# FATIGUE EFFECT ON LANDING BIOMECHANICS AMONG INDIVIDUALS WITH ANTERIOR CRUCIATE LIGAMENT RECONSTRUCTION: A SYSTEMATIC REVIEW

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***Abstract***

It is well established that knee stability can be altered during fatigue, which may increase the risk of anterior cruciate ligament (ACL) injury. This is due to a reduction in neuromuscular control that leads to abnormal movement patterns. This study aims to review the impact of fatigue on landing biomechanics among individuals who have undergone anterior cruciate ligament reconstruction. Four databases (Scopus, EBSCO, Web of Science, and Google Scholar) were searched for relevant articles, with a focus on full-text English-language research articles published between 2012 and 2022. The quality of the included studies was evaluated using the McMaster Critical Review Form for Quantitative Studies, and two independent reviewers were involved in the study evaluation, with a third reviewer resolving any discrepancies. Data on study demographics, fatigue simulation methods, landing tasks, outcome measures, and results were extracted from included studies. Eight studies met the inclusion criteria and were included in the analysis. The results of these studies showed that fatigue simulation reduced knee flexion only in two studies and increased hip flexion moment only in two studies during landing among individuals with ACLR. These inconclusive results show that fatigue may negatively impact landing biomechanics in people who have had an ACLR, potentially increasing their risk of re-injury. Fatigue did not affect the landing strategies adopted by individuals who have undergone ACLR. Some of these changes, such as reduced knee flexion and reduced hip flexion moment, could potentially increase the risk of re-injury. However, other changes, such as an increased hip flexion angle, may protect the joint from further injury. More research is needed to better understand the impact of fatigue on landing strategies in this population and to identify strategies that can minimize the risk of re-injury.

***Keywords:*** Anterior Cruciate Ligament Reconstruction, Fatigue, Injury, Landing

## *Introduction*

Anterior cruciate ligament (ACL) reconstruction is a surgical procedure used to repair a torn ACL using a replacement tendon or ligament graft. An estimated 200,000 cases of ACL injury occur in the United States annually, and half of those cases undergo ACL reconstruction (1). Meanwhile, Asian countries like Korea reported approximately 10,248 to 14,500 cases between 2008 and 2016 (2). Even though the patient underwent the reconstruction, the possibility of re-injury or re-rupture remains high, with reported incidence ranging from 20-40% after five years of surgery (3). Several factors are known to be associated with the risk of re-injury, such as age, sex, level of activity, the placement and type of graft, the duration of surgery, and reduced control of the lower limb (4). Consequently, an ACL injury can be significant both financially and in terms of time consumption, as surgery and subsequent rehabilitation can take up to 9-12 months (5). Furthermore, athletes may face economic hardship as an ACL injury can end their career and prevent them from returning to play, adding to the burden of the injury (6).

ACL injuries can be caused by a variety of risk factors, including anatomical, hormonal, environmental, and biomechanical factors. Biomechanical factors such as an imbalance imblance in muscle strength (7, 8), and coordination (9) can be influenced by fatigue, which can increase the risk of injury. Studies have shown that ACL injuries are more likely to occur during the first and last 15 minutes of a game, highlighting the potential impact of fatigue on a player's risk of injury (7, 10). Furthermore, fatigue can lead to decreased knee stability and increased tibial translation, which can contribute to the mechanism of an ACL injury (11). Therefore, it is essential to address factors such as inadequate warm-up, muscle imbalance, and fatigue to reduce the risk of ACL injuries.

Identifying potential risk factors such as abnormal movement patterns, is crucial to preventing injuries. Abnormal movement patterns such as increased hip flexion or excessive hip internal rotation are often found in individuals at high risk for ACL injury (12). Commonly used tools for evaluating landing biomechanics and detecting abnormal movement patterns include the Landing Error Scoring System (LESS) and drop jump landing activities (11-14). These tools can help identify individuals at high risk for ACL injury and allow targeted prevention programs to be introduced.

