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Systematic Review

Interlimb Asymmetry of Vertical Ground Reaction Force as a Risk Factor for Re-injury and Knee Osteoarthritis Following Anterior Cruciate Ligament Reconstruction: A Systematic Review

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ABSTRACT

Background: Anterior cruciate ligament (ACL) reconstruction is performed as the gold standard of care for patients with ACL rupture. ACL reconstruction provides successful clinical outcomes, however, it cannot repair faulty lower limb mechanics. The loading asymmetry between right and left limbs during movement is often used to measure the effectiveness of surgical interventions and the potential risks of re-injury.

Objectives: This study aims to evaluate the interlimb asymmetry of vertical ground reaction in patients with ACL reconstruction.

Methods: An online search was done in the following databases: Science Direct, Scopus, PubMed, and Google Scholar. Then, studies from 2000 to 2022 were extracted. Selected articles were screened in a 4-step process according to the inclusion and exclusion criteria. Two researchers evaluated the methodological quality of the articles with the modified Downs and Black checklist. Finally, studies were classified into 3 categories: low (< 40%), medium (40% - 69%), and high quality (≥ 70%).

Results: Finally, 9 studies were selected for the systematic review. The average methodological quality was 68.33% (range 54% - 80%), which shows the medium quality of the studies. A total of 4 articles had high methodological quality and 5 articles had medium quality. The results of 8 studies reported asymmetric vertical ground reaction force after ACL reconstruction. Only 1 study reported no significant difference in the asymmetrical vertical ground reaction force.

Conclusion: Patients undergoing ACL reconstruction have knee flexion limitation and decreased quadriceps muscle strength. Eventually, this mechanism of energy absorption by the active tissue decreases, and mainly the shock absorption by the passive tissue increases. As a result, this mechanism leads to ACL re-injury and tibiofemoral joint cartilage damage.

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1. Introduction

Anterior cruciate ligament (ACL) rupture is the most rampant lesion of all knee ligaments that mostly occurs non-contact [1, 2]. The annual prevalence of ACL injury in the United States is reported to be 250 000. Annually, 100 000 ACLR surgeries are reported in the US [3] any alterations in co-contraction might be a risk factor for ACL injury. The most common autografts used for ACLR are the bone-patellar tendon-bone and the semitendinosus-gracilis grafts [4]. The goal of surgery is to restore knee constancy and enhance the chances of returning to sport and activity level before the injury, which is possible 6 to 12 months after ACLR [5-9].

ACL re-rupture is one of the most common problems after ACLR. Almost 30% of patients sustain an ACL re-injury within 24 months of the initial injury [10]. One of the influencing factors in ACL re-rupture is the asymmetry in the lower extremity biomechanics, which is evident 6 months after surgery [11, 12]. Studies have reported that patients who have asymmetry in biomechanical variables after ACLR are at least 3 times more susceptible to ACL re-injury [11]. Asymmetry in mechanical behavior between the right and left limbs during movement is often used to measure the effectiveness of surgical interventions and the potential risks of re-injury [13]. Although ACLR provides successful clinical outcomes, it cannot repair faulty lower limb mechanics [14]. In this regard, patients with ACLR show decreased knee flexion, extensor moment, and vertical ground reaction force (vGRF) [15]. As a result, these compensatory mechanisms correlate with an increased risk of secondary ACL rupture [2, 12]. Therefore, identifying modifiable factors that predict ACL re-injury is essential to diminish the risk of re-injury and subsequent consequences [10, 11].

The inverse dynamics method is used to measure the kinetic asymmetry of the knee in patients with ACLR by measuring the motion capture and ground reaction force (GRF) [5, 7]. From the perspective of inverse dynamics, GRF is the crucial component in calculating knee kinetics [5]. As a result, the kinetic asymmetry of the knee may be predicted by GRF asymmetry [5]. Accordingly, one of the qualitative methods for evaluating the symmetry of lower limb loading is through vGRF measurement [1]. Lower limb asymmetry in patients with ACLR, which can be detected by the asymmetry between the right and left legs, is defined by the difference between the limbs of more than 10% or a symmetry index of less than 90 [1].

