated with some sports contribute to lower extremity injuries, specifically to the anterior cruciate ligament (ACL). Evaluating the effects of fatigue (neuromuscular) and exercise intensities on landing mechanics is another component in the complexity of understanding factors associated with ACL injury.

Methods: Twenty recreational level athletes (10 M, 10 F; 22.5 ± 1.5yrs) volunteered. Eleven subjects performed the Lateral Hop Test (LHT, 5 M, 6 F) and nine subjects performed the Wingate Anaerobic Test (WAT, 5 M, 4 F). The fatigue protocols included LHT for maximum time (43.5±10.7 sec) at a standardized cadence (60 bpm) or a 20 sec WAT followed by a Jump Landing Task (JLT). Subjects were randomly assigned to a fatigue protocol. All subjects performed three baseline JLT. Each subject had a control period of no activity (30 sec) before completing their assigned fatigue protocols a total of four times. Peak Ground Reaction Force (PGRF) values and LESS scores were collected after each JLT.

Results: There were no significant (p>0.05) three-way interactions for PGRF or LESS. In addition, there were no significant (p>0.05) main effects of time or fatiguing condition on PGRF. There was a significant main effect of time ($F_{4,64}$= 9.5, p= 0.0001, ES= 0.37) for LESS. Collectively, the data demonstrated that both fatigue protocols increased the LESS score by 21.7% from control to the 2nd attempt, 32.6% from control to the 3rd attempt, 26.1% from control to the 4th attempt, and lastly a 30.4% decrease from control to the 5th attempt.

Conclusion: The fatigue protocols produced different levels of fatigue and the data suggests that training with a landing strategy that has been shown to reduce ACL injury during different levels of fatigue may help to decrease high risk landing mechanics and reduce ACL injury risk.

Publication History:

Received: August 17, 2021
Accepted: September 11, 2021
Published: September 13, 2021

Keywords:

Anterior Cruciate Ligament (ACL) injury; Fatigue; Exercise intensity; Jump landing task (JLT); Lateral hop test (LHT); Landing error scoring system (LESS); Wingate anaerobic Test (WAT)

Introduction

Anterior cruciate ligament (ACL) injuries are commonly due to noncontact mechanisms caused by rapid deceleration, pivoting, or landing maneuvers, especially while landing [1-7]. Noncontact ACL tears occur at a high annual rate, with higher incidence in females [1-3,5-9]. Females have reported greater strength imbalances and neuromuscular differences between their dominant and non-dominant leg that result in inadequate knee stability compared to males [7]. Deficits in landing positioning during initial ground contact, such as increased knee valgus, leg internal rotation, and decreased trunk flexion, have been shown to increase the risk of lower extremity injuries in both males and females [4,10-13]. Thus, it is necessary and pertinent to study modalities to assess landing mechanics.

Muscle fatigue has been classified as an additional factor that alters landing mechanics and predisposes an athlete to an ACL injury [14-19]. Landing mechanics and fatigue are considered modifiable risk factors that may decrease a potential ACL injury [15]. Current research is limited in the understanding of the type of landings that should be performed, the assessment tools that evaluate landing mechanics, and the effects of different magnitudes of muscle fatigue has on landing mechanics and perceived exertion. The other modifiable risk factor, fatigue can be defined as a reduction of muscular work or a failure of a specific task. Fatigue can be classified as central, metabolic, or peripheral, and all three influence one another in regards to physical function and performance of a specific task [20,21]. In addition, fatigue is highly variable due to its time dependent nature and is also highly individually specific. Accordingly, the effects of various degrees of fatigue on landing mechanics are not clearly understood. For the purpose of this study, the term "fatigue" addresses peripheral muscle fatigue only. Quantifying muscle fatigue and its effects on landing mechanics and perceived exertion can be challenging due to differences in the type of fatigue protocols used. Performing an exercise, skill, or task all produce various levels of fatigue. The Wingate Anaerobic Test (WAT) has been a standard assessment test to measure anaerobic power and also measures fatigue by measuring the percentage of power drop called the fatigue index [22]. A 20 or 30 sec WAT has been shown to induce a high level of overall anaerobic fatigue with some aerobic effects [22]. In addition, a Lateral Hop Test (LHT) has been used as an exercise, skill, or task to assess ankle and knee stability as well as return to play [23-25]. The LHT can be performed either single or double leg and in many variations that can include hoping for time, or distance, and induces fatigue that is more functional in movement than the WAT. Consequently, these tests can be used to induce muscle fatigue and to investigate their interactions on landing mechanics [17,19,26,27] and thus ACL injury risk.