Studies have shown that fatigue can have negative effects on functional performance and knee stability, as well as exacerbate abnormal movement patterns (7, 15). Despite this, there is a significant research gap in understanding how fatigue impacts landing biomechanics in individuals who have undergone ACL reconstruction. Therefore, this systematic review aims to focus on understanding the effect of fatigue on landing biomechanics among post-ACL reconstructions with respect to the risk of re-injury. This study hypothesizes that fatigue negatively impacts landing biomechanics among post-ACL reconstruction, thus increasing the risk of re-injury.

## Materials and Methods

### Data source and search strategy

The review is conducted according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. The literature was reviewed according to the Population, Intervention, Comparison, Outcome (PICO) framework, in which the participants with ACLR, fatigue stimulation, and landing biomechanics were considered as population, intervention, and outcomes, respectively. An electronic search was systematically conducted, utilizing an advanced approach, across four main databases subscribed to by the university: Web of Science (WoS), EBSCO, Scopus, and Google Scholar.

The article search was carried out between November 2022 and January 2023 to search peer-reviewed articles. The inclusion criteria for this study are landing biomechanics regardless of the outcome measure used, post-ACL reconstruction as participants, and fatigue simulation in their method. Additionally, to avoid any misperception by the reviewers, all the articles were written in English. Those articles are being screened between the year range of 2012-2022. Letters to the editor, symposium publications, conference abstracts, books, expert opinions, critically appraised topics, and literature reviews were excluded from this review.

### Study selection

After the search process, the articles found went through the final stage, which is the eligibility process. During this stage, the researchers thoroughly examined all articles manually to ensure that they fit the criteria of the articles searched for. The first phase is to find keywords related to the title being searched. Based on previous studies, the terms that can be applied to substitute fatigue simulation are fatigue protocol, fatigue, and functional exercise protocol. The words that been used for landing biomechanics are landing mechanic, jump-landing mechanic, jump-landing biomechanics, and landing performance. Both keywords must be combined with Post Anterior Cruciate Ligament Reconstruction/ Post ACL Reconstruction/ Post ACLR/ ACL-reconstructed (Table 1).

### Data extraction and analysis

The authors extracted relevant data from the included literature based on demographic data, fatigue simulation, landing task, outcome measure, and result, which focus on biomechanics, including joint kinetics and kinematics during landing. The retrieved data was then analysed to answer the research questions. Finally, the findings were summarized in a narrative synthesis to bring together the findings of the studies.

### Quality assessment

In this review, the McMaster Critical Review Form – Quantitative Studies was used to rate the quality of the included articles. This tool directs reviewers to consider 16 items of methodological quality related to the purpose of the study, literature review, study design, sample, intervention, results, and study conclusions. If the articles met each criterion outlined in the appraisal guidelines, they received a score of "one" for that item, and if they were not met, they received a score of "zero". The individual item scores were then combined to provide a total score of methodological quality out of 16, with a higher score reflecting higher methodological quality. Once quality scores were calculated, these were divided into five quality categories that were poor (score: 0-8), fair (score: 9-10), good (score: 11-12), very good (score: 13-14), and excellent (score: 15-16) methodological quality, as defined in previous research (16, 17). Two reviewers independently assessed the critical appraisal tool. In the event of a

