Understanding the Impact of ACL Reconstruction on Normalization Methods and Identifying Predictive Factors of Landing Symmetry

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Abstract

ACL injuries are one of the most common knee injuries[1–4], occurring in 1 out of every 3500 individuals in the Unites States[5]. Over 200,000 ACL reconstruction surgeries occur each year[2,6–9]. Following a primary ACL tear, the likelihood of experiencing a second tear increases to 10-25%[3,10–15]. This rate of reinjury can fluctuate based on activity level[3,10,16–18]. Athletes returning to sports, specifically, have higher retear rates[16,17]. Load symmetry has been used to assess performance and risk in patients with ACL reconstruction (ACLR)[19–22]. While there are ample amounts of research investigating this injury, there are gaps within the literature that need to be addressed to continue to better understand ACL injuries. When analyzing data from patients with ACLR, there are common assumptions used by many different scientists that may influence the way data can be interpreted[23]. Additionally, previous literature has identified influences of psychological components on injury risk of a primary ACL injury and throughout rehabilitation[24–27], but there is minimal knowledge on how these components can be used to predict second ACL risk factors. Therefore, the purpose of this study was to investigate the assumptions made when data is being analyzed for this clinical population, and if psychological components can be used to predict risk factors for a second ACL injury. The common data analysis assumption tested in this study was percent stance normalization because this method has not been validated to produce accurate data in patients with ACLR. Percent stance was then compared to a time independent method. In a cohort of healthy controls and patients with ACLR, using symmetry to assess loading differences, there were differences found in symmetry metrics commonly used to assess performance, including peak impact force (PIF), loading rate, impulse, and time to peak. These results show a need to revisit common assumptions used to analyze data when including patients with ACLR. Future studies could conduct a similar analysis in different clinical populations. Following this analysis, psychological components, ACL-RSI, M-LOC, and GAD-7 surveys, and physical factors were combined in a regression model to predict landing symmetry. In both unilateral and bilateral landings load asymmetry has been identified as a risk factor for reinjury[28]. Backwards multivariate regression models were created for three unilateral and two bilateral landing tasks. Each model included both one or more psychological components and previously identified risk factors in the final factors to best predict PIF. However, the only models that could explain an adequate amount of variance were the unilateral landing models (single hop R^2= .351, triple hop R^2= .423). These models show the importance of including psychological components and previously researched risk factors to best understand reinjury risk in patients with ACLR. The results from this study indicate ways to potentially improve analysis of patients with ACLR. When investigating this population, testing common assumptions made for healthy controls and inclusion of psychological components when assessing performance may improve interpretation and can help clinicians better identify risk for patients with ACLR.

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General Audience Abstract

ACL injuries are one of the most common knee injuries[1–4], occurring in 1 out of every 3500 individuals in the Unites States[5]. Over 200,000 ACL reconstruction surgeries occur each year[2,6–9]. Following a primary ACL tear, the likelihood of experiencing a second tear increases to 10-25%[3,10–15]. Athletes returning to sports can have higher retear rates[16,17]. Differences in how load is distributed between the injured and non-injured limbs have been used to assess movement and reinjury risk in patients with ACL reconstruction (ACLR)[19–22]. Symmetry is used to quantify the load differences. While there are ample amounts of research investigating this injury, there are still gaps that need to be addressed to continue to better understand ACL injuries. When looking at data from patients with ACLR, there are common assumptions used by many different scientists that may influence the way data can be interpreted[23]. Additionally, previous literature has identified psychological components, such as beliefs and emotions, can influence injury risk of and recovery following a primary ACL injury[24–27]. However, there is minimal knowledge on how these components can be used to predict second ACL risk factors. Therefore, the purpose of this study was to investigate the way data is typically analyzed to see if there were any differences between healthy participants and patients with ACLR; and if psychological components can be used to predict risk factors for a second ACL injury. In a cohort of healthy controls and patients with ACLR, using symmetry to assess loading differences, there were differences found in symmetry metrics commonly used to assess performance. These results show that analyzing and interpreting data from patients with ACLR should not be done the same way as healthy participants. Psychological components, ACL-RSI, M-LOC, and GAD-7 surveys, and physical risk factors of a second ACL injury were combined into a model to predict landing symmetry. Unilateral and bilateral load asymmetry has been identified as a risk factor for reinjury[28]. There were three different unilateral landings, and two bilateral landings. The unilateral landing models, single hop and triple hop, could explain a large amount of differences results found within the landing symmetry. Each of these models included psychological and physical factors. These results emphasize the importance of including psychological components and previously researched risk factors to best understand reinjury risk in patients with ACLR. The results from this entire study indicate ways to potentially improve our understandings of patients with ACLR, which can help clinicians better identify risk for patients with ACLR.

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List of Abbreviations

ACL	Anterior Cruciate Ligament
ACLR	Anterior Cruciate Ligament Reconstruction
AE	Athletic Exposure
GRF	Ground Reaction Force
vGRF	Vertical Ground Reaction Force
RTS	Return to Sport
LOC	Locus of Control
M-LOC	Multidimensional Locus of Control
ACL-RSI	Anterior Cruciate Ligament Return to Sport after Injury
GAD-7	General Anxiety Disorder
OA	Osteoarthritis
BTB	Bone-Patellar Tendon-Bone
BW	Body Weight
SI	Symmetry Index
RI	Ratio Index
LSI	Limb Symmetry Index
NSI	Normalized Symmetry Index
Sx	Surgical limb
NSx	Non-Surgical limb
D	Dominant limb
ND	Non-Dominant limb
LMEM	Linear Mixed Effects Model
DVJ	Drop Vertical Jump
CMJ	Counter Movement Jump
SJ	Stop Jump
ms	milliseconds
SH	Single Hop
TH	Triple Hop
CH	Crossover Hop
PIF	Peak Impact Force
LR	Loading Rate
ROM.	Range of Motion
AIC	Akaike Information Criterion

Chapter 1: Introduction

Motivation

Bilateral landings are a key exercise in rehabilitation for numerous injuries. Specifically, following anterior cruciate ligament (ACL) injuries and ACL reconstruction (ACLR), bilateral landings are used to assess differences between the lower limbs, performance ability, and readiness to return to unrestricted physical activity. These landings assume two feet contact the ground at the same time, however, in most cases this does not occur. When an individual lands, regardless of injury status, the time at which both of their feet hit the ground is not the same. In most biomechanical studies, the outcome data is normalized in time based on the time it takes to complete a task, and the outcomes are reported as a percentage of the movement. This normalization is done by converting the contact time of each limb individually during the movement from 0-100% completion. The initial contact is 0% and toe off is 100% of the movement. This normalization process, commonly referred to as percent stance, removes the possibility of identifying differences in how the limbs perform relative to each other. Prior work has demonstrated the importance of limb contact order and limb dominance or surgical limb and are crucial to understanding the rehabilitation process. The removal of time as a component of the movement allows for simplification of data processing, however, no research has been conducted focusing on the effect of the normalization method on bilateral landing metrics, specifically measures of side-to-side symmetry. The effect of percent stance normalization versus time-independent limb mechanics is needed to understand the differences in limb symmetry during landing and the potential impact of these differences when assessing participant injury risk and recovery. This gap in knowledge is specifically needed within the ACL population as there could be an effect of limb landing order and timing in performance and rehabilitation that could be masked when the normalized data is used when making clinical decisions. The implications of normalization for patients with common sport injuries, such as ACL tears, will provide opportunities to better assess injury risk for athletes returning to sports. To understand the effect of percent stance normalization, vertical ground reaction force (vGRF) symmetry will be quantified for each limb to compare the time between ground contact and the peak impact force, peak impact force, time to task completion, loading rate, and impulse during a bilateral landing to determine side-to-side differences in the vGRF output between percent stance and time independent output.

During rehabilitation in patients following ACLR, the primary focus has been the physical functioning of the injured knee. However, recent literature demonstrated the importance of considering psychological factors on the success of rehabilitation and returning to sport. Prior work has suggested a need to monitor psychological readiness with questions relating to anxiety and fear throughout the rehabilitation process. Psychological readiness can be assessed through a series of patient reported outcomes. The following patient reported measures are considered essential when determining psychological readiness; fear of reinjury, anxiety, and locus of control (LOC). A higher fear of reinjury is the main reason for completely halting or delaying participating in sports. Also, greater self-reported fear is linked to an increased risk of reinjury following return to sport (RTS). Many studies have identified a relationship between pain and negative emotions. One study specifically found negative emotions to be predictors of the pain severity experienced by a patient following ACLR. When considering the locus of control, this has been associated with post ACLR rehabilitation outcomes as well as overall greater knee function and satisfaction. However, less literature has looked at relating the combination of these self-reported psychological readiness measures to knee function between surgical and non-surgical limbs, such as passive knee range of motion, hop distance, quadricep strength, and peak impact force symmetry. It is necessary to identify differences within patients' movement and landing strategies and eventually evaluate their impact on return to sport injury risk. For example, quadricep strength symmetry is known to be associated with greater psychological readiness. Common tasks in ACLR rehabilitation, such as unilateral and bilateral landings, are known to show greater asymmetry between limbs than movements such as performing a squat and walking. Previous literature has also found additional differences in patients with ACLR during landing tasks have an impact on their symmetry, including time since surgery, sex, and graft type. Incorporating knee function metrics from ACLR rehabilitation, including clinical factors, and landing symmetry with psychological surveys allows for identifying a predictive relationship between physical and psychological factors. Determining this relationship between the LOC, ACL-RSI, GAD-7 surveys, specifically, knee function and clinical metrics during unilateral and bilateral landings will provide information on their relationship and a more in-depth understanding of a patient's rehabilitation and possible reinjury status.

Specific Aim 1: Determine differences in side-to-side symmetry when using percent stance vs time independent discrete data during bilateral landings in patients following ACLR and healthy adults.

Hypothesis 1a: Time independent landing phase data of patients following ACLR will have a significant increase in asymmetry across all metrics when compared to percent stance normalized data during bilateral landings.

Hypothesis 1b: Healthy adults will not have a significant difference in each symmetry metric between time-independent vs percent stance data.

Specific Aim 2: Determine if the LOC, ACL-RSI, and GAD-7 coupled with symmetry of quadricep strength, hop distance, and passive knee ROM, sex, graft type, and time since surgery are predictive factors of peak impact force symmetry during unilateral and bilateral landing.

Hypothesis 2a: The LOC and ACL-RSI coupled with hop distance and quadricep strength symmetry will predict landing symmetry in bilateral landings.

Hypothesis 2b: The LOC, ACL-RSI, and GAD-7 coupled with hop distance and quadricep strength symmetry will predict the landing symmetry in unilateral landings.

The combination of biomechanical and psychological data will provide more personalized and in-depth understanding of a patient's rehabilitation process. Upon completion of the study, this information can be used in sport and clinical settings to improve the analysis methods being utilized when making clinical and performance decisions.

Chapter 2: Background

The ability to move is a part of daily life. When an individual can no longer move pain-free or without assistance, the human body can adapt, but ultimately it is a challenge to continue daily activities. Injuries are incredibly common and are likely to be experienced at some point in any individual's life. More and more research has been focusing on injuries with the goal of translating information and results to clinicians to better diagnose and treat patients. However, to eventually predict injuries, researchers must first understand their mechanisms, symptoms, and effects, both short and long term. Injuries effecting large populations of individuals are typically studied more often. For example, there has been a surge of female participation in sport over the last 50 years and the rate of anterior cruciate ligament (ACL) injuries in female athletes has also seen a significant increase, making this injury one of the most common within this population[4,10,16,29,30].While the increase of female athletes is a factor, it is not the only reason for high incidences of ACL tears in female athletes. Researchers must consider a multitude of different influences when studying human movement and injury. This includes not only the physical injury, but the psychological components and methods used to analyze injury data.

Psychological readiness is a term that has become increasingly popular over the last 10 years because it is being included as a factor to evaluate following injuries[25,31,32]. This is done by including psychological surveys to evaluate the readiness of an individual[33,34]. There have been many relationships found between emotions such as fear[25–27,35] and confidence[18,25,27] on reinjury risk and quality of rehabilitation. Specific psychological surveys and their scoring have been found to be risk and/or predictive factors for injuries[25,27,33,34,36]. More research including alternative psychological surveys measuring different emotions, such as anxiety, and how individuals perceive the world around them, is needed to better understand how more psychological components can influence an individual's choices and possibly recovery from injury.

Typically, data from different populations is analyzed using similar methods. These methods have primarily been tested and used in healthy participants to ensure accurate data and results[37]. Few researchers have asked the question whether the methods may be inaccurately interpreting data when these methods are applied to patients following injuries or surgical interventions. No previous literature has looked at these methods across the different populations. This begs the question; are the common data analysis techniques and assumptions correct across all different participant populations? We, as researchers in the biomechanics community, must determine if these methods influence data based on populations to ensure the most accurate data and interpretations of results. This is critical in clinical populations because recovery expectations and rehabilitation can be improved and better understand when the data is interpreted accurately.

ACL injuries are one of the most common knee injuries in both males and females[1–3,29] with between 200,000-400,000 occurring in individuals each year[2,6–9]. In a PubMed® search, over the last 25 years with more than 19,000 articles published on ACL injuries. Many of these studies use similar data analysis methods. There has also been an increase in psychological measures used in studies to track recovery from primary ACL reconstruction (ACLR). According to PubMed®, 468 articles have been published in the last 10 years. The ACL is responsible for connecting an individual's femur to their tibia and to limit the amount of movement from the femur[2]. An injury to this ligament occurs when an individual has a greater amount of force moving the femur forward that the anterior cruciate ligament cannot withstand, and so the ligament tears[2].