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Citation: Dominguese DJ, Kingsley JD (2021) Exercise Intensity and Type of Activity Effects Landing Mechanics and Increases Anterior Cruciate Ligament (ACL) Injury Risk. Int J Phys Ther Rehab 7: 176. doi: https://doi.org/10.15344/2455-7498/2021/176

Drop landings from a platform onto a force plate have historically been employed to standardize landing conditions and assess landing mechanics. However, drop landings aren't always considered athletically functional because the landings are controlled for height and velocity. An exercise or skill such as a Jump Landing Task (JLT) which incorporates a combination of horizontal and vertical jumping components from a specific height, is often seen in sports training in many forms. Therefore, a JLT may be more functional and a more appropriate way to examine landing mechanics [13,28].

Evaluating landing mechanics by the use of motion analysis systems isn't always feasible for coaches, strength and conditioning specialists, clinicians, and others as an assessment tool to screen athletes for ACL injury risk due to lack of resources, training and expertise. The Landing Error Scoring System (LESS) is an assessment tool that has been developed to evaluate landing mechanics [27-31]. The LESS provides a score based on an established set of landing criteria that identifies landing errors that are potential predisposing factors for ACL injury [27-31]. The LESS has been designed to evaluate landing biomechanics in a time conserving fashion with minimal equipment and resources [2,13,26-28]. The LESS evaluates 17 quantitative characteristics of landing mechanics and joint positioning. A quantitative score based on performance is assigned, indicating if an individual demonstrates at-risk landing mechanics that may predispose them to an ACL injury. The LESS can help identify athletes with modifiable risk factors [15,18] for lower extremity injuries, such an ACL injury by using this assessment tool in research or in sports training and practice setting.

Evaluating athletes during various time intervals during different levels of fatigue, provides valuable information on how different forms of exercises, skills, and tasks influence landing mechanics, ACL injury risk and perceived exertion. This information may improve jump and landing performance and decrease lower extremity risk that may be overlooked at the start, middle or upon completion of a training session.

The data and observation obtained via the LESS can also be used to enhance overall landing performance by educating and training athletes how to jump and land.

Therefore, this study aims to investigate the effects of different levels of fatigue on landing mechanics of recreational athletes and to provide the end user with information on how the body performs with high and low levels of fatigue throughout a training session using common exercise modalities. This model provides a sample of recreational athletes' responses to fatigue while performing a functional skill and task which provides valuable information on how to screen athletes for ACL risk factors as well as how to design better prevention and intervention programs [10-13,15,18,32]. We hypothesized that different levels of fatigue and exercise modality will mediate alterations in magnitude of force and landing strategies as their LESS scores will increase.

Methods

Experimental approach to the problem

All subjects volunteered for this study and attended an information session before their scheduled data collection appointment that focused on educating the subjects about the two fatigue protocols. The fatigue protocols included a 20 sec WAT or a LHT followed by a JLT. Subjects were randomly assigned to a fatigue protocol. Subjects performed one to three practice JLT with a five-minute rest prior to performing their three baseline JLT to ensure that the JLT were performed safely and correctly as well as to provide the baseline data. Each subject had a control period of no activity (30 sec) before completing their assigned fatigue protocols a total of four times. During the control period, subjects were instructed to walk at self-selected speeds (pace back and forth) in preparation of the next task. Peak Ground Reaction Force (PGRF) values and LESS scores were collected after each JLT.

Subjects

Twenty recreational level athletes (10 males, 10 females; Mean±Standard Deviation; males 22±1 yrs; females 23±1 yrs). Eleven subjects performed the LHT (5 males, 6 females) and nine subjects performed the WAT (5 males, 4 females). Subjects that self-reported that they had participated in basketball, volleyball, or running, a minimum of three times per week for greater than 30 min for each session over the last two months participated in this study. Subjects were excluded if they had a history of cardiovascular/pulmonary illnesses, or lower extremity injury within the last six months, such as an ankle sprain. No subject reported any history of ACL injury. Subjects that participated in any form of exercise or consumed any alcohol or caffeine 24 hours prior to data collection were also excluded. This information was collected and screened by survey questions prior to data collection.

All subjects completed a health care questionnaire regarding their medical history to elicit the inclusion and exclusion criteria. The same athletic trainer performed an orthopedic exam on each subject to evaluate lower extremity joint stability and screen subjects for adherence to inclusion and exclusion criteria. This research project was approved by the university's Institutional Review Board and all subjects voluntarily signed an informed consent form prior to participation in this study.