**Table 1:** The search string

| Database | Keywords used | Date range | Refine result |
|---|---|---|---|
| **Scopus** | TITLE-ABS-KEY (("fatigue simulation" OR "fatigue protocol*" OR "fatigue" OR "functional exercise protocol") AND("landing biomechanics" OR "landing mechanic*" OR "jump-landing mechanic*" OR "jump-landing biomechanics" OR "Landing error scoring system" OR "LESS" OR "landing performance*" OR "single-limb landing" OR "dynamic landing" OR "drop landing" OR "drop jump landing") AND ("Post Anterior Cruciate Ligament Reconstruction" OR "Post ACL Reconstruction" OR "Post ACLR" OR "ACL-reconstructed")) | 2012-2022 | - Full text<br>- English language |
| **EBSCO: MEDLINE Complete** | ("fatigue simulation" OR "fatigue protocol*" OR "fatigue" OR "functional exercise protocol") ("landing biomechanics" OR "landing mechanic*" OR "jump-landing mechanic*" OR "jump-landing biomechanics" OR "Landing error scoring system" OR "LESS" OR "landing performance*" OR "single-limb landing" OR "dynamic landing" OR "drop landing" OR "drop jump landing") ("Post Anterior Cruciate Ligament Reconstruction" OR "Post ACL Reconstruction" OR "Post ACLR" OR "ACL-reconstructed") | 2012-2020 | - Full text<br>- Abstract available<br>- English language |
| **Web of Science (WoS)** | TS= ((fatigue simulation OR fatigue protocol* OR fatigue OR functional exercise protocol) AND (landing biomechanics OR landing mechanic* OR jump-landing mechanic* OR jump-landing biomechanics OR Landing error scoring system OR LESS OR landing performance* OR single-limb landing OR dynamic landing) AND (Post Anterior Cruciate Ligament Reconstruction OR Post ACL Reconstruction OR Post ACLR OR ACL-reconstructed)) | 2012-2022 | - Language: English<br>-Document types: Article |
| **Google scholar** | All in title: fatigue reconstruction anterior OR cruciate OR ligament OR ACL | 2012-2020 | |

disagreement between the two reviewers, a third reviewer was consulted to determine the final McMaster score.

## Results

### Literature search

The literature research yielded 103 possible articles. After eliminating duplicates, the final count was 89 articles. Each article's title and abstract were evaluated in accordance with the inclusion and exclusion criteria, 77 articles were excluded as they did not fit the criteria. The full texts of the remaining ten articles were obtained for a full review to determine whether they were appropriate for this review, where the analysis of the title and abstract alone was not sufficient. The review led to the exclusion of two articles (one article evaluated biomechanics without using a landing task (swinging manoeuvre) and one article did not assess biomechanics, leaving eight articles for inclusion in the review (Figure 1).

All the study subjects have undergone Anterior Cruciate Ligament Reconstruction (ACLR). The time from surgery to participation in the studies ranged from three to more than 12 months. Of the eight studies, four analyzed both males and females, three assessed male-only, and one analyzed female-only. Six studies measured the landing kinetics and kinematics for at least one lower limb joint, with two studies including trunk and pelvic (18, 19). Two studies measured the landing using the LESS (landing Error Scoring System) (11, 13). The kinematic variable includes peak joint angle and joint displacement during the loading phase. Kinematic variables include peak joint moment. All eight studies used pre-fatigue-post-fatigue analysis of landing tasks. Fatigue levels were measured using a few different methods, with studies using Borg's rating of perceived exertion scale, measuring jump height or hop distance, or failure to complete some sequential repetitions. There were a few variations on the type of landing task used and how they were administered. Three studies used double-limb landing (11, 13, 20), while four other studies used single-limb landing (18, 19, 21, 22).

### Risk of bias in included studies

Two reviewers independently assessed the methodological quality of included studies (n=8) using the McMaster Critical Review Form for Quantitative Studies. Discussion with the third reviewer was required to reach an agreement regarding the justification of the sample size calculation (11, 18-20), the use of valid and reliable outcome measures (18-22), and the adequacy of the intervention description (18).

A minimum of 11 and a maximum of 15 were obtained from a total score of 16, representing "good" to "excellent" methodological quality 'good' to 'excellent' (Table 2). There is one study classified as excellent, five studies are very good, and two studies are good.