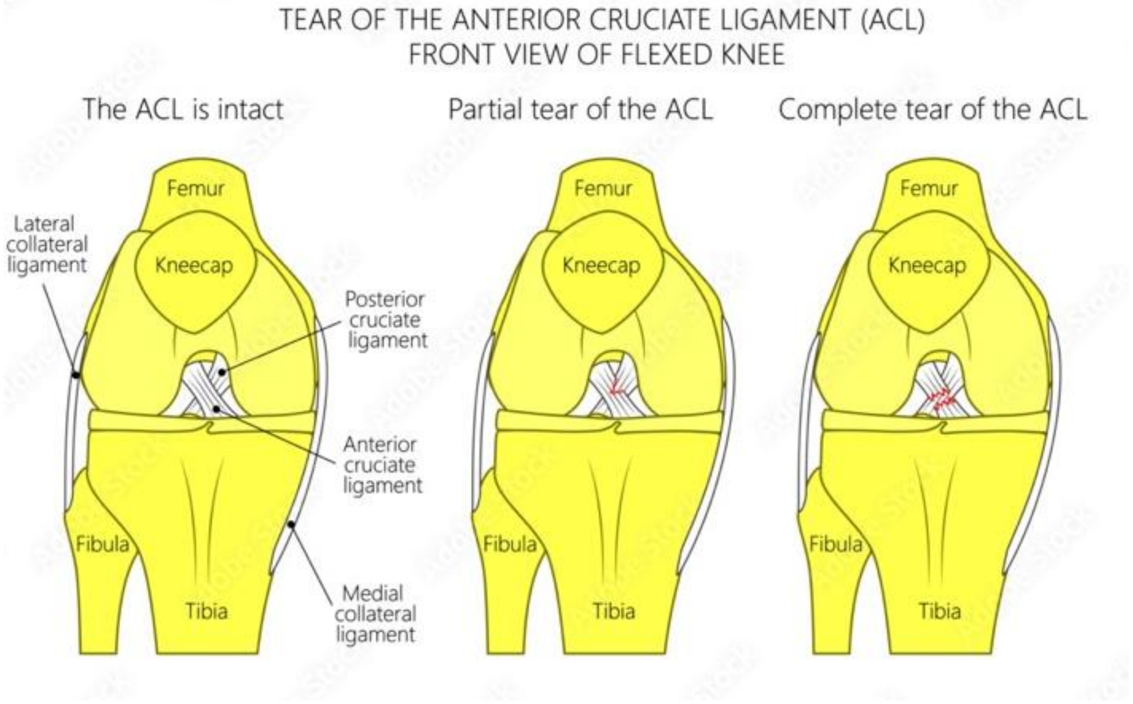


Figure 1 An ACL ligament intact, partially torn, and completely torn[38].

This occurs most commonly when decelerating, performing a sharp cutting, or pivoting movements[7,11,39–41]. Many risk and predictive factors have been established for primary ACL tears in previous literature[1–3,4,6,11,14,19,26,28–33]. Participating in activities or sports that involve pivoting and sharp cuts, such as soccer, football, rugby, basketball, etc. increase the risk of an ACL injury[3,11–13,16,17,40,48,49]. For example, girls playing soccer and basketball have around a four times higher risk than those playing other sports[16]. An individual's activity level and number of athletic exposures can influence the risk for this injury as well. Higher activity and competitive levels can increase the risk[3,10,16–18]. Athletic exposures (AE) are calculated based on the number of games or practices[16,48,50]. Overall, 6.5 ACL injuries occur every 10,000 AE. The highest rates seen in girls' soccer with 12.2 ACL injuries per 100,000 AE, and boys playing football had a fourfold chance of sustaining an ACL injury than those who did not play football[16]. Additionally, internal factors can impact an individual's risk of an ACL injury. Females experience ACL injuries at a rate of between 1.5-4.5 times higher than males[29,30]. Even having a family member with a history of an ACL injury almost doubles the likelihood of the injury[42]. Many factors, both internal and external, can increase or decrease an individual's likelihood of experiencing an ACL injury.

There are also many short- and long-term implications following this injury. It is well documented that within 10-15 years of the ACL injury, knee osteoarthritis can begin to develop[51–55]. Osteoarthritis (OA) is a degenerative disease of a joint due to loss of cartilage over time, typically occurring in older adults, that can lead to pain, reduced knee function, and potentially disability[56,57]. More studies determining predictive factors for ACL injuries could decrease ACL injuries and possibly lead to fewer young adults experiencing knee OA. Additionally, movement mechanics of the patient with an ACLR are altered for over two years following surgery[14,19,58–61]. If a patient has the desire to return to sports, altered movement mechanics can put them at risk for future injuries[28,59,62–64] which is incredibly difficult to prevent because few athletes are willing to wait for two years to return to their sport[65]. Short term implications following the injury include inflammation[22,66,67], knee instability[1,66,68], pain[21,29,66], and loss of knee range of motion[21,66,69]. Surgical intervention may also occur depending on the grade of ACL tear[69]. A fully torn ACL requires surgery, and partial tears typically result in a complete tear which is then surgically repaired[70,71].

Following the initial ACL tear, there is a 10-25% likelihood to experience another ACL injury in the ipsilateral or contralateral limb[3,3,10–15]. Previous studies have determined multiple risk factors for the second ACL injury[10,16,24,26,29,44,48,72]. Factors such as graft type[22,46,73], time returning to sport or activity following surgery[46,47,74] and activity level[12,48,75] all influence the risk of a second tear. However, fewer studies have found predictable metrics to prevent the second injury.

The type of graft used in the first ACLR has an influence on rehabilitation and recovery of a patient[22,29,44]. A graft is the tissue used to reconstruct the ACL ligament[29]. Grafts have been found to rupture at a rate of 5.8-6.5%[12,45,76]. Typically, surgeons will harvest this graft from three sites from an individual's body, the patellar tendon, hamstring tendon, or the quadricep tendon[77]. There are two types of grafts, autograft and allograft[29]. An allograft is tissue donated from another individual, whereas an autograft is the graft taken from the patient's own body[78]. Autografts are more commonly used than allografts for ACLR[29,44,78]. While each graft type has its pros and cons, allografts have shown 4-5.5 times higher failure rates[29,73] and those rates are higher in adolescent patients[15,79]. Differences have also been found between the graft sites. Patients with bone-patellar tendon-bone grafts (BTB) reported higher pain levels[29,44] and longer recovery time[80]. The hamstring tendon graft site is most common[29] but has a higher retear rate[72]. Quadricep grafts are becoming more frequently used after patients report less pain but similar amounts of knee stability following a BTB graft[81]. Overall, one of the largest effects of each graft is the decreased strength of the graft site[22,78]. Strengthening muscles on the surgical limb following ACLR surgery is crucial regardless of the graft site[22,26,28,29,46,72].

Time returning to activity following surgery has a large influence on the rate or reinjury[46,47,74]. The majority of second tears occur within two years following the initial ACLR[3,14,42,64,82,83]. Grindem, H., et al found that, up until it was nine months post-surgery, each month RTS was delayed the risk of an ACL reinjury halved[47]. Other studies strongly discourage patients returning to sport or activity because patients rarely pass RTS criteria prior to nine months[43,46,72,84], and still see deficits between limbs for much longer[14,19,43,58–61]. However, many athletes are being cleared by their surgeons around six months following their ACLR[72,85] and immediately returning to high level of activity[72]. Patients are also returning to sports or activities before they are officially cleared to do so, thus putting themselves at an even higher risk for a reinjury[86]. This is a factor of human subject research that must be considered. Most patients will not wait to RTS or participate in unrestricted activities for the time it takes to adequately recover from an ACLR[65].

The level of activity a patient returns to also can increase their risk of a second tear[3,10,42,48,49,73,75]. Participating in high activity level or sports including cutting and pivoting increases the chances of a contralateral ACL injury over three times[40]. While no differences were found in the risk of injury between practice and games, Slater, L.V., et al found competition level has a significant impact on recurrent ACL injuries[17]. NCAA student athletes are 11 times more likely to experience a recurrent ACL injury than high school athletes[17]. When returning to activity, beginning sport-specific drills without sharp pivots or an opponent and adding to that over a few months is incredibly beneficial in avoiding injuries[31,46]. It gives an individual the opportunity to improve their neuromuscular control throughout rehabilitation, which is important to improve to decrease risk of reinjury[61,69,72,87]. This refers to the ability to control an individual's movements and functions with their central nervous system[88]. Previous studies have found neuromuscular control should be trained to promote recovery and minimize altered movement mechanics, specifically in patients RTS following ACLR[19,61,62,66,69,72,87].

Similar to the risk factors for an initial ACL injury, there are also internal factors for a second tear that can increase or decrease the risk. Females have a higher incidence of both a primary and second ACL tear compared to males[3,4,10,29,30,40,82]. Patients between the ages of 13-18 have the highest likelihood of experiencing a second tear[11,49,89,90], and have the highest graft failure rate[79,83]. In addition to sex and age, previous literature has found psychological readiness, or the psychological impact from the first injury, has an effect of the risk of injury in a patient with ACLR[18,24–27,35,36]. Fear of reinjury is one of the most researched emotions and has been associated with altered movement mechanics following ACLR[24–27]. It is common during rehabilitation following ACLR[11]. Confidence and self-efficacy in an individual's ability to complete or perform a task has also been included into studies following patients with ACLR[18,91–94]. These have been related to the improvement of recovery in a patient following injury[24,25,91,93,94]. Additionally, second ACLR has been associated with increased anxiety following the initial ACL procedure[95]. Females are more likely to experience increased anxiety and depression following ACLR[95]. Another measurement used with patients who have had ACLR, is locus of control. Reich, J.W. et al describes an individual's locus of control (LOC) as their "perception of control" and beliefs on an outcome[96]. When an individual believes they have control of their own outcomes and actions, that is considered an internal LOC[97–99]. An external LOC, sometimes also referred to as chance, is when an individual does not believe they control their own fate or decisions[97–99]. Fewer studies have incorporated the LOC into their analysis of patients with ACLR. However, internal and external LOCs have been associated with outcomes following ACLR[61,92,100]. Greater psychological readiness, knee function, and satisfaction has been associated with an internal LOC [61,100]. There are many different questionnaires being used to measure psychological readiness in patients with ACLR, and previous studies have shown incorporating psychological components into analysis and rehabilitation are important for a holistic understanding of ACL injuries on patients [25–27,31–34,61,72,91,94,100].

Rehabilitation following ACL injury and/or surgery is critical to return-to-sport (RTS)[22,26,46,47,80,101]. Unfortunately, there is no rehabilitation program following surgery that has been deemed "standard", but there is an urgent need for an agreed-upon-protocol to optimize all patients' recovery[102]. However, there have been suggestions for exercises and strategies developed by clinicians and researchers that evaluate patients' ability to return to sport or high level of activities[16,29,31,62,67,72,103,104]. Patient education is incredibly important when creating realistic expectations and understanding of rehabilitation[46,102]. Peebles et al. and Schoenfield et al advocate for the squat exercise as an effective, translatable task patients can perform to improve strength and optimize their rehabilitation[62,103]. Previous studies and medical centers have published different protocols with suggestions for goals during certain phases following surgery[29,67,105]. Common consensus between these is restoring knee range of motion (ROM) and control inflammation during the early phase following surgery, quadricep strengthening following week five post-surgery, and working on jump/landing training and neuromuscular control during the final parts of rehabilitation[29,67,105]. Despite these timeline suggestions, there has not been one protocol agreed upon for typical rehabilitation for patients following ACLR. However, Noyes, F.R., et al developed a scale to quantify levels of performance during recovery that clinicians typically use as criterion to test patients' ability and readiness to RTS[106]. This scale identifies ranges of symmetry between the surgical (Sx) and non-surgical (NSx)[106]. 100% symmetry indicates equal performance on both limbs, and 0% is complete asymmetry between limbs[106]. The symmetry during a movement or task must be greater than or equal to 90% to be considered a healthy range, which typically results in the ability to RTS[46,106]. This rating scale has given clinicians a threshold to track and cater an individual's rehabilitation program to achieving symmetries of 90% during tasks between the non-surgical and surgical limbs. Values less than 90% have led to higher risk of reinjury[20,28,59,106–110].

Symmetry has been a measurement used throughout rehabilitation to quantitatively assess a patient's movement[69,80,86,104]. This is beneficial to identify possible deficits or determine readiness to RTS and daily activities. Previous studies have used symmetry following rehabilitation to understand how an ACL tear impacts an individual's movement[19–22,25,26,43,59,62,87,101,107,111]. There have significant asymmetries found in patients with ACLR over two years following their surgery[14,19,58–61]. These differences between the surgical and non-surgical limb span across the amount of force each limb exerts into the ground to how they move in space[14,19,58,59,61]. Many studies have found significant differences in the forces exerted by each limb across tasks, such as walking[26,99,112], running[113,114], and landings[25,58,59,62]. From these, it is known patients typically apply more force onto their non-surgical limb during the previously mentioned tasks[25,58,59,62,99,112,114]. Recent studies have found relationships between fear and confidence from psychological questionnaires and symmetry during gait[26,115] and landings[116,117]. Peebles, A., et al was able to predict knee extension moment symmetry using an ACL-Return to Sport (ACL-RSI) questionnaire, graft type, and jump height[25]. Using symmetry on common exercises done throughout rehabilitation is an effective way to track individual progress of patients.