Procedures

A flow sheet of this protocol can be found in Figure 1. A warm-up was administered before the subjects performed practice and baseline JLT. The warm-up consisted of five minutes of cycling a Monark Ergomedic 894E Peak Bike (Monark, Sweden) between 60-70 W. The JLT was conducted from a 30-cm platform followed by one of the two fatigue protocols immediately followed by three JLT to assess changes in landing mechanics due to the selected fatigue protocol. These fatigue protocols were repeated for a total of four times with a five-minute rest session between each attempt. The rest period allowed subjects ample recovery time prior to performing the next exercise bout and to ensure safety; although physiologically, fatigue effects have been shown to last upwards of forty minutes [17,33,34]. Each subject served as their own control with this study design. Repeated bouts were performed to ensure that fatigue status was achieved with different levels for each bout and to determine if there was an effect between each.

A 20 sec WAT was used in this study to induce a high level of fatigue and to encourage subject compliance for maximal effort [17,22,34]. It has been shown to be a valid alternative to the standard 30 sec test [2,17,20,21,34] and still requires maximal effort [17,22,34,42]. The LHT was used in this study because it's often used for lower extremity dynamic training and as an assessment tool for ankle and knee stability

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[26,35,36] that can be used to induce low levels of muscle fatigue [35,36]. The LHT, side to side movement is commonly represented in part during ACL injury [17,23,26,27,34].

The jump landing task

The JLT included both horizontal and vertical jumps starting from a 30-cm platform. Each subject jumped a distance of 50% of their height away from the platform (horizontal), to the force plate, followed immediately by a maximal vertical jump. Subjects were given verbal and visual instructions on how to perform the task but were not coached on how to land, unless performing the task improperly, in order to investigate their current landing mechanics. Each subject was given as many practice jumps as needed (mean±SD: 3±1 jumps) to perform the task correctly and to become familiar with the protocol. After the practice jumps, subjects rested for five minutes to eliminate fatigue effects prior to data collection. Jumps were classified as valid by (1) jumping from the platform with both feet; (2) jumping horizontally, not vertically to reach the force plate; (3) landing with the dominant foot with full contact of the force plate; (4) landing with the non-dominant foot beside the force plate; and (5) completing the task while maintain balance. Dominant leg was identified by asking each subject what leg they would prefer to kick a ball [17,34,35]; all subjects reported right leg dominance and this information was gather by the researchers to assist with possible interpretations of the results. All subjects performed the JLT with their own athletic shoes that they used while exercising. The JLT were collected 30 sec after their warm up and 30 sec from each other to control for time to fatigue, recovery, and to ensure safety.

Landing error scoring system

All LESS data were collected and scored based on previously published data [27-31]. In short, the LESS data were collected during the JLT tasks using two of the same high-definition cameras (Panasonic DMC-FZ 100, Osaka, Japan) placed 3.5 m away from the side and front of the edge of the force plate [30]. Scoring was based on video recordings assessed after all data were collected for each subject for the existence or nonexistence of different landing characteristics by assessing 17 items that included the trunk, hip, knee, and ankle motion in the sagittal plane (8 observations) at initial contact and completion of landing, as well as examining trunk, knee, ankle and stance characteristics in the frontal view (9 observations) [29]. Two experienced raters (DJD and a research assistant, all athletic trainers) were used in this study and had several years of experience using the LESS as an assessment and research tool. Total scored items created an overall score ranging from 0-17. Higher LESS scores indicated poor landing mechanics and lower LESS scores indicated excellent mechanics. A score of less than or equal to 4 is considered excellent; greater than 4, but less than or equal to 5 is good; greater than 5, but less than or equal to 6 is moderate; and greater than 6 is considered poor mechanics. The LESS scores were averaged for each fatigue