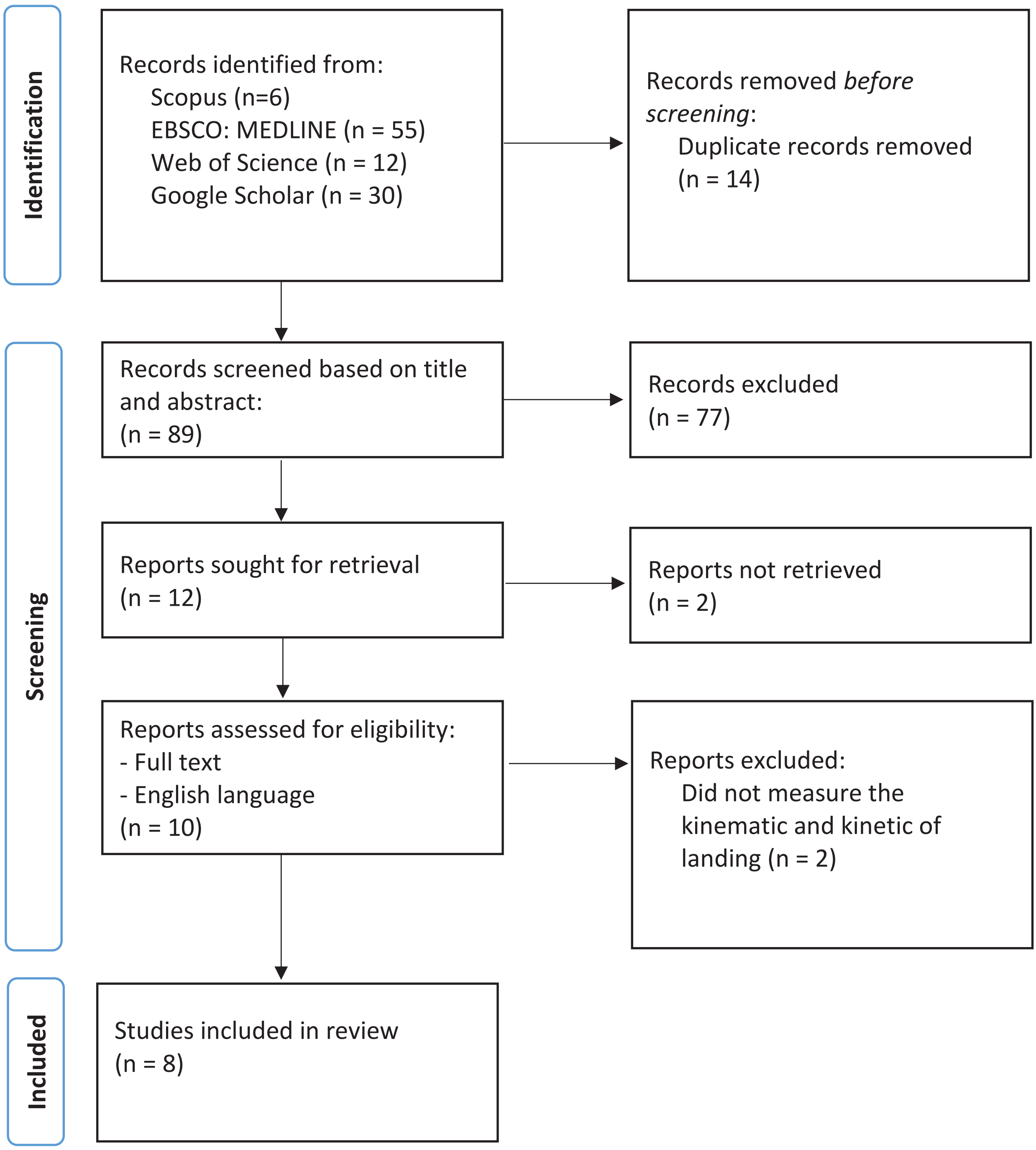


**Figure 1:** PRISMA flow diagram

**Table 2:** Assessment of methodological quality by study

| Study | Webster et al., 2012 (22) | Frank et al., 2014 (20) | Gokeler et al., 2014 (13) | Thomas et al., 2015 (21) | Lessi & Serrão, 2015 (18) | Lessi, Silva, & Serrão, 2018 (19) | Melick et al., 2019 (11) | Alanazi et al., 2021 (23) |
|---|---|---|---|---|---|---|---|---|
| **Study Purpose** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **Literature Review** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **Study Design** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **Blinding** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Sample Description** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **Sample Size** | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 1 |
| **Ethics and Consent** | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| **Validity of Outcomes** | 0 | 0 | 1 | 0 | 1 | 0 | 1 | 1 |
| **Reliability of Outcomes** | 0 | 0 | 1 | 1 | 1 | 0 | 1 | 1 |
| **Intervention Description** | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 |
| **Statistical Significance** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **Statistical Analysis** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **Clinical Importance** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **Conclusions** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **Clinical Implications** | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 0 |
| **Study Limitations** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **Total Score (/16)** | **12** | **13** | **15** | **13** | **13** | **11** | **13** | **14** |
| **Qualitative Descriptor** | **Good** | **Very Good** | **Excellent** | **Very Good** | **Very Good** | **Good** | **Very good** | **Very good** |