The most common index is the symmetry index (SI)[118,119]. The SI allows for a direct comparison between the surgical (Sx) and non-surgical (NSx) side of the body independently, with 0% indicating complete symmetry and 100% or greater means asymmetry[119]. The SI is a modified equation from the ratio index (RI)[118,119].

$$SI = \frac{X_{NS} - X_S}{0.5(|X_S| + |X_{NS}|)} \tag{Eq 1}$$

There are also modifications of the SI used in literature for specific comparisons. An example of an applied SI would be the Limb Symmetry Index (LSI) used to compare the symmetry between the lower limbs[109]. The range of the LSI indicates complete symmetry at 100%, where less than and greater than 100% indicates asymmetry[109].

$$LSI = \frac{X_S}{X_{NS}} * 100$$

(Eq 2)

There are also modifications of the SI. One recent example of this is the Normalized Symmetry Index (NSI)[118]. The NSI is a continuation of the SI but incorporates variance within the calculation[118].

$$= \frac{X_{NS,t} - X_{S,t}}{max_{t=1:n}\left(\max\left(0, X_{NS,t}, X_{S,t}\right)\right) - min_{t=1:n}\left(\min\left(0, X_{NS,t}, X_{S,t}\right)\right)} *100$$

(Eq 3)

This ensures the bounds of the output to be between 0-100%, 0% meaning complete symmetry and 100% meaning complete asymmetry[118]. While the LSI is most common inter-limb SI in literature[120], the NSI's translatability into clinical settings can be impactful when studying clinical populations, specifically patients with ACLR[118].

There is an extensive amount of literature that exists investigating factors that influence ACL injuries and its implications[10,16,18,22,24,26,29,44,46–48,72,80,91–94,101]. However, there is still more to understand about this injury. Less is known about predictors or how to decrease the likelihood of obtaining a second ACL injury. Possible predictors should include psychological components. There is a need to identify ways to prevent and/or predict second ACL injuries. This is especially pressing for psychological components. Investigating specific emotions or beliefs could result in predictive factors for a second ACL injury. Clinicians should be able to help a patient recover holistically, so determining predictive factors that include psychological components is needed for patients with ACLR.

Establishing predictive factors relies on previous literature having analyzed and interpreted data accurately. Many studies that include patients with ACLR use common methods to analyze data[25,26,28,58,59,62,63,87,101,107,111,121]. These methods depend on different variables, such as tasks and technology available. Gait tasks include walking and running tasks, but landing includes bilateral and/or unilateral. Others, such as squatting or hopping, can also be classified as bilateral or unilateral. A bilateral task is one that involves two limbs whereas unilateral only involves one. Landings, both bilateral and unilateral, are used frequently in rehabilitation when returning to sport from ACLR[25,28,34,58,59,62–64,104,107,111,122]. These landing tasks require the athlete to exert more force and move quickly which can reveal deficits between the surgical and non-surgical limb that may not have been observed during gait[69]. Forces generated and the movement of a landing can be observed in different ways during data collection. Force plates and high-speed and -resolution cameras are common in biomechanics laboratories to quantify movement with high accuracy, but these spaces are not portable or easily accessible to everyone and cost thousands of dollars. Less expensive technology is more accessible and translatable into clinics but can have limitations with accuracy[123]. Clinical populations need clinicians to be educated on recent research, but typically that research is conducted with biomechanics laboratory equipment making it difficult to translate findings. Therefore, identifying predictive factors using the same technology that can be accessed in clinics may help translate findings to clinicians and patients.

Whether data is collected from expensive laboratory equipment or portable equipment used in clinics, there are common methods and assumptions used to analyze and process data. Normalization refers to standardizing or scaling data[23]. This is done to more easily conduct data analysis. There are different ways to normalize data. To compare between participants, data is typically normalized to body weight (BW)[121]. Dividing the ground reaction force (GRF) applied into the ground by BW, for each participant, allows for a comparison between participants and across populations. For example, their maximum force is three times their body weight, and this can be understood across all participants. After the magnitude of data is scaled and comparable, common methods to compare datapoints between participants are percent stance and 101-point normalization[23,121]. Percent stance normalization converts the data into 0-100% of stance. Stance is the duration of the task. At 0% stance, the task begins and at 100% the task is complete. 101-point normalization occurs when there are a large number of data points during the tasks and are then downsampled to 101 points. Downsampling reduces the number of data points in a dataset[124]. The 101-point method makes the data span from 0-100% of stance with a datapoint at each percentage. Converting data into a percentage of a movement gets rid of the true instance a task occurs. In healthy controls, it is assumed there are no timing differences between limbs across tasks, like gait or during a bilateral landing, but in a clinical population like patients with ACLR, these assumptions are no longer valid[125]. For example, during a bilateral landing, patients with ACLR land with an average difference of seven milliseconds between each limb initially contacting the ground[125]. No previous studies have investigated the possible implications of removing the timing difference due to percent stance or 101-point normalization.

These methods have been tested to not skew or significantly alter data in healthy controls. However, this and other methods have not been validated in patients with ACLR. Therefore, in this population, these methods could potentially skew or significantly change data. Before being able to identify predictive factors in patients with ACLR, there needs to be a comparison of normalization methods in the clinical ACL population and healthy controls. Overall, there is a need to challenge common assumptions in biomechanics research to ensure accurate data when including different populations, specifically clinical, in studies.

Motivation, Purpose, and Hypothesis

Over 200,000 ACL injuries occur each year in the United States[2,6–9]. Following an initial ACL injury, the probably of a second tear increases to 10-25%[3,10–15]. These injuries require extensive rehabilitation and can have long-term implications[14,19,58–61]. Previous literature has identified risk and predictive factors for a primary tear[3,10,16,18,25,26,29,30,40,42–48,58]. There is a critical need to find factors that can predict and ultimately reduce the instances of a second ACL injury. Recently, psychological components have been incorporated into research and rehabilitation[18,24–27,35,36]. Surveys measuring emotions and beliefs are used to evaluate reinjury risk, like high asymmetry[19–22,25,62]. Including other psychological components with previously identified risk factors may improve reinjury risk understanding. However, identifying predictive factors relies on previous studies to have methods that accurately analyze data from patients with ACLR. There are common assumptions in biomechanics research made when analyzing data. These assumptions have been tested primarily using healthy controls, not clinical populations. Normalization of data to percent stance is one of the common assumptions[23]. This removes the timing component of tasks such as bilateral landings. Time independent normalization does not get rid of time but analyzes data from the first to the last contact of the lower limbs with the ground[63]. Before identifying predictive factors for a second ACL injury, common analysis methods need to be challenged to ensure accurate results in the ACLR clinical population. The purpose of this study was to compare normalization methods between healthy controls and patients with ACLR during bilateral landings, and to identify predictive factors of symmetry including psychological components. The first hypothesis was time independent landing data in patients with ACLR will significantly increase asymmetry when compared to percent stance normalization. The second hypothesis was healthy controls will not have significantly different results between the time independent and percent stance normalization data. The third hypothesis was the LOC and ACL-RSI coupled with hop distance and quadricep symmetry will predict symmetry in bilateral landings. The fourth hypothesis was the LOC, ACL-RSI, and GAD-7 coupled with hop distance and quadricep strength symmetry will predict landing symmetry in unilateral landings. The results of this study can influence data analysis methods for studies involving clinical populations and determine factors that can predict landing symmetry in patients who have ACLR.

Chapter 3: Implications of Time Normalization During Bilateral Landings in Patients with ACLR Compared to Healthy Controls

Abstract

Normalization can be used to standardize or scale data. Different methods have been developed to analyze data. In healthy participants, common methods are assumed to not significantly alter results. However, this assumption is being applied for clinical populations that have movement deficits[25,58,62]. Specifically, patients with anterior cruciate ligament reconstruction (ACLR) have significant differences between limbs for 2-10 years following surgery[19,43,58,59]. There is no validation these common normalization methods do not influence or skew data for patients with ACLR. For example, a bilateral landing assumes both feet contact the ground at the same exact time. This is a valid assumption for healthy populations, but Ford, KR., et al found an average difference of seven ms between the surgical (Sx) and non-surgical (NSx) limbs during a bilateral landing for patients with ACLR[125]. There are no prior studies investigating whether this timing difference, that is typically normalized, could significantly influence measures calculated during landings. The load each limb applies during landing is typically quantified and compared using symmetry[19–22]. The symmetry of peak impact force (PIF)[28,62], loading rate (LR)[125], impulse[62], and time to peak[125] are used in previous literature to describe landing mechanics in patients with ACLR. These load measures are calculated following normalization of bilateral landing data, Previous literature most commonly normalizes to percent stance during bilateral tasks, such as a stop jump[23,37,87]. This method converts the time to a percentage, making 0% the beginning of stance, or task, to 100% the end of the trial[37]. Another method, referred to as the time independent method, uses the first initial ground contact of either limb to the final take-off point of either foot[64]. Comparison between these two methods will allow for a better understanding of how normalization assumptions may influence data and its interpretation in clinical populations. Therefore, the purpose of this study was to compare PIF, LR, impulse, and time to peak in healthy controls and patients with ACLR using the percent stance and time independent normalization methods during a bilateral landing. 17 healthy participants and 17 patients with ACLR performed three repetitions of a stop jump task with loadsol® sensors in a pair of standardized shoes provided during data collection. PIF and LR symmetry was calculated for each limb's absolute peak and at the corresponding datapoints for each limb's peak. A linear mixed effects model (LMEM) in JMP (SAS Institute Inc.) was used to compare differences between normalization method and group. Significant group*Method interactions were found in absolute PIF, D/NSx PIF, absolute LR, D/NSx LR, Impulse, and time to peak, Patients with ACLR had larger average asymmetry values using the time independent method for D/NSx and ND/Sx PIFs, absolute, D/NSx, and ND/Sx LRs. These results indicate differences exist between a clinical population and healthy controls using different normalization methods. Lower symmetry values in the most common normalization method could result in patients with ACLR getting released to return to sport (RTS) or daily activities before they are ready. Understanding how normalization methods can influence data, and its interpretations are important to ensuring the lowest risk of reinjury for this population.

Introduction

Bilateral landings are common tasks performed in many different studies that include varieties of different populations[21,25,58,62,63,101,107,111]. These landings are used frequently in rehabilitation to aide in patients' strengthening and recovery[21,25,58,59,62–64,101,111]. Examples of typically bilateral landings include drop vertical jumps (DVJ), stop jumps (SJ), and counter movement jumps (CMJ). Studies looking at athletes or patients planning on RTS typically include the SJ task because it more resembles sport-like maneuvers compared to the DVJ and CMJ[25,69]. The SJ includes two bilateral landings that require quick changes in direction[25,126]. When patients' recovery from injury, such as an ACL injury, are aiming to RTS, the SJ is similar to movements that require quick changes in momentum and when many ACL injuries occur[25,39,126,127]. Additionally, the loads produced the participant during this jump resembles that of a game scenario[62]. When testing athletes wanting RTS following injury, it is important to simulate sport-specific movements before they participate in practice or games[69,86]. This decreases the risk of reinjury[86]. While bilateral landings can simulate sport-specific scenarios, these tasks do have limitations. These landings are assumed to be truly bilateral, when both feet contact the ground at the exact same time. However, this is almost never the case. For example, patients with ACLR have an average of seven ms between their initial contact in both limbs[125]. In many clinical settings, an acceptable bilateral landing, when both limbs land in similar time, is limited to observation or technology available[128]. There is no quantifiable method to ensure a true bilateral landing with zero timing differences between limbs during data collections. This requires assumptions to be made when analyzing the data afterwards.

Within the biomechanics research community, there are assumptions made that allow researchers to normalize data. Normalization is a process that scales or standardizes data. It allows for simpler data processing. These practices have been tested in healthy controls. In this population, normalizing does not skew or create inaccurate data. However, there has not been prior literature testing these methods in clinical populations, such as patients with ACLR. Common methods included percent stance and 101-point normalization[23,26,37,87,129]. These methods have the same procedure but are used depending on the data being interpreted. Percent stance can be used on any length of data. This method normalizes the time it takes for the entirety of a task and converts it to a percentage. 0% is the first data point, or the beginning of the task, and 100% refers to the final data point on the end of the task. 101-point normalization implements the same percentage across the task; however, this method can only be done with 101 data points. Each point corresponding to a percentage of the task being completed. This method is used with equipment that has the ability to collect data at high sampling frequencies and record a large number of data points over time, such as force plates[130], and then can be downsampled to 101 points. Collecting data over time refers to sampling. Sampling rates differ between different pieces of equipment. Force plates can have high sampling rates but are difficult to move and not clinically feasible[123,130]. An important component to investigating different assumptions made in scientific communities is so that results are accurate and able to be translated into clinical populations and to clinicians. If force plates are not common in clinic settings, it is important to create and use technology that can produce accurate results that are translatable. Loadsol® (novel, Electronics, Pittsburgh, PA) sensors are less expensive, easily portable, and fit inside of a shoe.

Figure 2 loadsol® sensor.

Figure 3 loadsol® sensor inserted into a shoe

The sensors record normal force. Loadsols® have been validated and used in multiple studies where the results have proven to be repeatable[107,118,123,131,132]. These sensors provide a more easily translatable method for clinicians to collect information on patients with ACLR during the rehabilitation. Therefore, this study included the loadsol® sensors to collect force data during a SJ.

The force data from the loadsol® sensors can be used to calculate many different metrics. Common metrics extracted from force data include peak impact force (PIF)[28,62,107,132], loading rate (LR)[123,131–133], impulse[107,123,131,132], and time to peak[125,133]. In a bilateral landing, the PIF is the first peak following each limb's initial contact with the ground[123]. In rehabilitation for patients with ACLR, being able to produce high and fast loads during landings is important to assess performance[31,46,69,86]. Previous literature has found this metric to be comparable to the speed and amount of loading applied by athletes during sport[62,127]. To ensure adequate recovery from ACLR, tasks should be performed that are similar to the speed and amount of loading produced by athletes during sports[31,86]. Larger differences, or asymmetry, between limbs during PIF, has been associated with higher reinjury risk[28,62,134]. In most instances, the PIF for each limb do not occur at the same exact time. Typically, the absolute PIF for each limb is extracted and symmetry is calculated on those values irrespective to the real time in which they occurred[26,87]. There is then no understanding of the behavior and symmetry of both limbs at each peak if they occur at different times. Calculating symmetry at each limb's respective peak with the contralateral limb's data point can provide more information to understand the lower limbs performance ability and true landing timing. Large asymmetries between one limb's peak and the contralateral limb's datapoint could have implications in injury risk due to compensation strategies or changes in motor control[19,28,62,134]. Not only will these metrics be important to understand lower limb movement, but also to compare between the percent stance and time independent normalization methods. If the symmetries are significantly different dependent on each method, it could imply the time component is important to include in data analysis methods.