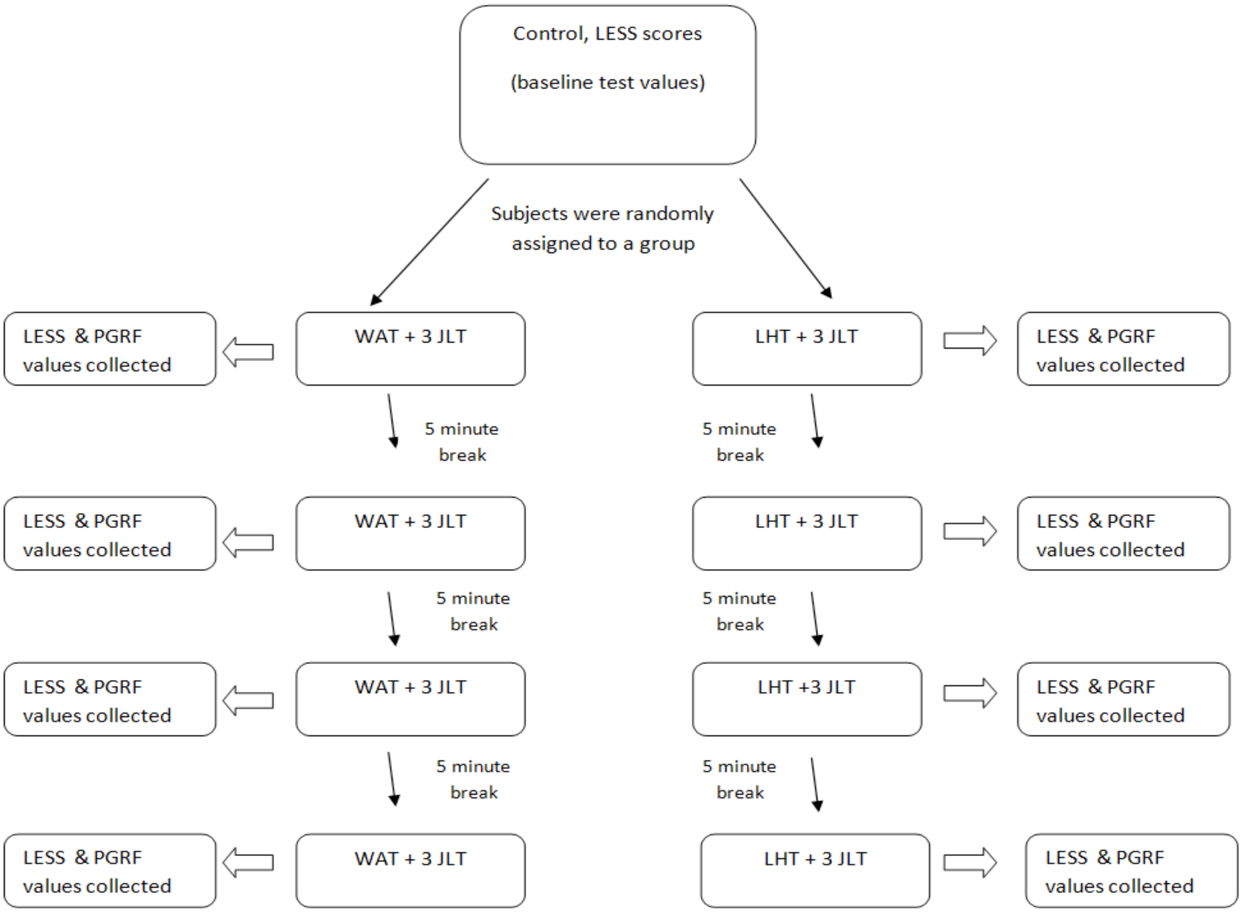

Figure 1: Flow chart describing the experimental protocol.
Wingate anaerobic test (WAT), lateral hop test (LHT), jump landing task (JLT), landing error scoring system (LESS), peak ground reaction force (PGRF).

protocol (WAT and LHT) to establish the baseline measures and each was compared separately across all subjects.

Wingate anaerobic test (WAT)

During the WAT, the subject pedaled as hard as possible with no resistance for three sec followed by adding a resistance of 7.5% kg of their body weight for 20 sec with an all-out effort, followed by instructions to prepare for the JLT. This process was repeated four times with five minutes of rest between each repeated bout of the WAT. The results of the WAT can be seen in Table 1.

Variable	Males (n=10)	Females (n=10)
WAT Power Drop (W), %	41.0 ±6.8	46.2 ± 8.8
WAT RPE	17.8 ± 1.3	17 ± 2
LHT RPE	13 ± 1.4	13 ± 2.2
LHT, sec	47 ± 13	40± 8.4
PGRF, BW	6.94 ± 1.79	6.71± 1.37

Table 1: Participant Results (n=20).
Values are mean ± SD, Wingate Anerobic Teat (WAT), Watts (W), Lateral Hop Test (LHT), Rate of Perceived Exertion (RPE), Peak Ground Reaction Force (PGRF), Body Weight (BW).