### *Kinematic and kinetic data on landing*

The eight studies report on kinematic and kinetic data among participants who have undergone post-ACLR (Table 3). However, two of them used LESS, and those who scored 5 or more were identified as being at a high risk of sustaining ACL injuries (11,13). The joint angle that has been evaluated the most is knee flexion, followed by knee abduction and hip flexion (Table 4). Two out of six studies found a significant decrease in knee flexion angle ($p = 0.01$, $p = 0.004$) after fatigue (18, 21). Meanwhile, in hip flexion angle, only one study found a reduction ($p = 0.01$) (20), one showed an increase after fatigue protocol ($p < 0.05$) (22), and the other three did not find any significant differences (18, 19, 23). The data for knee abduction showed a significant increase in two studies ($p = 0.029$) ($p < 0.05$) (19, 22). Conversely, one study showed a significant reduction ($p < 0.001$) (21), and the other two showed no significant difference (18, 20).

Kinetic data were reported in three studies (20-22). Based on these studies, some changes in hip flexion moment, knee abduction, and knee flexion moment were observed after the fatigue. Two studies showed increases in hip flexion moment after fatigue ($p = 0.04$, $p = 0.05$) (20, 22). Furthermore, a study found a reduction in knee abduction moment after fatigue ($p = 0.003$) (21).

**Table 3:** Summary of study

| AUTHOR | PARTICIPANT | FATIGUE SIMULATION | LANDING TASK | OUTCOME MEASURE | RESULT (POST FATIGUE) |
|---|---|---|---|---|---|
| **Alanazi et al., (2021) (23)**<br>The effects of a high-intensity exercise bout on landing biomechanics post anterior cruciate ligament reconstruction: a quasi-experimental study | - 36 males<br>- Age: 18 and 35<br>- soccer players<br>- 1 year but not more than 10 years post ACLR<br>- Patellar tendon autograft, (n = 10)<br>- hamstring autograft (n=7)<br>- allograft (n=1) | - High-intensity exercise 30-s Wingate anaerobic protocol | - Landing maneuvers | - Kinematic: Ankle dorsiflexion, knee flexion, and hip flexion peak angle<br>- Kinetic: Plantar flexion, knee extension, and hip extension peak joint moment. | - No significant differences in all variables during the post-exercise landing compared to the pre-exercise landing for both groups. |
| **Melick et al., (2019) (11)**<br>Fatigue affects the quality of movement more in soccer players than in healthy soccer players | - 33 males<br>- Age: 18 and 30<br>- Recreational soccer players<br>- 12.4 months post ACLR | - 1 hour soccer-specific field training session (Soccer specific drills, exercises focussing on speed, stability, and coordination) | - A double-leg CMJ | - LESS | - LESS scores were significantly higher in ACLR ($p = 0.026$)<br>- LESS scores increased significantly more in ACLR compared to healthy ($p<0.001$) |
| **Lessi et al., (2018) (19)**<br>Comparison of the effects of fatigue on kinematics and muscle activation between men and women after anterior cruciate ligament reconstruction | - 7 Males, 7 Females<br>- Age: 18-35 years<br>- Recreational athletes<br>- ≥ 12 months post ACLR<br>- Patellar tendon / Hamstring tendon graft | - 10 single-limb squats (90° knee flexion) + 2 max vertical jump + 20 steps (Steps' height 31 cm)<br>- Until reduced hop distance by 20%- Borg scale | - Single limb landing from 31 cm drop maximal vertical jump | - Kinematic: Trunk, pelvic, hip, knee joint peak angles | - Peak knee valgus of the reconstructed limb of female athletes was greater than the observed in the non-reconstructed limb.<br>- No significant different in other angles for both groups. |
| **Lessi & Serrão, (2015) (18)**<br>Effects of fatigue on lower limb, pelvis and trunk kinematics and lower limb muscle activity during single-leg landing after anterior cruciate ligament reconstruction | - 26 Males and 14 Females<br>- Age: 25.1 ± 4.2<br>- Recreational athletes<br>- ≥ 12 months post ACLR<br>- Patellar tendon / Hamstring tendon graft | - 10 squats (90° knee Flexion) + 2 max vertical jump + 20 steps (Steps' height 31 cm)<br>- Until reduced jump height by at least 20 % | - Single limb landing from 31 cm drop maximal vertical jump | - Kinematics: knee flexion and abduction, hip flexion, adduction, and internal rotation, contralateral pelvic drop and trunk flexion, and ipsilateral trunk lean | - Peak knee flexion significantly decreased<br>- The maximum contralateral pelvic drop significantly increased<br>- Peak trunk flexion significantly inceased |
| **Thomas et al., (2015) (21)**<br>Effects of Neuromuscular Fatigue on Quadriceps Strength and Activation and Knee Biomechanics in Individuals Post-Anterior Cruciate Ligament Reconstruction and Healthy Adults. | - 15 Males and 18 Females<br>- Age: 21.41 ± 4.73<br>- 7 -10 months post ACLR<br>- Patellar tendon/ semitendinosus/ gracilis tendon graft | - 8 squats (90° knee Flexion) + 3 dynamic landings<br>- Until no longer perform 5 consecutive repetitions to 90° of knee flexion without assistance nor consistently reach the force platform during landing | - Single limb landing from 17 cm drop with lateral hop | - Kinematics: knee joint angle at initial contact and peak angle<br>- Kinetic: Knee peak joint moment | - Peak knee flexion and abduction angle significantly decreased<br>- The knee abduction moment significantly decreased |