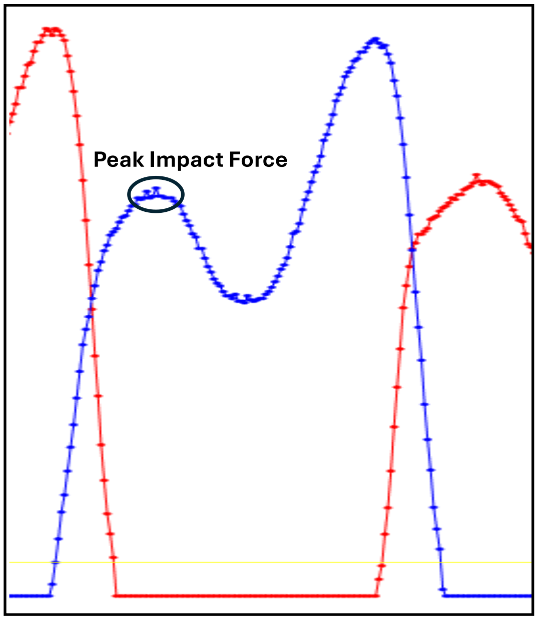


Figure 4 Peak impact force (PIF) data point

Time to peak is the time it takes from initial contact of each limb with the ground to reach the PIF. Differences between the Sx and NSx limbs in time to peak can contribute to injury risk[133]. Bates, N., et al found shorter time to peaks during a bilateral landing may have similar amounts of load to the ACL that may strain the ligament or be linked to injury risk[133]. Identifying asymmetries in the time to peak also differs between percent stance and time independent normalization methods. The time independent method measures the time to each limb's peak beginning at the initial ground contact, while in percent stance, both limbs start at 0% and go to their respective peaks. This negates the real time component of landing. Therefore, it is critical to compare whether the slight difference in time to peak between methods can significantly impact results between patients with ACLR and healthy controls.

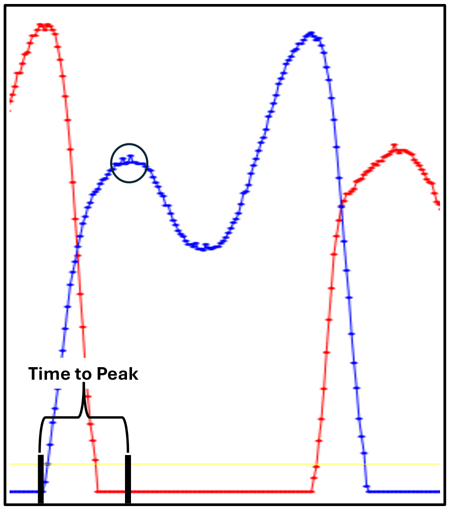


Figure 5 Time to peak calculated from the beginning of the movement to the PIF

LR is calculated using PIF and the time to peak. The LR is the rate at which force is developed in each lower limb from initial ground contact to the PIF[123,135]. Differences between the NSx and Sx limb during rapid loading of a bilateral landing has been linked to reinjury risk and the inability to RTS in patients with ACLR[87,134]. LR is used when evaluating performance, making it is important to compare this metric between normalization methods. It also uses time to peak in its calculation. Similarly to time to peak, the time independent method begins at the initial ground contact during the landing and calculates metrics from that starting point. Comparing LR between time independent and percent stance normalization may provide information to understand the implications of the real time landing. There may be differences in the timing that ultimately influence the results of the percent stance method. LR is calculated independently for each limb. When one limb reaches its peak and can calculate its LR, there is no incorporation of the differences between that limb's LR and the contralateral limb's datapoint. Similarly to PIF, this study included the comparison of the real time and the differences in LR between limbs and the contralateral limb's data point.

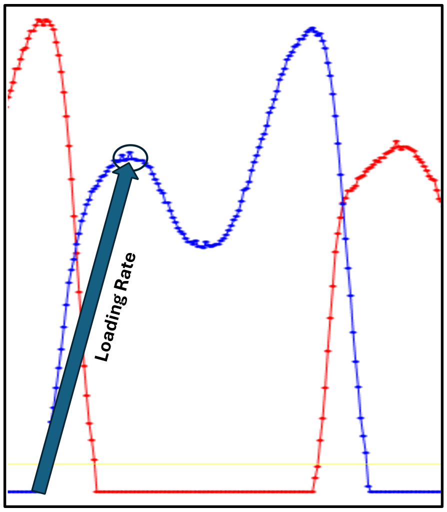


Figure 6 Loading rate (LR) calculated as the slope of the PIF

Impulse is calculated as the area under the GRF curve. Differences in impulse can be due to less ground contact time for one limb, or less force produced by one limb, which can related to injury risk for patients with ACLR[19,28,133–135]. Impulse is measured independently from each limb's initial contact to the respective limb's toe-off [123,135]. Peebles, AT., et al could identify differences in impulse between healthy participants and patients with ACLR in a clinical setting[21]. Therefore, this study included impulse to compare normalization methods because it is a common metric used to distinguish differences between patients with ACLR and healthy controls.

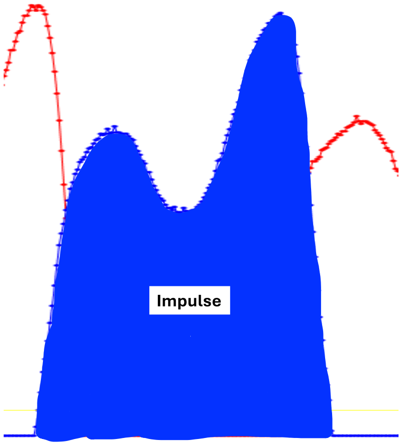


Figure 7 Impulse calculated as the area under the signal curve

Calculating symmetry is used to compare the differences of between the NSx and Sx limbs[14,19,58–61] . Previous literature has used symmetry indexes to calculate differences in patients with ACLR between limbs during bilateral landings[21,25,59,62–64,111,135]. This study used the normalized symmetry index (NSI) because it can compare the differences between the NSx and Sx limbs while incorporating the varying force outputs between trials within a participant[118]. By including the maximum and minimum values within the metric of interest, the NSI is therefore bounded from 0-100%[118]. This allows for a translatable interpretation of the symmetry percentages across each participant[118].

$$= \frac{X_{NS,t} - X_{S,t}}{max_{t=1:n}\left(\max\left(0, X_{NS,t}, X_{S,t}\right)\right) - min_{t=1:n}\left(\min\left(0, X_{NS,t}, X_{S,t}\right)\right)} *100$$

(Eq 4)

Overall, a method that does not compromise the true timing of a bilateral landing is needed to compare between a normalization method. This is incredibly important to investigate between healthy control and the clinical population of patients with ACLR because there could be implications of the normalizations methods that impact the interpretation of landing data in patients with ACLR. Previous literature has not investigated if there are any implications in the normalization methods between different clinical populations. Therefore, this study aimed to compare a time independent and percent stance normalization method on healthy controls and patients with ACLR landing symmetry. It is hypothesized the time independent landing phase data of patients following ACLR will have a significant increase in asymmetry across all metrics when compared to percent stance normalized data. The second hypothesis is healthy adults will not have significant differences between normalization methods for any symmetry metric.

Materials and Methods

Participants

This study included 34 participants, 17 patients with ACLR and 17 healthy controls. Patients with ACLR were from a larger, ongoing study to develop a predictive model for second ACL tears (R01 AR078811-03). Healthy control participants were included from a previous study looking at sex differences in landing mechanics[126]. All healthy controls were recreationally active, exercising for 30 minutes at least three times a week, and between the ages of 18-30 years old. If control participants experienced any lower extremity injuries that altered their typical level of activity they were excluded. Patients with ACLR were included if they had primary ACL reconstruction using an autograft were between 13-25 years old. Patients were tested following clearance from a clinician or their first sport exposure. Sport exposure is an activity level, such as unrestricted practices and games, that is high risk for reinjury[3,10,40,42,48,49,73,75].

Testing Protocol

All participants signed informed consent before beginning data collection. Following consent, all participants were fitted in a standardized running shoe, Nike Zoom Pegasus (Nike, Inc., Beaverton, OR) with loadsol® (novel electronics, Pittsburg, PA) sensor insole placed inside the shoe. Luftglass, A., et al reported standardizing shoes provides more accurate results when looking at loading data[107]. Loadsol® sensors have been validated using force plates, the primary method to measure forces for biomechanics research[123,131]. This sensor outputted the normal force as the participants performed tasks throughout the data collection. The loadsols® were sampled at 100Hz. Limb dominance was measured by rolling a ball towards the participants and asking them to return the ball back[136]. The limb that returned the ball was considered the dominant limb[136]. Participants were then given five minutes on a stationary bike to warmup. Following the warmup, the loadsol® sensors were calibrated to the participants' body weight. All participants completed the bilateral stop jump. Patients with ACLR completed three trials, and healthy controls completed seven. The bilateral stop jump consisted of a few jogging steps, jumping forward off any one foot to then land on both feet, then jump vertically as high as possible and land with both feet maintaining balance for up to three seconds[137].

Figure 8 Participant performs Stop Jump (SJ)

Participants were given an opportunity to practice the task prior to recording data. If a trial was not completed correctly, it was repeated until three successful trials were recorded for patients with ACLR and healthy controls, respectively.

Data Analysis

All loadsol® data was analyzed using a custom MATLAB script, LAP Analysis (insert github link), that normalized to BW before extracting PIF, LR, Impulse, and time to peak for each limb. A custom Python script was written to normalize and calculate the previously mentioned metrics for the percent stance method. This included downsampling, interpolating, and normalizing the GRF curve to percent stance[124]. The data for each trial was interpolated to the lower number of data points for each limb using a cubic spline filter[124]. For example, if there was 35 data points for the left limb's GRF curve and 33 for the right limb, the python script interpolated the left limb's data to 33 data points. The same number of data points is required when normalizing 0-100% of stance[23]. The interpolated data was then plotted from 0-100% of stance. 0% occurred at the first data point and 100% occurred at the last. PIF, LR, Impulse, and time to peak were then calculated for each limb.

PIF was defined at the initial peak in the GRF curve[123]. To compare between the normalization methods, each metric can be calculated for each leg independently. However, looking at each limb independently and in relation to one another could provide more information to understand how the normalization methods affect the outcome metrics. In this study, three different PIFs and LRs were calculated. An absolute PIF was the peak impact for each limb regardless of when in time it occurred. The two other PIF calculations were based on the D/NSx and ND/Sx peaks. Each limb’s peak with the corresponding limb’s point was reported. D/NSx PIF and ND/Sx PIF were calculated to understand the differences between limb in the different normalization methods.

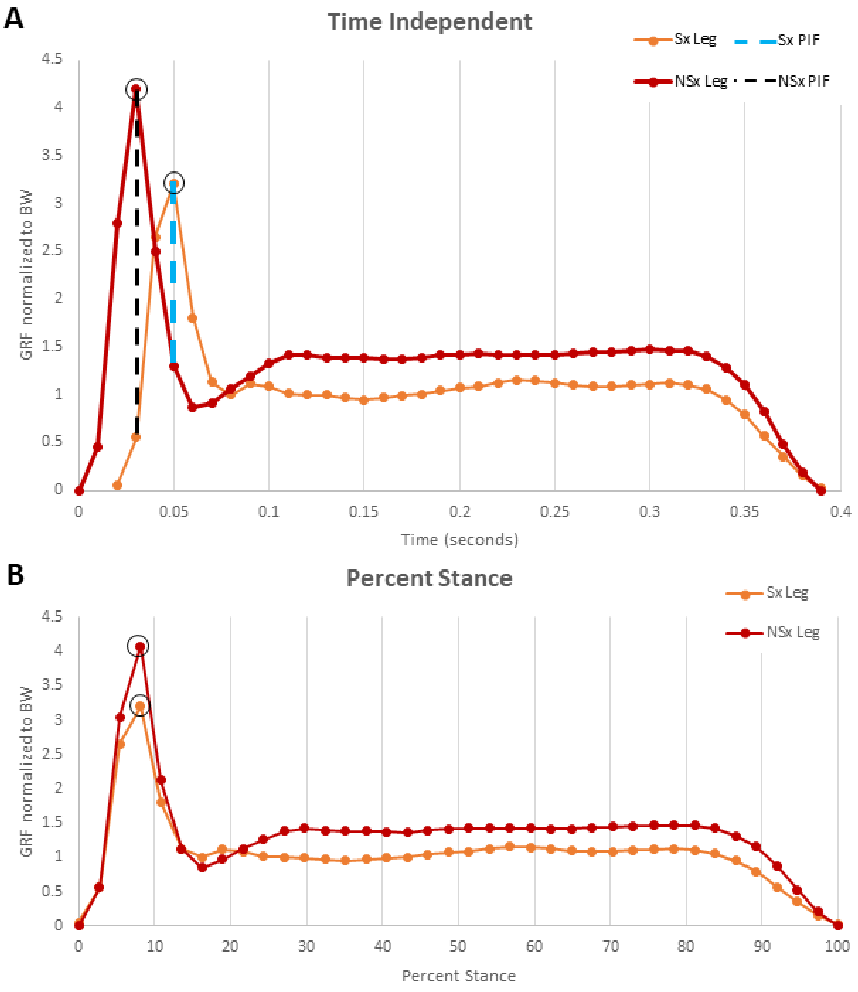


Figure 9 A) PIF values calculated using time independent method. B) PIF values calculated using percent stance normalization method

Similarly, three LRs were calculated, absolute LR, D/NSx LR, and ND/Sx LR. Absolute LR was calculated from the initial contact of each limb to their respective peaks. D/NSx and ND/Sx LRs were calculated from the first ground contact regardless of limb to the PIF for each limb. This was done to directly compare the timing component between the time independent and percent stance normalization method. The LR was calculated the same way in each method. However, the time independent method's LR included timing differences during landing between both limbs.