Lateral hop task (LHT)

The LHT used a double leg hop movement. A metronome cadence of 60 (1 Hz) beats per minute, was used to standardized speed of the hop while subjects hopped over a line placed on a hard-wood basketball floor while keeping pace with the beat of the metronome. Subjects were required to maintain an erect posture, land with their heel of their feet up for as long as possible. Subjects used bilateral poles with a base tip to help maintain balance and ensure safety while hopping. The LHT ended when the subject was unable to maintain the cadence, jumping out of the frontal plane, unable to perform three consecutive jumps, fail posture, and drop heel for three sec. The results of the LHT can be seen in Table 1.

Borg Rate of Perceived Exertion was used to evaluate the exertion level after each of the fatigue protocol (WAT and LHT), whereas 6= no exertion at all, 13= somewhat hard, and 20= maximal exertion [36].

Force platform

Peak ground reaction force was collected using a 9281C Kistler force plate (Kistler Instruments Corporation, USA) and amplified with an external 8-channel 9865B change amplifier (Kistler Instruments Corporation, USA) and analyzed with Peak Motus Software 8.0 (Peak Performance Technologies Inc., USA). Analog data (PGRF) were sampled at 8500 Hz and filtered using an eight-order low-pass Butterworth filter with a cutoff frequency of 293 Hz to remove oscillation from the landing that was demonstrated at ~833 Hz resonant frequency. The settings were determined based on manufacturer's guidelines and equipment applications. All data were normalized to the subjects' body weight for practical application rather than in Newtons.

Statistical analyses

The means and standard deviations were calculated for each PGRF and LESS score condition. Interrater reliability was assessed by a single experienced rater from a pool of five randomly assigned subjects on two separate occasions. A minimum of two weeks separated the two sessions. The second rater, who was blinded to the LESS scores of the first rater, graded the same subgroup of subjects previously tested by the first rater. Intraclass correlation coefficient (ICC) and standard error of measure (SEM) values were determined to assess interrater reliability. All data were normalized based on a Shapiro-Wilk normality test. The independent variables (sex, time and fatigue conditions) were used in a mixed-factor analysis of variance (ANOVA) with fatigue as the repeated measure for the dependent variable. A repeated measures ANOVA was used to assess the effects of sex x fatigue conditions (LHT versus WAT) x time (base-line control 1st attempt, 2nd attempt, 3rd attempt, 4th attempt, 5th attempt) on the dependent variables of PGRF and LESS scores. Based on the data by Bates et al. [37], performance strategies using 5 trials (1st attempt (control) through 5th attempt) suggested that a sample size of 10 subjects per group is sufficient to achieve statistical power of greater than 90% if using a two-factor repeated measures ANOVA. The dependent variables were treated separately to test within, between, and interactions with an *a priori* alpha of 0.05. T tests were used to identify differences if the ANOVA was significant based on the F test within both fatigue conditions using a Bonferroni adjustment (p=0.01).Measurements of power include effect size determined using partial eta (ES) and 95% confidence intervals (CI) for the ANOVA and t-tests, respectively. Data were analyzed using SPSS statistical software, version 24 (SPSS Inc., Armonk, NY).

Results

The subject characteristics are presented in Table 2. The ICC and SEM values for interrater reliability were 0.80 and 0.75, respectively, indicating good interrater reliability [38]. There were no significant (p>0.05) three-way interactions for PGRF or LESS (Figure 2). In addition, there were no significant (p>0.05) main effects of time or fatiguing condition on PGRF. There was a significant main effect of time ($F_{4, 64}$= 9.5, p= 0.0001, ES= 0.37) for LESS. Collectively, the data demonstrated that both fatigue protocols increased the LESS score by 21.7% from control to the 2nd attempt (CI: -1.7 to -0.26), 32.6% from control to the 3rd attempt (-2.5 to -0.59), 26.1% from control to the 4th attempt (-1.9 to -0.63), and lastly a 30.4% decrease from control to the 5th attempt (-2.1 to -0.58).

Variable	Males (n=10)	Females (n=10)
Age, yrs	22±1	23 ± 1
Height, m	1.75 ± 0.92	1.73 ± 0.82
Weight, kg	84.4 ± 9.0	60.6 ± 10.3
BMI, kg/m^2	27.6 ± 3.9	23.0 ± 4.1

Table 2: Participant Characteristics (n=20). Values are mean ± SD.