**Table 3:** Summary of study (continued)

| AUTHOR | PARTICIPANT | FATIGUE SIMULATION | LANDING TASK | OUTCOME MEASURE | RESULT (POST FATIGUE) |
|---|---|---|---|---|---|
| **Frank et al., (2014) (20)** Neuromuscular Fatigue Alters Postural Control and Sagittal Plane Hip Biomechanics in Active Females With Anterior Cruciate Ligament Reconstruction | - 14 Females<br>- Age: 19.6±1.5<br>- Physically active<br>- 3-11 months post ACLR<br>- Patellar tendon, Hamstring graft | - Repetitive squats (0°-60° knee Flexion) with barbell (30% of participant's weight)<br>- 25 squats/min<br>- Until no longer able to complete fatigue protocol-Borg scale | - Double limb landing from 30 cm drop with maximal vertical jump | - Kinematic: Hip and knee joint peak angle at initial contact and laoding, joint displacement<br>- Kinetics: Hip and knee peak joint moments | - Hip flex angle significant decreased in initial contact<br>- Hip flex displacement significantly increased<br>- Hip flex moment significant increased |
| **Gokeler et al., (2014) (13)** Effects of Neuromuscular Fatigue on Quadriceps Strength and Activation and Knee Biomechanics in Individuals post Anterior Cruciate Ligament Reconstruction and Healthy Adults | - 11 Males, 11 Females<br>- Age: 27.4 ± 9.6<br>- 10±24 months post ACLR<br>- Hamstring tendon graft | - Repetitive squats (90° knee Flexion) + 2 reps CMJ<br>- Until reduced jump height by 30% | - Double limb landing from 30 cm drop with maximal vertical jump. | - LESS | - LESS between pre-fatigue and fatigue conditions showed no significant differences between the groups (p=0.165).<br>- Frequency of error:<br>- Knee flexion at initial contact (ACLR 90%, Control 30%),<br>- Extension on the hips (ACLR 60%, Control 20%)<br>- Knee valgus at initial contact (ACLR 70%, Control 90%)<br>- Lateral trunk flexion (50% ACLR, Control 0%)<br>- Asymmetrical foot contact (ACLR 60%, Control 10%)<br>- Maximal knee valgus (ACLR 90%, Control 100%). |
| **Webster et al., (2012) (22)** Effect of Fatigue on Landing Biomechanics after Anterior Cruciate Ligament Reconstruction Surgery | - 26 Males<br>- Age: 27.0 ± 5.9<br>- > 12 months post ACLR<br>- Hamstring tendon graft | - 10 squats (90° knee Flexion) + 2 vertical jumps + 10 drop landings (5 right leg, 5 left leg)<br>- Until reduced jump height by 20% / No longer able to complete fatigue protocol-Borg scale | - Single limb landing from 30 cm drop | - Kinematics Hip, knee, ankle joint peak angle<br>- Kinetics: Hip and knee peak joint moment | - Peak hip flexion decrease<br>- Peak hip abduction increase<br>- Peak knee abduction increase<br>- Peak knee internal rotation increase<br>- Peak ankle dorsiflexion decrease<br>- Peak Knee flexion and adduction moment decrease<br>- Hip flexion moment increase |