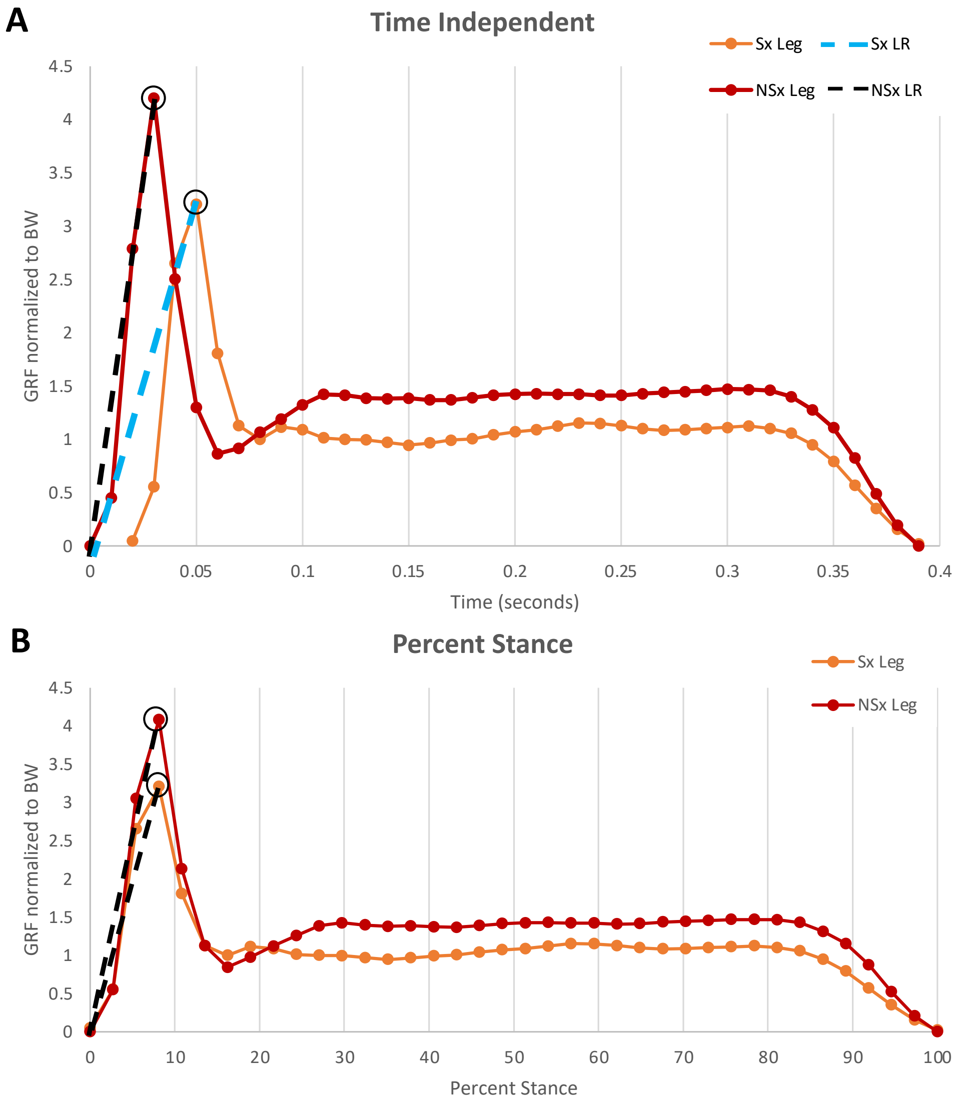


Figure 10 A) LR calculations using time independent method. B) LR calculations using percent stance method.

Impulse was calculated using the area under the curve[123]. The initial contact of the first limb during the landing was used as the starting time until each limb's PIF to calculate the time to peak[123]. It was recorded which limb landed first, D/NSx or NS/Sx, for each participant across all trials. The LAP Analysis was used to calculate the metrics using the time independent method, and the python script was used the percent stance normalization[107].

Symmetry between the outputs was used to compare between the data analysis methods. The NSI was used to calculate symmetry percentages between the methods for each metric 17. This index was chosen due to its ability to account for variability[118]. This allows for the range of the NSI to remain between 0-100% which may be more translatable to clinicians and patients[118]. The absolute value of the NSI was taken to determine overall symmetry between limbs.

Statistical Analysis

An A priori power analysis was used to determine the number of participants required for this study with a power of 0.95 and effect size of 1.16[153]. A linear mixed effects model (LMEM) was performed using JMP software (SAS Institute Inc.) to determine the difference between group (healthy control and patients with ACLR) and method (time independent and percent stance) on the NSI metrics. Participant was used as a random effect in this model. Group, method, age, and sex were included as fixed effects. A full factorial was calculated using group and method. Statistical significance was defined as having a p-value equal to or less than 0.05. If interactions or main effects were found to be significant, a Tukey HSD post-hoc analysis was performed to further understand which variables were significant[138,139].

Results

Table 1 Participant Demographics

	Sex	Age at Visit (years)***	Height (m)	Weight (kg)	D/NSx Limb
ACLR (n=17)	M: 8 F: 9	18.1 ± 2.2	1.75 ± .08	73.9 ± 13.1	R: 5 L: 12
Control (n= 17)	M: 8 F: 9	22.3 ± 3.9	1.73 ± .08	67.3 ± 9.5	R: 17 L: 0

Age at Visit, Height, and Weight is mean ± standard deviation.
**** indicates p< 0.001*

The main effects of age, weight, and sex were not significant between groups across any of the symmetry metrics. Interactions were found in six of the eight metrics calculated.

Peak Impact Force

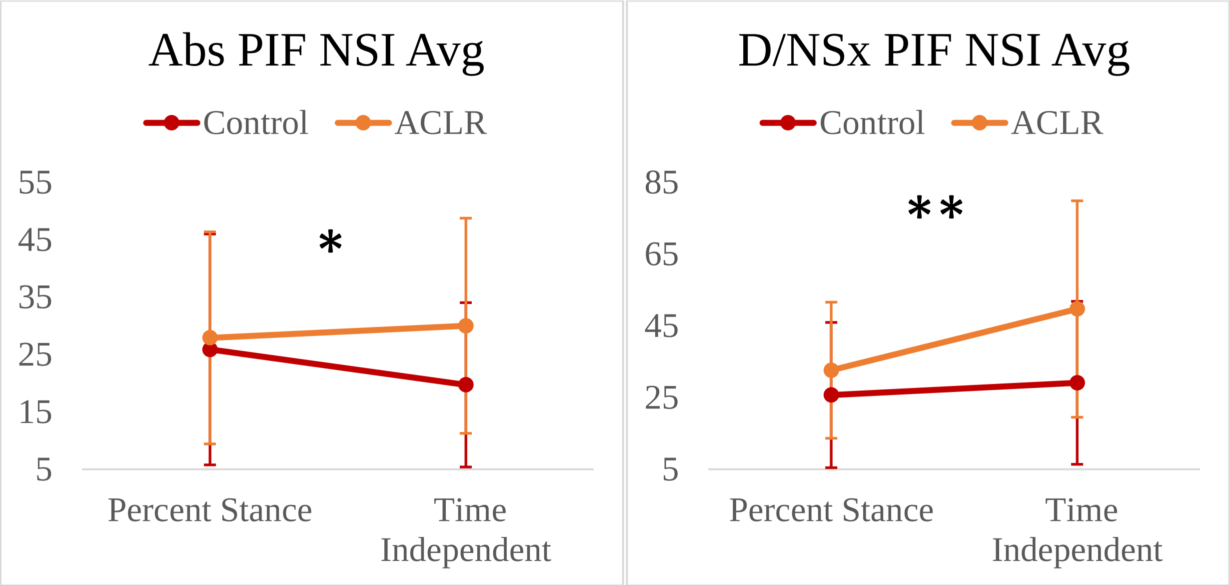


Figure 11 PIF average NSI values for different normalization methods. * indicates p<0.05 and ** indicates p<0.01.

Absolute PIF had a Group*Method interaction (p= 0.0437). While no specific differences were found following a Tukey post-hoc analysis, patients with ACLR (time independent: 30.01% ± 18.7, percent stance: 27.9% ± 18.5) had higher average asymmetry than controls (time independent: 19.7% ± 14.3, percent stance: 25.89% ± 20.1) in both methods. D/NSx PIF had a Group*Method interaction (p= 0.008). The post-hoc analysis revealed a difference between normalization methods for patients with ACLR (p< 0.001). The time-independent method (49.69% ± 30.2) resulted in greater asymmetry than the percent stance (32.62% ± 19) method. There was a main effect for both group (p= 0.01) and method (p= 0.002) for the ND/Sx PIF. Patients with ACLR (33.32% ± 26) had greater asymmetries when compared to control participants (26.45% ± 18.3). Between methods, greater symmetry was observed in the time independent method (31.85% ± 24.3) compared to percent stance (25.87% ± 18).

Loading Rate

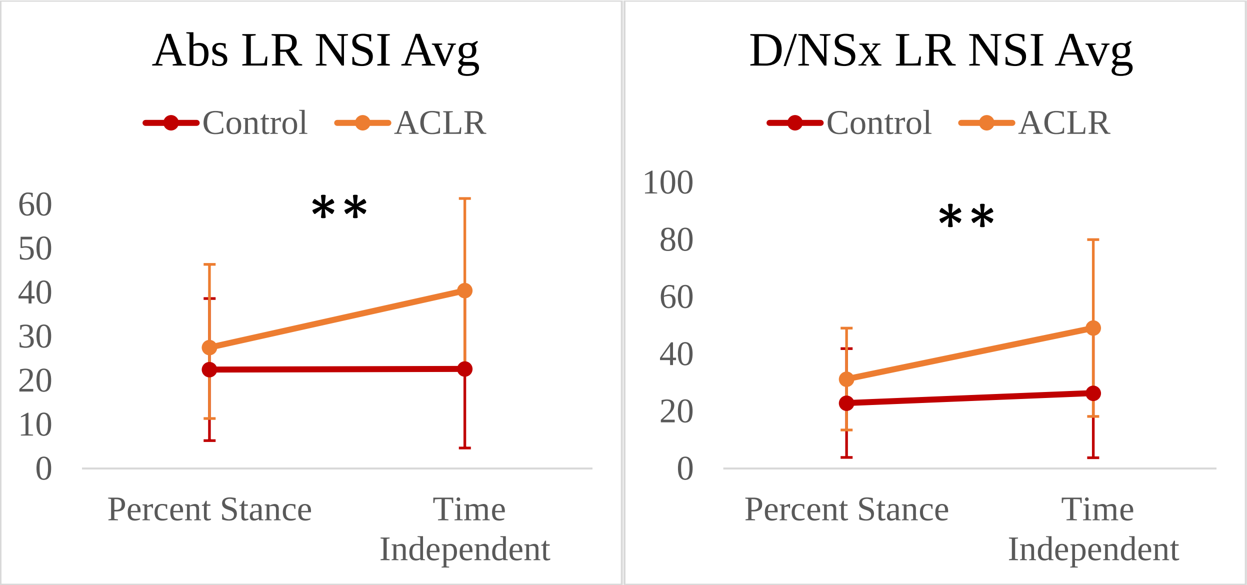


Figure 12 Different LR average NSI values for different normalization methods. ** indicates p<0.01

A Group*Method interaction was found in absolute LR (p= 0.004). Further post-hoc testing revealed absolute LR symmetry in patients with ACLR using the time independent method were significantly different for both group (p< 0.001) and method (p= 0.001). Controls (22.63% ± 18) had more symmetry than patients with ACLR (40.42% ± 20.9) in the time independent method. Between methods, patients with ACLR reported higher asymmetry in the time independent method (40.42% ± 20.9) compared to percent stance (27.5% ± 18.9). Another Group*Method interaction was found in the D/NSx LR (p= 0.005). Following a Tukey HSD post-hoc analysis, normalization method was found to have different results in patients with ACLR (p< 0.001). Higher asymmetry was found when using the time independent method (49.11% ± 30.9) compared to the percent stance (31.27% ± 17.8) method. Group differences were significant in ND/Sx LR (p= 0.019). Control participants (23.83% ± 18.8) had greater symmetry than patients with ACLR (29.92% ± 24.7).