Discussion

Investigating ACL risk factors such as fatigue, sex, landing mechanics, and the type of protocols used are challenging. Muscle fatigue has been shown to alter landing mechanics [1,4,8,9,15,17-19,34,39] and adds to the complexity of understanding landing strategies among athletes and ACL injury risk [17,34]. Evaluating landing mechanics by using state of the art motion analysis systems is not always feasible for coaches, clinicians, and researchers. Using an assessment tool such as the LESS, or the modified LESS-Real Time (RT) technique, is considered a valuable tool for assessment of at-risk landing strategies [13,27-29,40]. This study shows that using the LESS identified altered landing mechanics while various levels of muscle fatigue were induced. This study investigated landing mechanics before and after two different fatigue protocols. The data from the present study suggest that although differences in landing mechanics were not significantly different across sex and fatigue protocol, landing mechanics did significantly decrease across time. Therefore, the data from the present study demonstrated that fatigue initiated from multiple WATs and/or the LHT is a sufficient stimulus to negatively alter landing mechanics regardless of sex.

Previous studies reported a decrease in PGRF as a result of fatigue [16,17,34,39]. The reduction in PGRF is beneficial in reference to peak force; however, the landing mechanics that resulted in the reduction may be undesirable as the majority of the subjects were observed increasing their overall time executing each landing to maintain balance as determine by the time from toe contact to heal contact. This form of landing may predispose the individual to an ACL injury [1,7,14,16,17]. A reduction of PGRF was seen for 60% of the total subjects, however not statistically significant, affected males and females equally regardless of the fatigue protocol. Data revealed that the LHT which was considered to have lower levels of fatigued and perceived as less difficult, had worsened LESS scores when compared to the WAT. Fatigued from the LHT, the subjects trended towards landing stiffer (less knee flexion) as evaluated by the LESS and higher scores.

The LHT significantly affected LESS scores, as scores worsened while repeated bouts of low level of fatigue was induced among subjects. The LESS and LESS-RT has been shown to evaluate individuals with at-risk landing mechanics [2,13,27-31] and revealed changes in landing mechanics in this study. In comparison, Smith et al. [27] found no correlation between individuals with a poor LESS score and ones that sustained an ACL injury [27]. The author reports that in their study, the LESS criteria may not investigate the most at-risk factors associated with ACL injury and the JLT may not resemble the movement patterns that predisposes someone to injury. Therefore, the current LESS protocol of 17 visually identifiable risk factors that are scored may not be a comprehensive list of biomechanical risk factors for ACL injury as other additional risk factors may exist.

In this study, the LHT when used as a low-level fatigue protocol that displayed reductions in respect to LESS scores. The LHT is considered a valid method to induce muscle fatigue and evaluate ankle and knee