Since movement symmetry is crucial, providing a comprehensive and reliable method to achieve movement symmetry is a major concern for physicians and researchers [16]. Therefore, the lower limb loading symmetry after ACLR during rehabilitation has been considered by rehabilitation specialists [17]. The study of GRF symmetry in patients with ACLR seems important and necessary [16]. In addition, knowledge of load symmetry may be effective in developing screening methods that may diagnose the risk of ACL re-injury and compensatory strategies during unilateral and bilateral movements following ACLR [17]. Despite the above-mentioned issues, there is limited scientific documentation in the field of loading asymmetry after unilateral ACLR.

Objectives: This study aims to evaluate the inter-limb asymmetry of vGRF in patients with ACLR.

2. Methods

Study protocol

The present systematic review study has been designed and compiled following the PRISMA 2009 guidelines [18]. Since the PRISMA statement is designed for review and meta-analysis studies, we have considered articles that are only related to review studies [18]. We conducted a comprehensive search on PROSPERO that finally found a similar review study.

Search strategy

Two researchers independently used the following online databases: PubMed, ScienceDirect, Springer Link, Scopus, and MEDLINE. These databases were searched for articles from 2000 to 2022. Furthermore, the Google Scholar citation database was used as a complementary search engine. An updated search was conducted on April 01, 2022, to identify newly published articles. The PICO (population, intervention comparison, and outcome) framework was used to determine the keywords. In the present study, the PICO was defined as follows: "P" as patients with ACL rupture, "I" as ACL reconstruction, "C" as comparison with non-injured limbs, and "O" as vGRF symmetry index. For a comprehensive search, the researchers used the keywords related to the PICO index, common keywords, and MeSH terms (Table 1). Meanwhile, the operator "OR" was used to combine the synonyms, and "AND" was used to combine the categories.

Eligibility criteria

Two researchers independently screened the extracted studies according to the following inclusion and exclusion criteria.

Inclusion criteria

The inclusion criteria comprised the following items:

1: Articles published in English;

Cross-sectional studies;

Articles that have compared the vGRF symmetry index between non-surgical and surgical limbs in patients with ACLR;

Sample size of studies related to active people and athletes;

The sample size does not have upper and lower limb deformity studies.

Exclusion criteria

The exclusion criteria included the following items:

2: letters, conference proceedings, case reports, and cadaveric studies;

Non-English articles;

Clinical trials;

Reviews articles;

Comparison of patients to ACLR with healthy individuals.

Screening process

Firstly, the extracted studies were transferred to the Mendeley Reference Management software and were classified alphabetically. Secondly, duplicate articles were automatically eliminated by the software. Thirdly, the titles and abstracts of the articles were screened based on the inclusion and exclusion criteria. Fourthly, the full text of the articles that did not provide sufficient information on their titles and abstracts were reviewed. As a result, studies that met the eligibility criteria were selected for the systematic review. In case of disagreement about the eligibility of the studies, a meeting was held between the researchers to make a final decision.

Methodological quality assessment and data extraction

The methodological quality evaluation by the two researchers was independently done through the Downs and Black checklist. The Downs and Black checklist has a good intra-rater (r=0.88) and inter-rater (r=0.75) reliability [19]. The modified checklist consists of 15 questions which are classified as follows: report (questions 1, 2, 3, 5, 6, 7, and 10), external validity (questions 11 and 12), internal validity (questions 16, 18, and 20), and confounder internal validity (items 21, 22 and 25) [18]. The scoring scale is as follows: 1=yes (Y), 0=no (N), and (U)=unable to determine. With the exception of question 5, the letters "Y" (complete=2), "P" (partial=1), and "N" (no=0) were defined as well. Finally, the quality of the articles were classified into 3 categories: low (< 40%), medium (40%-69%), and high quality (≥ 70%) [18]. Two researchers independently extracted the selected articles' demographic data (authors, year of publication, purpose, sample size, and results). Furthermore, the descriptive characteristics of the participants (age, height, body weight) were extracted.

3. Results

Study selection

Overall, 457 potentially relevant papers were extracted, of which 154 duplicate articles were removed. Then, the two researchers screened the remaining 303 papers based on the title and abstract, which led to the omission of 245 papers that did not meet the inclusion criteria. The authors investigated 58 papers in full text and omitted 49 articles because they did not meet at least one of the inclusion criteria. Finally, 9 studies [2, 5, 10–12, 20–23] met the eligibility criteria and were included in this review as shown in Figure 1.

Study characteristics

Table 2 reports the demographic information of the studies. There was a total of 317 patients (women=159 / men=158) with ACLR in 9 study (age: 18 years, height: 174 cm, and weight: 68 kg). The patients were tested on average 9 months after the surgery. The vGRF data were collected using force plates with 100 to 1920 Hz sampling frequency. The symmetry index was assessed during daily tasks and sports, such as sit-to-stand, walking, jumping-landing, squats, and side-cutting.