Impulse and Time to Peak

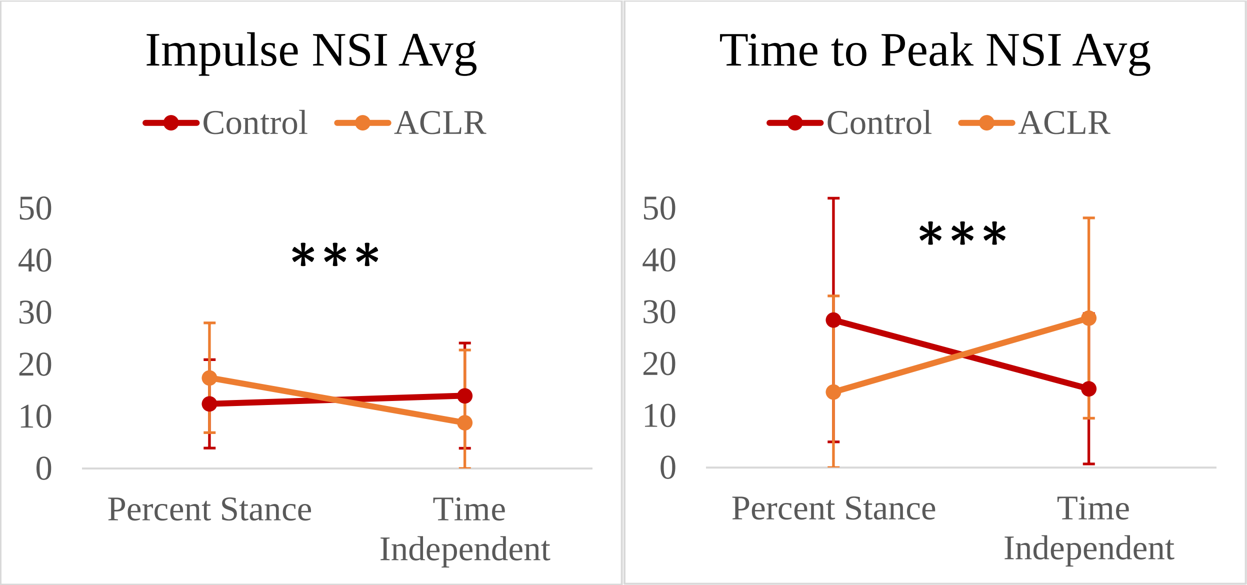


Figure 13 Impulse and Time to Peak average NSI values for different normalization methods. *** indicates p<0.001.

Impulse also had a Group*Method interaction (p< 0.001). Further post-hoc analysis revealed significant differences between the normalization methods (p< 0.001) in patients with ACLR (time independent: 8.8% ± 14, percent stance: 17.45% ± 10.6). Lastly, there was a Group*Method interaction seen in the time to peak force symmetry (p< 0.001). Following a Tukey post-hoc analysis, differences were found between normalization method and groups. Both control participants (time independent: 15.2% ± 14.6, percent stance: 28.46% ± 23.5) and patients with ACLR (time independent: 28.84% ± 19.3, percent stance: 14.58% ± 18.5) had significant differences between their time independent (p= 0.001) and percent stance (p< 0.001) methods. Additionally, each method was significantly different between groups. Patients with ACLR had greater asymmetry compared to controls in the time independent method (p= 0.018), but not for the percent stance method (p< 0.001).

Discussion

The purpose of this study was to compare common normalization methods between healthy controls and a clinical population. Information given to patients and clinicians must be accurate and interpretable to give patients the best opportunities for recovery and rehabilitation. Multiple differences in the results were found between methods when different normalization methods were used to calculate symmetry between patients with ACLR and healthy controls. Patients with ACLR had a higher average asymmetry in all PIFS and all LRs. The normalization method influenced whether control participants or patients with ACLR had greater asymmetry in impulse and time to peak impact force. The changes seen in impulse and time to peak between methods does not align with previous literature that reported patients with ACLR having higher asymmetries than healthy controls for many years following ACLR[14,19,58–61]. Between methods, there was higher average asymmetry values for patients with ACLR using the time independent data in all PIFs and all LRs. Percent stance results in higher average asymmetries in impulse and time to peak only for patients with ACLR. Healthy control participants had higher average asymmetries in D/NSx PIF, ND/Sx PIF, all LRs, and impulse using the time independent method compared to their percent stance results. This control group reported higher average asymmetries in absolute PIF and time to peak using the percent stance normalization.

There were multiple Group*Method interactions found as result of this study's comparisons. Many of the interactions reported differences in patients with ACLR only. This suggests the normalization method may influence this clinical population differently than healthy controls, with greater asymmetries begin reported using the time independent method. D/NSx PIF, absolute LR, D/NSx LR, impulse, and time to peak had interactions where the method used to calculate the results of patients with ACLR was significantly different. In the D/NSx PIF, ND/Sx PIF, and D/NSx LR, the time independent method had higher average asymmetry. Differences in symmetry between the D/NSx and Sx/ND limbs at their respective peak forces and loading rates indicate the timing component is important to consider when looking at symmetry especially in patient populations. These results indicate there a difference in the amount of symmetry calculated when the lower limbs start at 0% of stance compared to time independent analysis. Normalizing to percent stance can report lower asymmetry values that may not be true to the performance of an individual. This is especially important in a clinical population that may have movement deficits between limbs during a bilateral landing. This could also lead to RTS decisions that are too early for the patient to return or these patients may return with a higher risk of reinjury.

Absolute LR and time to peak had interactions that were significant in both group and method. Group differences are expected based on previous literature[14,19,21,25,26,58,62,82,101,128,134,135]. However, method differences between these metrics indicates the time differences between the methods directly impact symmetry results. The absolute LR and time to peak had a higher average asymmetry in the time independent method for patients with ACLR. The rate each limb is being loaded during landing is important to understand risk for reinjury or possible movement deficits, specifically in clinical populations. These results further support the importance of including the timing component between limbs during landing.

No prior studies have investigated the differences between these normalization methods in healthy controls and patients with ACLR. These values indicate the need to investigate common assumptions made for healthy controls when used in clinical populations. Normalizing differently during a SJ task produced significant differences in both a clinical population and healthy controls. This both supports and disagrees with one of the hypotheses for this aim. It was hypothesized there would be differences between method in patients with ACLR, but not healthy controls. However, there were differences found between both groups. This indicates, not only should normalization method be investigated across different populations, but there should also be validations performed across different methods and tasks. The other hypothesis was also almost entirely supported. It was hypothesized patients with ACLR would have higher asymmetries in each symmetry metric in the time independent method. This hypothesis was supported in all symmetry metrics except for impulse where higher asymmetry was in the percent stance normalization for patients in ACLR.

Limitations

This study does come with limitations. The loadsol® sensors were sampled at 100Hz during data collections, which is lower than typical force plates[123,131]. The lower sampling rate during the explosive stop jump movement was not able to collect as many data points in the GRF curve as previous studies have used. There was not a consistent number of data points used for each participant. There was a range of between 30-60 data points in each trial to capture the bilateral landing. However, this equipment is similar to the technology clinicians use and therefore is why lower sampling rates were used making these results translatable to data collected by clinicians.

Healthy control participants also were all right limb dominant. Participants with both right and left limb dominant participants may make the dataset more reflective of the population. While these limitations are important to address, the study team does not believe the results produced in this study would be drastically changed if these limitations were met.

Conclusion and Future Directions

Overall, differences were found between percent stance and time independent normalization methods. This occurred in both healthy controls and patients with ACLR. While a larger number and magnitude of differences were observed the patients with ACLR, there needs to be consideration for the common assumptions used in data processing for all populations, specifically clinical. Normalizing to percent stance can decrease asymmetry in patients with ACLR and may inaccurately depict their symmetry during a stop jump task. This can lead clinicians and researchers to release patients to RTS or daily activities earlier than the time independent method, which could lead to an increase reinjury risk. The results of this study demonstrate a need for normalization methods to be compared in multiple clinical populations as well as in tasks. It is critical the information and data published in the biomechanics community, specifically relating to clinical populations, is accurate to be able to aide patients to return to pre-injury activity level or return to daily activities to maintain a healthy and positive life.

Chapter 4: Implications of Including Psychological Components when Predicting Peak Impact Force Symmetry in Unilateral and Bilateral Landings

Abstract

The risk of experiencing a second ACL injury is up to 25% and continues to increase[4,10,12,13,15]. However, this percentage can change depending on certain risk factors[10,16,24,26,29,44,48,72]. Previous literature has identified factors, including but not limited to, age[49,89,90], sex[10,29,30], and time following injury[46,47,74] to influence the risk of a second ACL injury. For example, female athletes below the age of 18 have the highest risk of this injury[10,16,89,90]. Most patients who have experienced ACL injuries or ACL reconstruction (ACLR) go through rehabilitation to regain knee function, strengthen their surgical limb, and often to return to sports (RTS)[26,31,101]. While no standard rehabilitation protocol has been agreed-upon by clinicians[102], there are common tasks and methods used to assess performance in patients with ACLR[16,29,62,72]. Previous literature has used unilateral and bilateral landing tasks, specifically, to identify deficits between limbs for RTS[62,63,101]. This can be done using symmetry measures, such as peak impact force[28,62]. Patients with ACLR often load their non-surgical (NSx) limb more to compensate during these landings[28,62,63]. Noyes, F., et al determined symmetries less than 10% are considered healthy[106], and greater than 10% can contribute to second ACL injury risk[20,108,109]. Identifying PIF symmetry greater than 10% can allow clinicians to make more informed RTS decisions for patients with ACLR. However, many clinical settings do not have the equipment to collect PIF. However, other previously determined ACL injury risk factors more easily collected in clinics may be able to predict PIF symmetry. Previous literature has identified psychological components, such as fear[24–26] and confidence[18,91,92], can influence movement and contribute to ACL injury risk[61,94,100]. These are often measured in validated surveys[33,140,141]. Combining attainable measurements, both physical and psychological, inside clinical settings may be able to better predict risk factors for a second ACL injury. Therefore, the purpose of this study was to combine psychological and physical risk factors to predict PIF symmetry during unilateral and bilateral tasks. Up to 69 participants were included in this analysis using loadsol® sensors in standardized shoes during data collection to collect PIF force in the single (SH), triple (TH), and crossover hops (CH), drop vertical jump (DVJ), and the stop jump (SJ). Backwards multivariate regression models were coded in RStudio (RStudio, Boston, MA) for each task. Each regression model initially included both physical and psychological components. However, the models explaining the most amount of variance were the SH and TH, 35.12% and 42.27% respectively. Females and increased hop distance were associated with higher PIF asymmetries in both models. Lower general anxiety and locus of control (LOC) scores were associated with higher PIF asymmetry. This study found the combination of psychological components with physical risk factors was able to explain a good amount of variance in two common RTS tasks. Being able to predict PIF symmetry in a clinic without expensive technology may be able to assist clinicians in making more informed RTS decisions for patients with ACLR.

Introduction

Some of the most reported knee injuries involve the anterior cruciate ligament (ACL)[2–4,29]. There are over 200,000 ACL injuries that occur each year[2,6–9]. However, the chances of experiencing an ACL tear continue to increase[4]. Following the first injury, the risk of a second tear increases to between 10-25%[3,10–15]. There is literature investigating risk factors for a second ACL injury[10,16,24,26,29,44,48,72]. Many internal and external factors increase the likelihood of sustaining a second ACL injury, including but not limited to age[11,49,89,90], sex[3,4,10,14,29,30,40,82], and psychological factors[18,24–27,35,36]. External factors can include graft type[22,29,73], quadricep strength[22,26,29] 4,11,21, time following ACL reconstruction (ACLR)[46,47,69,74], sport the athlete is returning to[3,11–13,16,17,22,40,48,49], activity level[3,42,48,49,73,75,103]. Rehabilitation is incredibly important to regain knee function, decrease the risk of injury, and RTS following ACLR[22,26,46,47,80,101]. While is no standardized protocol, there are components of rehabilitation for patients with ACLR that are commonly used between clinicians[16,29,31,62,67,72,103,104].

Symmetry has been used to assess rehabilitation progression[69,80], RTS readiness[69,80,86,104], and reinjury risk[80,86,104]. The Limb Symmetry Index (LSI) is the most common index used in clinical settings[120] and directly compares the difference between limbs ranging from 0 to greater 100% symmetry, with 100% indicating perfect symmetry and anything greater or less than 0% indicating asymmetry[120].

$$LSI = \left(\frac{Involved\ Limb}{Uninvolved\ Limb}\right) * 100 \tag{Eq 5}$$

There are limitations when using the LSI. With multiple trials, there can be differences in loading that the LSI’s single comparison does not consider[120]. Additionally, it is often difficult to interpret the severity of the asymmetry the LSI calculates because there are no set bounds for asymmetry. The Normalized Symmetry Index (NSI) acknowledges both limitations found within the LSI[118]. The NSI can only be used with minimum three trials because it accounts for magnitude of variation between trials[118]. This bounds the range of possible symmetry values to 0-100%, where 0% means complete symmetry and 100% being total asymmetry[118]. These provide the NSI will the ability to be easily translatable and representative of an individual's movement across trials[118].

$$= \frac{X_{NS,t} - X_{S,t}}{max_{t=1:n}\left(\max\left(0, X_{NS,t}, X_{S,t}\right)\right) - min_{t=1:n}\left(\min\left(0, X_{NS,t}, X_{S,t}\right)\right)} * 100$$

(Eq 6)

A range of acceptable, healthy performance has been established for assessing athletes wanting to RTS[106]. Asymmetry equal to or less than 10% between limbs is considered healthy[106]. Asymmetries greater than 10% have been linked to higher risk of injury[20,28,59,64,106–110]. Previous literature has used this range to assess performance deficits of athletes returning to sport following ACLR[25,26,28,59,62,101,110]. Paterno, MV., et al found athletes that experience second ACL tears tend to have greater asymmetries across tasks[64]. Many studies investigating symmetry use loading, or ground reaction forces (GRF), during tasks to track rehabilitation and assess performance[26,28,59,62,111]. Peak impact force (PIF) can be calculated and compared between limbs using SIs during landing tasks[28]. Previous literature has identified compensatory strategies in patients with ACLR during landings that can be seen in PIF asymmetry[28,62,63]. One common strategy is offloading the Sx limb to apply more force onto the NSx limb, resulting in high asymmetry outside of healthy range[25,58,59,62,99,112,114]. PIF symmetry can be used by clinicians as RTS criteria for athletes following ACLR.