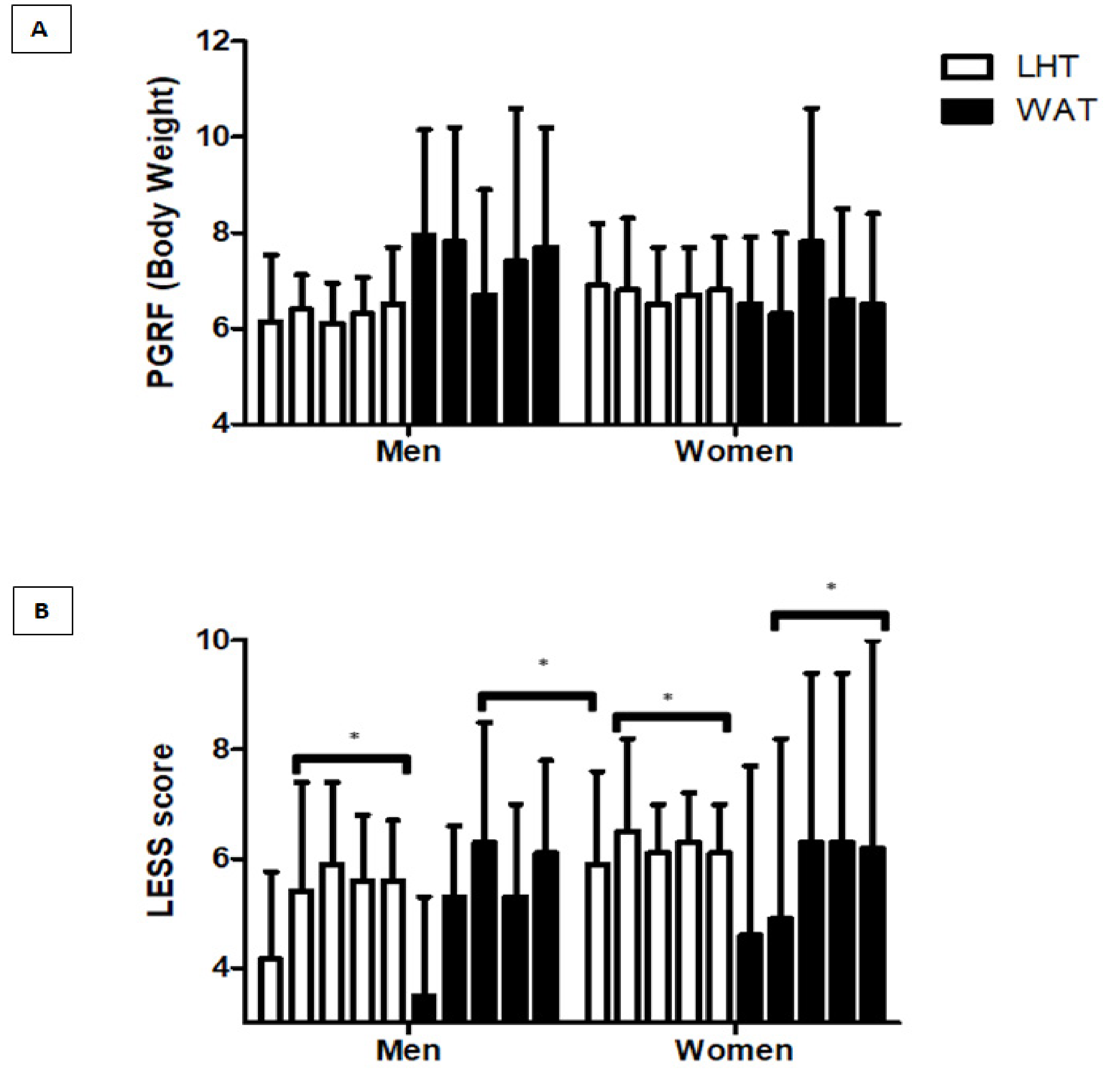

Figure 2: The collated effect of the four different trials of LHT and WAT on A) PGRF and B) LESS scores in healthy, college-aged recreational men (n=10) and women (n=10). *$p<0.05$, significantly different from control.

instability because of the nature of the functional task [19,23-26]. The WAT is a standard modality used that induces a high level of fatigue. The WAT is limited in the ability to utilize the elastic component of tissue, although concentric and eccentric muscular work is still performed [2,17,19,34,35,42]. Conversely, the LHT is performed to specifically induce lower extremity muscular fatigue, performed in a more functional plane of movement, and is commonly used in most sports in some respect as part of their training and activity. The findings from the LHT trials indicated that performing a more functional task to induce fatigue of lower extremity musculature, not just the musculature utilized in sagittal plane movement, produces a significant increase in altered landing mechanics. Comparing and using the two fatigue protocols with various levels of fatigue is beneficial but may present some limitations in investigating other planes of motion that are associated with ACL injury.

Overall, sex did not affect time or fatiguing conditions for PGRF. Increasing the number of subjects and changing demographic variables such as recreational vs college athletes of subjects may influence different results in respect to peak force and gender. In addition, changes to platform height and distance to the landing surface may influence GRF characteristics as well. The first landing of the JLT (horizontal jump to the force platform) was recorded and not the second landing after the vertical jump. The jump to the force platform is linear in nature and common in most athletic skills and the reason for including in the analysis. Analyzing the second landing was not feasible because the subjects seldom landed with their foot in full contact with the force plate and would yield to incorrect force data. Following the LESS protocol, each subject performed three trials of the JLT after they were fatigued and the trials were averaged for PGRF and LESS scores [13]. Observations were made that most subjects resulted in higher values for both dependent variables for their first trials compared to their second and third trial. This may have been influenced by recovery from fatigue; however, the 30 seconds that was used was to ensure safety and control for time for each subject [17,34]. The JLT can also be considered part of the overall fatigue protocol but was treated as part of the assessment to measure PGRF in a specific landing task and was a standard for all subjects.

The JLT was from a height of 30 cm that required the subject to perform a horizontal jump which is different from a control drop landing. Drop landings, although controlled for distance and often used in research studies, don't always resemble the functional properties like a JLT. Using the JLT provided a functional landing task to better assess landing mechanics while fatigued.