Table 1. Keywords

Category	Keywords
Biomechanics	Kinetics (MeSH), Vertical loading, Ground reaction force parameters, Asymmetry, Symmetry, Vertical ground reaction force
Task	Running (MeSH), Gait (MeSH), Locomotion (MeSH), Ambulation (MeSH), Walking (MeSH), Squatting (MeSH), Weight-Bearing (MeSH),
Knee	Anterior cruciate ligament (MeSH), Anterior cruciate ligament reconstruction (MeSH), Anterior cruciate ligament injuries (MeSH), Ligament (MeSH)

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Methodological quality

The average score of the methodological quality of studies was 68.33% (range 54% - 80%), which showed the medium quality of the selected studies. A total of 44.44% of studies (n=4) had high methodological quality [10, 12, 21, 22] and 55.56 % of the studies (n=5) had medium quality [2, 5, 11, 20, 23] (Table 3). The strength of the quality studies was reported in particular. All studies showed poor external reliability scores (question 12). Also, most studies on the internal validity of the confounder were poor partly. No study that reported patients from the same period was employed.

Symmetry in vGRF

Overall, the results of 4 studies with medium and 4 studies with high quality reported asymmetric vGRF after ACLR [2, 5, 10–12, 21–23]. Only 1 study with medium quality reported no significant difference in symmetry in vGRF [20].

4. Discussion

This study investigated the vGRF symmetry in patients with ACLR. The results of this systematic review demonstrated that in patients with ACLR, there is a vGRF asymmetry between the surgical and the non-injured limb. vGRF is reduced in the ACLR limb compared to the healthy limb. Several factors affect the vGRF asym-

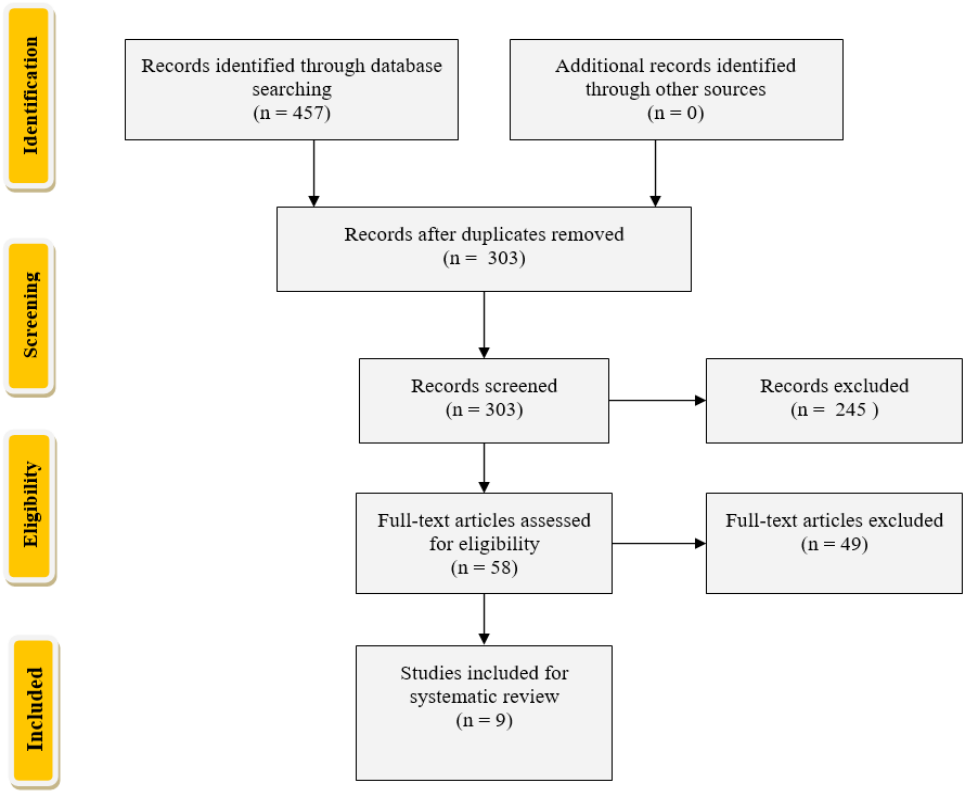

Figure 1. PRISMA flowchart for the study selection process

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Table 2. Demographic information