Equipment used to collect GRFs is common in research laboratories, but not all clinics have technology to collect forces, and therefore PIF. Other risk factors of ACL injuries, such as sex[3,4,10,14,29,30,40,82], age at surgery[11,49,89,90], quadricep strength[5,22,26], are more easily collected and used to determine risk or RTS decisions. PIF symmetry may be a risk factor that clinics are not able to determine. Identifying factors that can be collected in a clinic to predict PIF could improve performance assessment during rehabilitation and to better inform RTS decisions. Landing tasks, both unilateral and bilateral, are primarily used in RTS assessments because they can be sport-specific and produce higher loads, which typically result in greater asymmetries[62]. These landing tasks can increase in difficulty throughout the RTS assessment to challenge the patient. However, few studies have tried to predict PIF asymmetry across these tasks. Understanding factors that can predict PIF asymmetries may be able to allow clinicians to individualize rehabilitation and reduce reinjury risk without expensive equipment needed to quantify forces. Therefore, this study examines the ability of common second ACL injury risk factors to predict PIF symmetry during unilateral and bilateral tasks.

Prior literature has looked at the influence of psychological components on performance, and it has expanded the understanding of athletes during rehabilitation[24–27,31–34,61,100]. These components include, but are not limited to, anxiety[95], fear[24–27], confidence[18,91–94], locus of control (LOC)[61,100] and have been shown to influence an individual’s movement and performance. The LOC has been measured in fewer studies than fear, confidence, or anxiety, but, in patients with ACLR, it has been associated with rehabilitation outcomes[61,100]. Different components within LOC have been found to impact knee function and mental health[100,141]. As tasks assessing performance throughout rehabilitation can increase in difficulty, this can result in emotions changing based on specific tasks. Different levels of these psychological components can have implications during rehabilitation and injury risk in patients with ACLR[25,26,35,95].

These components are typically measured by participants completing surveys and questionnaires during study visits[25,27,33,34,36,61,92,100]. Previous literature has described the scores from these assessments using the term ‘psychological readiness’[25,27,32,34,115,116]. Psychological readiness describes a patient’s psychological capability or preparedness to return to activity or sports[142]. To quantify these psychological components accurately and effectively, each of these methods must be reliable and valid[33,91,98,140,141]. Multiple questionnaires measure different psychological components. For example, previous literature has used the total score of the ACL-RSI survey when assessing fear and confidence in patients with ACLR[25,33,34,115,116].

Incorporating psychological components could allow for a holistic understanding of patients with ACLR and may predict loading asymmetry giving clinicians the ability to train the physical and psychological components of patients following ACLR. Multiple risk factors and psychological surveys can be recorded or collected in clinical settings, making these results translatable to improve rehabilitation for patients with ACLR. The results of this study may help clinicians individualize rehabilitation and ultimately decrease the reinjury risk for patients with ACLR returning to activity or sports. Therefore, the purpose of this study was to determine if psychological readiness M-LOC, GAD7, and ACL-RSI coupled with sex, graft type, time since surgery, and symmetry measures of quadricep strength, hop distance, jump height can predict PIF symmetry during unilateral and bilateral landings. We hypothesize that the M-LOC and

ACL-RSI scores, jump height and quadricep strength symmetry will predict PIF symmetry during the bilateral landings. In addition, we hypothesize that the M-LOC, ACL-RSI, and GAD7 scores along with quadricep strength and hop distance symmetries will predict the PIF symmetry during unilateral landings.

Materials and Methods

Participants

This study included up to 69 patients with ACLR that were medically cleared to RTS or had returned to sport activity. These participants were from a larger, ongoing study to develop a predictive model for second ACL tears (R01 AR078811-03). Patients with ACLR were included if they were between the ages of 13-25, had primary ACL reconstruction using an autograft, and had received clearance from a clinician or returned to sport.

Testing Protocol

All participants signed informed consent before beginning data collection. Following consent, all participants were asked to fill out multiple psychological surveys, the M-LOC, GAD-7, and ACL-RSI. The Generalized Anxiety Disorder (GAD-7) survey, ACL-Return to Sport After Injury (ACL-RSI), and the Multidimensional-LOC scale (M-LOC) have all been validated[91,98,143], and shown to produce reliable data[33,98,143]. The ACL-RSI and M-LOC surveys assess different emotions and beliefs[91,98,100]. Specific emotions scored in the ACL-RSI survey involve fear, confidence, and risk appraisal[91]. Each of these components are summed together to obtain a total ACL-RSI score. The M-LOC survey scores differing views on an individual’s control of their life, these include internal LOC, external LOC, doctors, and others[98]. The LOC refers to the perceptions of how much control an individual feels they have regarding their own life[96]. An internal LOC reflects the belief that the individual is in control of their life, can make their own decisions and change the outcome of decisions[96,97]. External LOC describes a belief that is centered around fate, minimizing the control an individual has on their own life[96,97]. Powerful others quantifies how much control or influence an individual feels other people have their life[98]. The components of the M-LOC survey are negatively correlated, which results in reverse scoring. This makes the total score difficult to interpret because it does not specify which component is scored higher or lower. To properly assess the M-LOC survey, each component was included as a factor in this study. Consent, psychological surveys, and all other study data, excluding loadsol data, was recorded and stored in REDCap, a secure database to store participant information.

To ensure each participant could safely perform the tasks following ACLR, multiple clinical assessments were performed. Participants were palpated to assess knee effusion, or inflammation, to ensure minimal or no effusion was present before performing the study tasks[69]. To assess the stability of the reconstructed ACL, Anterior Drawer test was performed to ensure the participant's knee was stable for data collection[144].

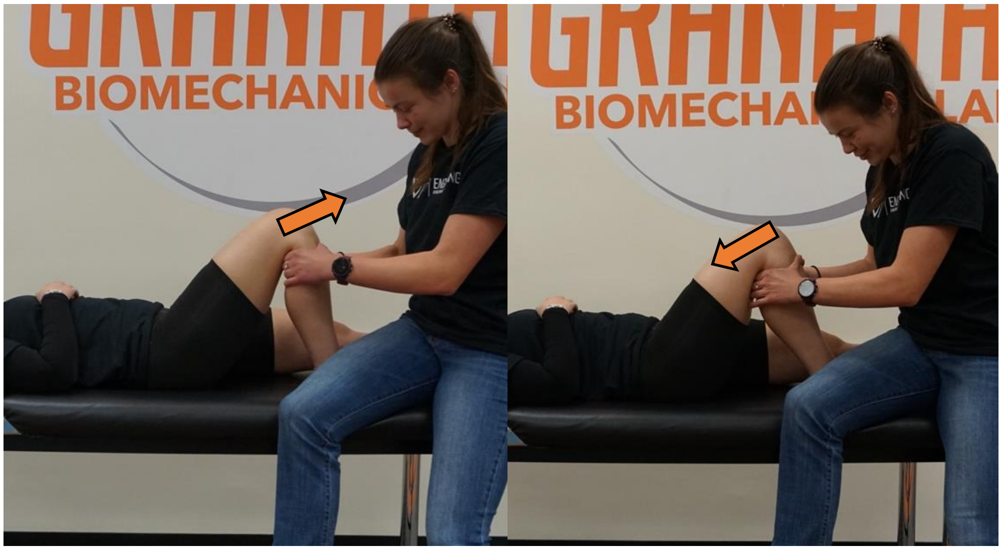


Figure 14 Performing Anterior Drawer Test

Upon completion of these clinical assessments, passive knee range of motion (ROM) and isometric quadricep strength were measured[144]. The passive ROM was calculated, with a goniometer, using the difference between relaxed knee extension and maximum knee flexion. Passive extension was found placing the goniometer on the participant's lateral epicondyle in line with the greater trochanter and lateral malleolus when the participant laid flat on a medical examination table. Maximum knee flexion, using the same goniometer positions, was found by bending the participants knee, while keeping their heel flat on the table, and pushing their foot as close to the glute as possible.

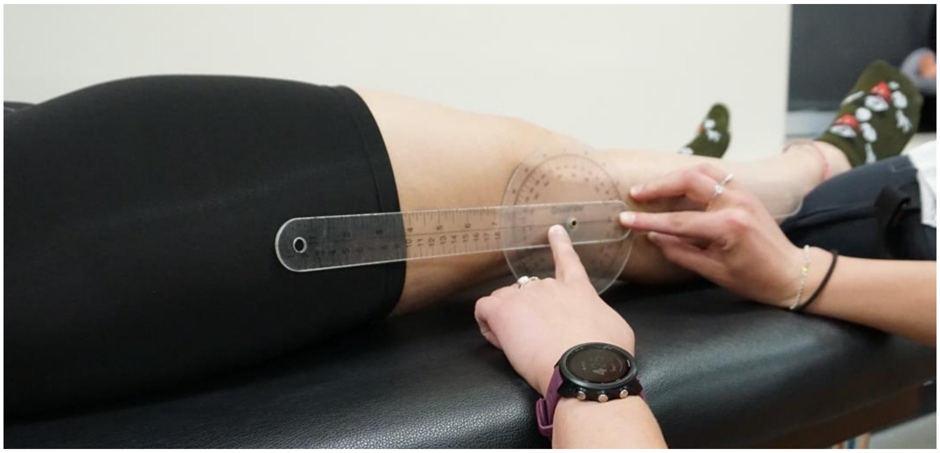


Figure 15 Calculating participant knee extension

Figure 16 Calculating participant knee flexion

Isometric quadricep strength was collected using a handheld dynamometer (Hoggan Scientific, LLC., Salt Lake City, UT). To isolate the quadricep muscle, the participant sat at the edge of the medical table with their knees off the table at 90 degrees and placed a cushion under their hamstring of the limb recording forces. A band was then wrapped around the leg of the medical table and placed loosely on the front of the participant’s shin, less than 5 inches above the ankle joint. The handheld dynamometer was placed between the shin and band. The band was tightened so the participants knee was at a relaxed 90-degree angle before beginning the strength measurement. The participant was told to not lean back and to place their hands on their thighs to ensure the isolation of the quadricep muscle. The participant was instructed to kick into the dynamometer for 3-5 seconds as hard as they could and then told to relax. Verbal encouragement was given while the participant kicked into the device. The moment arm, calculated from the lateral knee to the position of the dynamometer on the participant's shin was measured and used to normalize quadricep strength. This assessment was repeated for each limb until there were three measurements that were recorded and within 10% of each other to ensure accurate measurements. It was then performed on the other limb.

Figure 17 Performing quadricep strength assessment

Following these assessments, participants were given a pair Nike Zoom Pegasus (Nike, Inc., Beaverton, OR) running shoes to wear during data collection to standardize shoes[107]. These running shoes were fitted with loadsol® (novel electronics, Pittsburg, PA) sensors inside the shoe to collect the participant's normal force data during the tasks. These sensors have been included previous studies where they were found to be reliable and produce repeatable results[123,131]. The loadsols® were sampled at 200Hz[123]. The participant was then asked to warm up on the stationary bike for 5 minutes before calibrating the loadsols®. The sensors were then calibrated, tested, and then used to collect data for multiple tasks.

Figure 18 Loadsol® sensor

Figure 19 loadsol ® sensor inserted in standardized shoes

There were different sections of tasks. First included three different types of unilateral hop tests. The order of the unilateral tasks was the same for each participant. The first task was the single hop. The participant was asked to begin on one foot and then jump forward as far as they could while landing with control. Landing with control consisted of maintaining balance for minimum 2 seconds after takeoff. Hop distance was recorded. This was repeated, for both limbs, until three acceptable trials were obtained. An acceptable trial included landing with control.

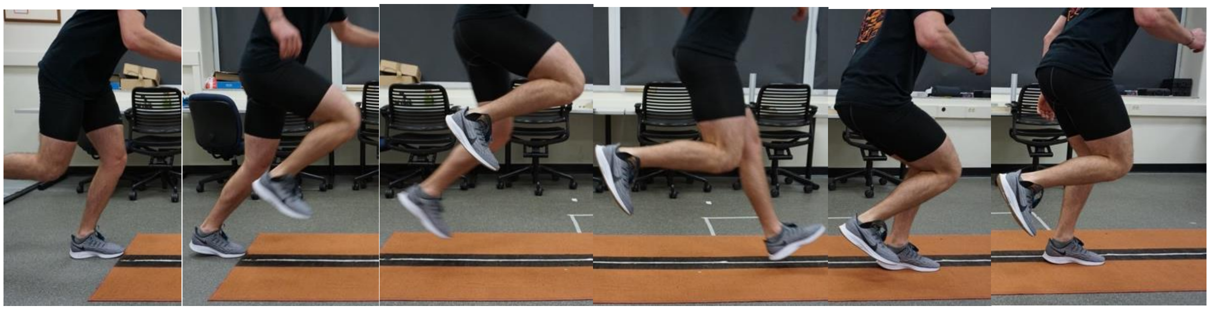


Figure 20 Participant performing single hop (SH)

Next, the triple hop was performed. This task required the participant to start on one limb again and hop forward three times continuously as far as they could, while maintaining control on the last landing. This was repeated until there were three acceptable trials on both limbs, and hop distance was recorded. An acceptable trial meant landing with control on the last landing.

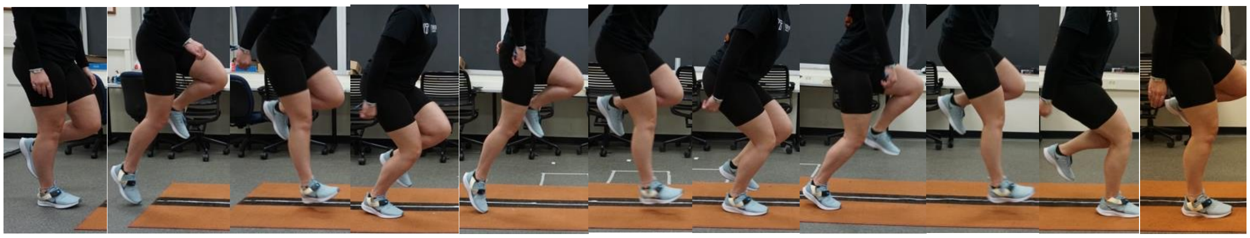


Figure 21 Participant performing triple hop (TH)

Lastly, the crossover hop was performed. This task was similar to the triple hop but added another level of difficulty. The participant was instructed to perform the same triple hop, but each landing had to cross medial or laterally by minimum 6 inches. This was done on both limbs, and repeated until the participant completed three acceptable trials on each limb. This included landing with control and jumping medial and laterally over six inches; any trials that landing less than that or without control was redone. Hop distance was recorded for this task as well.