Landing mechanics and risk factors associated with landing is a multidirectional movement. This study did not investigate landing during multidirectional movement patterns such as pivoting and cutting which are considered more at-risk movements [1-7,26,27]. Future studies that implement more at-risk landing patterns while fatigued and at different levels of fatigue are necessary to understand greater risk factors associated with ACL injuries. However, these studies provide greater safety challenges for the research subjects because of risk of injury.

This study used the LESS to evaluate landing mechanics while subjects performed different fatigue protocols at various levels of fatigue. The LESS or other landing mechanic screening tools serve as a foundation to understand at risk landing strategies. Anterior cruciate ligament (ACL) training and prevention programs have been shown to be effective in improving overall landing mechanics and decreasing injury risk [2,3,13]. Prevention and training programs are commonly used while athletes are not fatigued or have low levels of fatigue and as a result may not provide the entire picture on how athletes land and perform. Screening and assessment tools, along with understanding fatigue and other risk factors are continuing to be investigated and developed and further studies are warranted in order to prevent an ACL injury.

There are a few limitations to the present study. Differences weren't found in PGRF between the sexes and this may have resulted because of the 30 cm height used in the JLT. Using a WAT as a fatigue protocol isn't a dynamic test and a LHT is limited to mainly two planes of movement; therefore, they may not yield the greatest display of overall muscle fatigue. The nature of fatigue, both physical and central, are time dependent and highly individualized. The fatigue protocols can be classified as a test, an assessment tool, a task, and/or an exercise. Both require the subjects to perform at the set intensity of an all-out effort for the WAT and at lower intensity for the LHT controlled by a set cadence. Although all subjects responded based on RPE to the level of difficulty to each fatigue protocol as to what they believed was more difficult; some subjects may have had difficulty performing the overall fatigue protocols. The familiarity on how to perform each test can influence the results of each test. All of the limitations of the fatigue protocols and investigation fatigue as a factor, was controlled with the safety of the subjects in mind and within the available resources allotted to conduct the study.

Practical Application

Health care professionals train and rehabilitate athletes to enhance performance and prevent injury. Athletes prepare their bodies to deal with many forms of stress that is physiological and mechanical. Fatigue that is classified as central that involves responses that occur in the central nervous system (CNS), incorporates decision making processes, interpretations, and emotions that are present during exercise and performing specific skills. Peripheral fatigue involves the responses that occur outside the CNS and affects how muscles produces force. The interaction of both types of fatigue including metabolic fatigue (often referred as neuromuscular fatigue), influences how an athlete performs a skill or task [17,24,39].

This study demonstrated that fatigue influences how we perform a skill or a task and different levels of fatigue regardless of intensity and type of exercise, can predispose someone to at-risk movement patterns and potentially injury.

Conclusions

This study demonstrates that different levels of fatigue influences how athletes land and low levels of fatigue altered landing mechanics greater than high levels of fatigue. Athletes should be encouraged to train for low-risk landing strategies throughout the duration of their training program when fatigue exists in all forms and levels. One main goal with any training program is to train under conditions most closely mimicking the activity they must perform repeatedly. This study revealed the importance of evaluating landing mechanics of athletes while training and performing different skills and task under both fatigued and non-fatigued conditions with various levels of fatigue. The assessment of landing mechanics while performing a skill or task fatigued and non-fatigued, also serves as a training and exercise program that can improve overall landing performance, enhance skill technique, and possibly decrease at-risk landing patterns associated with ACL injury.

Historically, ACL prevention training programs have been performed in the warm up portion of athletic practices or training sessions for easy application into programs [1,2,8,18]. The results of this study indicate there may be merit to instituting training programs under fatigue conditions to decrease at risk landing strategies that have been shown to cause of ACL injury.

Competing Interests

The authors declare that they have no competing interests.

Author Contributions

Design of the study: DJD and JDK.
Analyzed the data: DJD and JDK.
Wrote the first draft of the manuscript: DJD.
Continued writing the manuscript: DJD.
Contributed to the writing of the manuscript: DJD and JDK.
Agree with manuscript results and conclusions: DJD and JDK.
Structure and arguments for the paper: DJD and JDK.
Made critical revisions and approved final version: DJD and JDK.
All authors reviewed and approved of the final manuscript.

Acknowledgments

We are thankful to all patients who participated in study. Special thanks, to Christopher Walther for his professional contributions to the review of literature, piloting methods, and reviewing and editing the manuscript.

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This article was originally published in a special issue:

Various Approaches for Rehabilitation Science-Vol III

Handled by Editor(s):

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