Abbreviation: LESS; Landing Error Scoring System, CMJ; countermovement jump, ACLR; anterior cruciate ligament reconstruction

**Table 4:** Summary of kinematic of lower limb

| Author | Trunk | | Pelvic | Hip | | | | Knee | | | Ankle |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Flexion | Ipsilateral trunk lean | Contralateral drop | Flexion | Abduction | Adduction | Internal rotation | Flexion | Abduction | Internal rotation | Dorsiflexion |
| **Alanazi et al., (2021) (23)** | - | - | - | ≠ | - | - | - | ≠ | - | - | ≠ |
| **Melick et al., (2019)(11)** | | | | | | | | | | | |
| **Lessi et al., (2018) (19)** | ≠ | ≠ | ≠ | ≠ | - | - | - | ≠ | **↑(female) ≠ (male)** | - | - |
| **Lessi & Serrão, (2015) (18)** | ↑ | ≠ | ↑ | ≠ | - | - | - | ↓ | ≠ | - | - |
| **Thomas et al., (2015) (21)** | - | - | - | - | - | - | - | ↓ | ↓ | - | - |
| **Frank et al., (2014)(20)** | - | - | - | ↓ | - | ≠ | ≠ | ≠ | ≠ | ≠ | - |
| **Gokeler et al., (2014) (13)** | | | | | | | | | | | |
| **Webster et al., (2012) (22)** | - | - | - | ↑ | ↑ | - | ≠ | ≠ | ↑ | ↑ | ↓ |
| **Total** | **2** | **2** | **2** | **5** | **1** | **1** | **1** | **6** | **5** | **1** | **2** |

*Note.* Symbol: ↑= Increase; ↓= Decrease; ≠= Not significant

## *Discussion*

The primary aim of this systematic review is to provide support for therapists who work with athletes after ACL reconstruction by examining the effect of fatigue on landing biomechanics. The study concludes that post-ACL reconstruction patients show no reduction in knee and hip flexion angle during fatigue compared to healthy individuals, inconsistency in the LESS score, and a greater hip flexion moment during landing after fatigue simulation.

Most studies examining the angle of the hip and knee during landing focuses on determining whether the landing is stiff. This is because stiff landings can affect shock absorption, which can lead to increased compressive force in the joints. Previous study have found that stiff landings result in poor energy dissipation, increasing the risk of lower extremity injury by allowing non-contractile ligaments to absorb more landing energy (24). Meanwhile, a stiff landing could also increase anterior tibial translation, which can cause ACL injury (25). Additionally, the hip angle is related to the knee angle during landing. Abnormal motion of the femur can directly affect the kinematics of the tibiofemoral joint (26). To be more precise, Hashemi et al. (27) proposed that restricted hip flexion during landing may contribute to ACL injury risk by increasing anterior tibial translation.