Author / Year	Purpose	Task	Outcome
Dai et al. 2014 [5]	Investigating the relationship between sagittal plane knee kinetic asymmetries and GRF asymmetries	Stop-jump and side-cutting	Patients with ACLR showed asymmetry in vGRF.
Labanca et al. 2016 [23]	Examining asymmetrical lower extremity loading after ACLR possibly predicting asymmetrical lower extremity loading at the time of return to sport	Sit-to-stand and vertical jump	Patients with ACLR showed asymmetrical lower extremity loading.
Renner et al. 2018 [2]	Investigating differences in movement and loading patterns across time and between limbs 12 months post-ACLR	Stop-jump	Patients with ACLR showed vGRF asymmetry between the surgical and nonsurgical limbs.
Pfeiffer et al. 2018 [10]	Determining the associations in peak knee biomechanics and limb-symmetry in patients with ACLR	Gait and jump-landing	Patients with ACLR demonstrate high-involved limb asymmetries during jump-landing.
Aizawa et al. 2019 [20]	Examining the relationship between asymmetrical landing impact and quadriceps strength after ACLR	Jump-landing	No significant difference was reported in limb symmetry index, but the vGRF of the ACL-reconstructed limb tended to be higher than the non-ACLR.
Ithurbrn et al. 2019 [21]	Examining double-legged and drop vertical jump (DVJ) landing and single-legged drop-landing symmetry changes 2 years after ACLR	Double-legged and single-legged and drop landing	There is an asymmetric loading after ACLR.
Taj Dini et al. 2021 [11]	Examining the relationship between kinesiophobia and asymmetry of vGRF and lower-extremity muscular activity after ACLR	Gait	Patients with ACLR showed an increase in asymmetry in the second peak of vGRF.
Peebles et al. 2021 [12]	Relationship between lower extremity biomechanics with ACLR	Bilateral landing and bilateral squatting	Patients who have undergone an ACLR continue to offload their surgical limbs.
Chan et al. 2022 [22]	Determine if limb loading throughout the day differs between individuals 3 months post-ACLR	Sit-to-stand	Asymmetrical loading quantified in the laboratory is practiced throughout the day in patients post-ACLR.

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N: Number; F: Female; M: Men; ACLR: Anterior Cruciate Ligament Reconstruction; vGRF: Vertical Ground Reaction Force.

metry: decreased quadriceps muscle strength, altered neuromuscular function, or fear of re-injury [5, 15, 24].

The GRF torque arms are partially affected by the knee flexion angle. Increasing knee flexion commonly enhances the GRF torque arm to the center of the knee joint, and decreases the knee flexion which can lead to increased kinetic asymmetry in the knee joint [5]. In patients with ACLR, fear of movement has been suggested as a factor in utilizing a biomechanical compensatory strategy [11, 24]. Patients with ACLR limit knee flexion to reduce loading on the ACL to avoid injury [24–26]. This inadequate mechanical loading leads to quadriceps muscle atrophy [27]. The quadriceps muscles, as the primary shock absorber, contract eccentrically during the weight acceptance phase to reduce vGRF action in the lower limbs [15, 28].

Evidence suggests that quadriceps muscle strength is associated with vGRF and loading rates in patients with ACLR [15, 29]. Decreased ability of the quadriceps muscles to absorb GRF leads to a stiff landing strategy [28]. This mechanism may reduce the attenuation of mechanical energy through the knee joint active tissue and expose the passive anatomical structures to higher forces, resulting in re-injury of the ACL [20, 28, 30]. In this regard, studies have reported that a soft landing by increasing flexion combined with optimal quadriceps muscle strength is a mechanism for reducing shock [31, 32]. Therefore, quadriceps muscle weakness in the surgical limb cannot tolerate or respond to GRF to maintain an optimal movement pattern [32]. As a result, altered movement strategies in patients with ACLR are somewhat effective in ACL re-injury [5].