In this systematic review, the knee flexion angle during landing was measured in six studies. Only two of these studies found a significant reduction in knee flexion angle among individuals who had undergone ACL reconstruction compared to healthy individuals during a fatigued state. Similarly to hip flexion, two studies showed significant effects but were inconsistent, and the other four did not find significant differences. These indicated that post-ACLR did not differ as healthy (19,20,22,23), possibly due to altering strategy techniques that improve soft landing by increasing the hip, knee, and ankle flexion angle (23). Another reason individuals with ACLR tend to land softly is by increasing hip flexion to reduce the demand on the knee flexion angle. This strategy was shown in Webster et al. (22) among 15 men who had undergone ACLR using a hamstring graft. The author mentioned that increased hip flexion might assist the knee in restricting excessive loss of control at the knee joint. Another reason could be the post-ACL rehabilitation protocol, which includes education in proper landing techniques.

Two studies evaluated the risk of re-injury of the ACL among the post-reconstruction using the LESS measurement tool. The lower the total score, indicate the lower the risk of ACL injury. However, both studies show contradictory results to each other. This inconsistency could be due to the different fatigue simulations that have been used. A study by van Melick et al. (11) used a 1-hour soccer-specific fatigue simulation. Meanwhile, Gokeler et al. (13) used repetitive squats (90° knee flexion) plus two repetitions CMJ. The 1-hour soccer-specific simulation is a long-duration fatigue simulation compared to the repetitive squad simulation. Although both simulations induced fatigue, the physiological changes could vary or be different. Furthermore, the muscle used in a soccer-specific simulation that involves some activities that mimic real soccer matches differs from a simulation of a repetitive squad. Therefore, although we are prone to believe that post-ACLR increases the risk of re-injury during fatigue, more studies should be conducted to obtain a conclusive statement on this issue.

A kinetic measurement found a greater hip flexion moment in the post-ACLR group compared to the healthy group during a fatigued state (20,22). The hip flexion moment can be defined as the torque produced by the hip extensors during landing by slowing the hip flexion to control and stabilizing the femoral adduction and internal rotation. Hip extensors, specifically the gluteus maximus, will contract eccentrically to control the femur (28). According to Leppänen et al. (29) an increase in the peak external hip flexion moment was not associated with ACL injury by restricting the dynamic knee valgus during landing, the main causative factor of ACL injury. Thus, it shows that post-ACLR demonstrated a good adaptive strategy in the kinetic aspect in reducing the risk of re-injury. Furthermore, a study showed lesser peak knee flexion peak moment in the post-ACLR group, which could reduce the risk of ACL re-injury by limiting quadriceps activity and thus prevent excessive anterior tibial translation forces (22).

All studies in the review show inconsistent results in joint kinematic and kinetic after fatigue simulation compared to before fatigue between the post-ACLR and control groups. Therefore, the hypothesis of this study was rejected that smaller knee and hip flexion after fatigue simulation, indicating that post-ACLR patients might have a high tendency for ACL re-injury after fatigue. These findings showed that fatigue simulation could not detect the risk of re-injury but may still provide valuable information to increase the confidence of athletes before returning to play.

The main limitation of this review was the varied landing task used to assess the movement pattern. The distinct landing base of support elicited in each task may influence overall movement strategies and the forces imposed on the lower extremity. Another limitation is that the included population have different types of graft, which may have affected the result. This review did not focus on a specific type of graft, making it impossible to provide recommendations on the effect of different types of graft on landing strategies after fatigue.

## Conclusion

Fatigue does not appear to affect the biomechanics of the lower extremities during landing tasks among post-ACLR. Some alterations that occur with fatigue, such as lower knee and hip flexion angles, may increase the risk of ACL injury, which has been identified in previous studies as risk factors for ACL injury. Other alterations reported, such as greater hip flexion moment, may serve to protect the joint from an ACL injury. Therefore, fatigue elements should be included in landing tasks as a return to sport assessment, as they may provide important information to evaluate the risk of re-injury among ACLR athletes before returning to play.

## Acknowledgement

The authors acknowledge the contributions of research assistance, and all the individuals that assist in completing this article.

## Competing interests

The authors would like to declare that there is no conflict of interest in conducting and publishing the present paper.

## Financial support

The authors received no financial support for the research, authorship or publication of this article.

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