Table 3. Methodological quality

Authors and Year of Publication	Reporting							External Validity		Internal Validity - Bias			Internal Validity - Confounding			Total	Percent (%)	Quality
	1	2	3	5	6	7	10	11	12	16	18	20	21	22	25			
Dai et al. 2014 [5]	Y	Y	Y	P	Y	Y	N	N	N	Y	Y	Y	N	N	N	9	60	M
Labanca et al. 2016 [23]	Y	Y	Y	P	Y	N	N	Y	U	Y	Y	Y	Y	U	N	10	67	M
Renner et al. 2018 [2]	Y	Y	Y	P	N	N	Y	N	N	Y	Y	Y	N	N	N	8	54	M
Pfeiffer et al. 2018 [10]	Y	Y	Y	P	Y	Y	Y	Y	N	Y	Y	Y	Y	U	N	12	80	H
Aizawa et al. 2019 [20]	Y	Y	Y	P	Y	Y	Y	N	N	Y	Y	Y	N	N	N	9	60	M
Ithurbrn et al. 2019 [21]	Y	Y	Y	P	Y	Y	Y	Y	N	Y	Y	Y	Y	U	N	11	74	H
Tajdini et al. 2021 [11]	Y	Y	Y	N	Y	Y	Y	N	N	Y	Y	Y	U	U	N	9	60	M
Peebles et al. 2021 [12]	Y	Y	Y	P	Y	Y	Y	Y	N	Y	Y	Y	Y	U	N	12	80	H
Chan et al. 2022 [22]	Y	Y	Y	P	Y	Y	Y	Y	U	Y	Y	Y	Y	U	N	12	80	H

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On the other hand, the results of the studies showed that changes in knee mechanics after ACLR may create knee osteoarthritis by altering cartilage loading patterns in the surgical knee [10]. By reducing knee flexion and consequently reducing the active shock absorption capacity through quadriceps muscle eccentrically contraction, the contact area of the tibiofemoral joint decreases during loading and the shock absorption in passive tissue increases, especially for cartilage in areas not accustomed to such loading [10, 25, 33]. As a result, this mechanism may increase the harmful pressure in the tibiofemoral cartilage contact area and accelerate the development of knee osteoarthritis [34]. In addition, patients with ACLR perform a loading/unloading compensatory mechanism during movement aimed at unloading the surgical limb [12]. Unloading behavior can be a compensatory strategy performed by patients to protect the healing graft [12].

The mechanism of unloading and protection of the injured knee may gradually increase the support phase and loading on the healthy limb, which increases the risk of knee osteoarthritis [31, 35] compared with healthy controls. In this regard, studies reported that patients with knee osteoarthritis are exposed to severe and frequent lower limb loading before the stage of osteoarthritis [36]. As a result, overloading and underloading tissue may have negative effects on knee joint health [34].

Clinical implications

This study provides a new insight for rehabilitation and orthopedic physicians. The vGRF symmetry assessment can be used as a method to identify compensatory strategies during unilateral and bilateral movements after ACLR or during the rehabilitation period [7]. Therefore, physicians must apply rehabilitation interventions during the end stage of ACL rehabilitation that focus on strategies for kinetics symmetric between the limbs [36] Managing fear of movement and gait retraining through the use of feedback mechanisms with a gradual increase in loading along with interventions, such as strength training for people undergoing ACLR, may be a new treatment option with improved long-term outcomes post-ACLR [2, 11, 12, 24]. As a result, patients undergoing ACLR may need different treatments during rehabilitation with more emphasis on knee load symmetry [38].

Study limitations

There are several limitations to the literature in this study that affect the strengths of the findings. First, the effect of psychological factors on the kinetic asymmetry of the limb has not been considered in some studies [23]. Second, in some studies, the statistical population included men and women; therefore, the characteristics of the results based on gender are unknown [20]. Third, the low sample size of some studies makes it difficult to generalize the results [11]. Fourth, the nature of cross-sectional studies does not allow an understanding of the

cause-and-effect relationships [11]. Therefore, it is recommended that researchers 1) examine vGRF symmetry in prospective studies on bigger sample sizes with gender segregation and 2) investigate the effect of psychological factors on vGRF asymmetry.

5. Conclusion

The results of the present study show that patients undergoing ACLR adopt abnormal movement patterns, such as decreased knee flexion due to factors, including fear of movement and decreased quadriceps muscle strength. With decreasing knee flexion and weakness of quadriceps muscles, energy absorption by active tissue decreases, and mainly shock absorption by passive tissues increases. As a result, this mechanism leads to re-injury of the ACL graft tissue and tibiofemoral joint cartilage damage.

Ethical Considerations

Compliance with ethical guidelines

There were no ethical considerations to be considered in this research.

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Authors' contributions

All authors equally contributed to preparing this article.

Conflict of interest

The authors declared no conflict of interest.

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