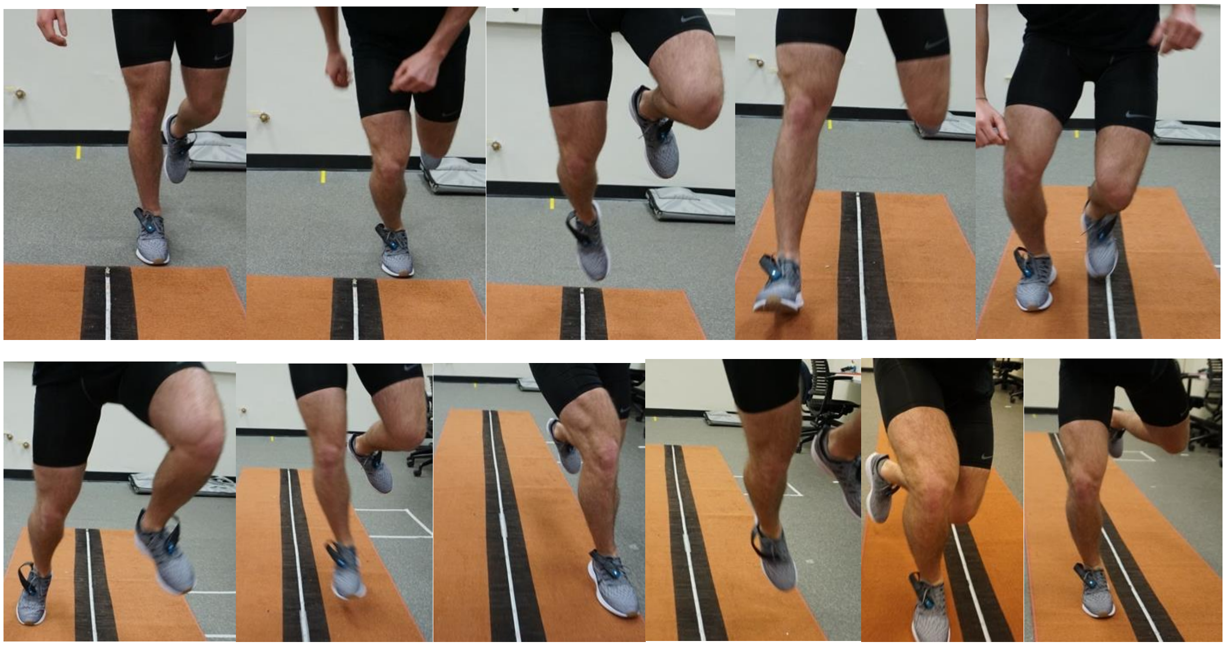
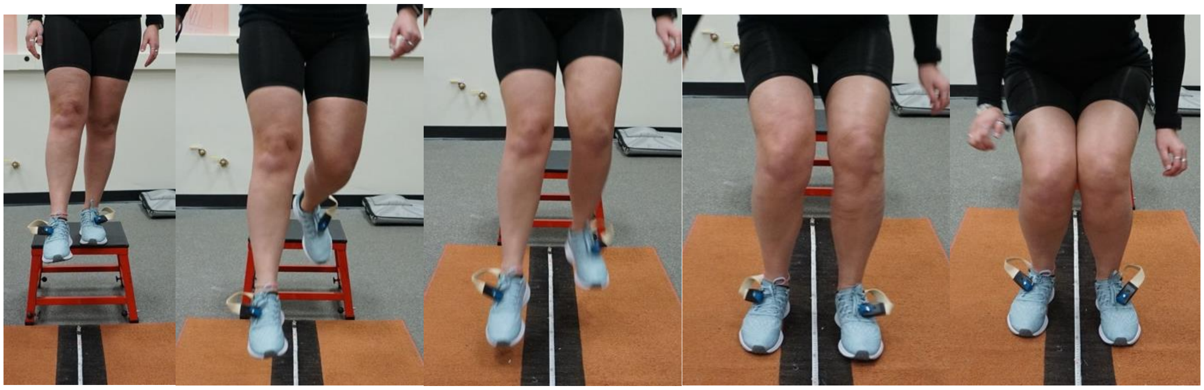


Figure 22 Participant performing crossover hop (CH)

Following the unilateral tasks, two bilateral landings were performed. The drop vertical jump (DVJ) consisted of beginning on top of a 20 cm box, then following forward a distance above half of the participant’s height, landing bilaterally and quickly jumping vertically as high as possible. This task was repeated until there were three acceptable trials. An acceptable trial was on that landed the second landing with control, and the second jump was purely vertical so the forward momentum from the initial takeoff from the box had ceased.



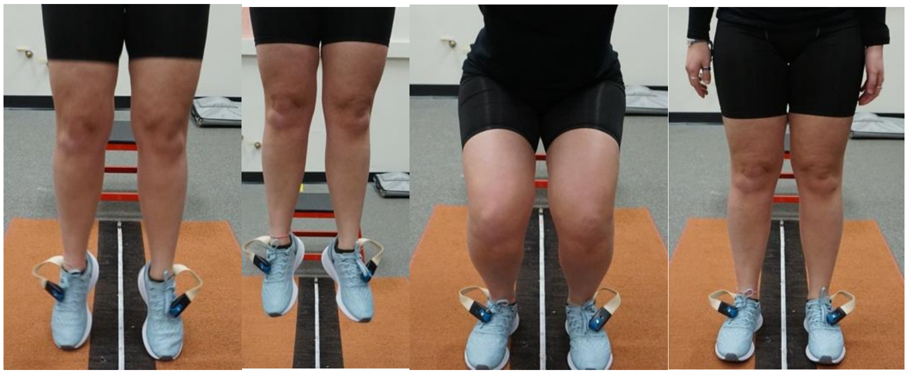


Figure 23 Participant performing drop vertical jump (DVJ)

The last task the participants performed was the stop jump (SJ). This task consisted of a few jogging steps forward, leaping forward off one foot, to then land on both feet and jump vertically as high as possible. Similarly to the DVJ, this was completed until three acceptable trials were obtained. An acceptable trial consisted of landing with control after the vertical jump, and ensuring the second jump was mainly vertical.

Figure 24 Participant performing stop jump (SJ)

Data Analysis

A custom MATLAB script was using to analyze all loadsol® data, LAP Analysis (https://github.com/GranataLab/LAP) 12. PIF loadsol® data was normalized to BW. All data external to loadsol® was collected and exported from REDCap.

Statistical Analysis

Cohen's d recommends 7 participants per factor included in a multivariate regression model[145]. Each regression model included 9 factors. Therefore, the minimum sample size determined for this study was 63 participants. There were 63 participants included in the unilateral tasks' regression models and 69 participants included in the bilateral tasks' regression models. The same 53 participants were included in both models. 10 and 16 differing participants were included in the unilateral and bilateral models, respectively.

Inclusion of surveys into studies requires certain levels of reliability to ensure the quality of the results[140,146]. Internal consistency, or reliability, is a measurement of survey's questions inter-relatedness[140]. To ensure reliability in the survey results within each participant, Cronbach's alpha was calculated for each survey[146]. Each of the surveys or survey components were included in the predictive model as factors if their reliability was greater than or equal to .71. The reliability of the participant's responses is important to ensure accurate results when used for further statistical analysis[146].

Table 2 Psychological Survey Reliability Coefficients

	GAD-7	**ACL-RSI**	**M-LOC INTERNAL**	**M-LOC EXTERNAL**	**M-LOC DOCTORS**	**M-LOC OTHERS**
CRONBACH ALPHA RELIABILITY COEFFICIENT	α= .79	α= .93	α= .79	α= .71	α= .53	α= .73

Pearson product moment correlation coefficients were calculated in RStudio (RStudio, Boston, MA) to identify the relationship between factors in unilateral and bilateral datasets. No factors included in any unilateral or bilateral models were highly correlated (r= 0.7)[147], therefore all factors remained acceptable for the models. Hop distance symmetries were included in each task's respective model. The .78 correlation between the SH and TH hop distance symmetry was ignored because they were not included in the same model.

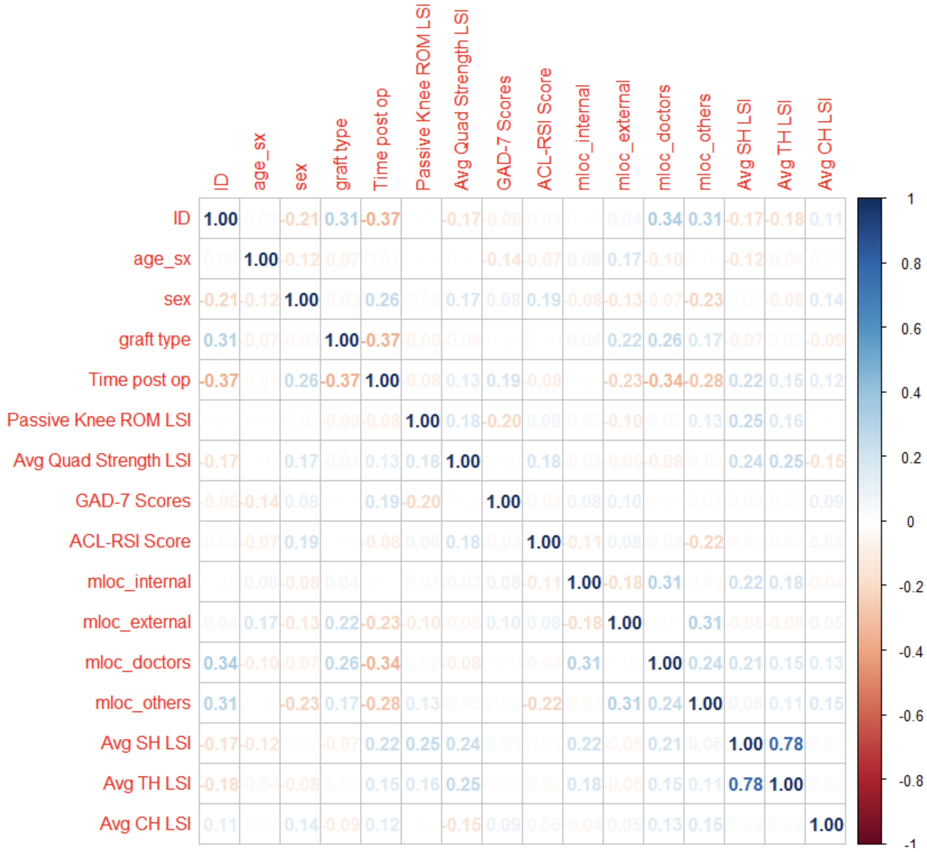


Figure 25 Unilateral landing correlation coefficients for all factors

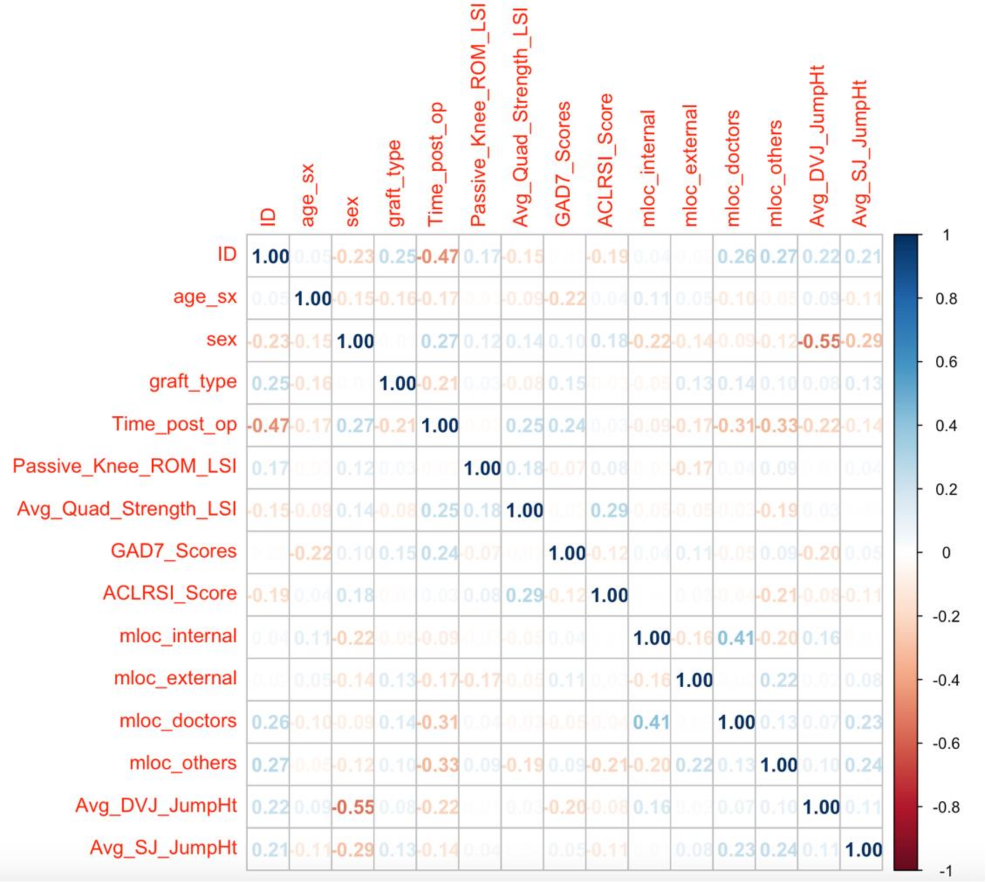


Figure 26 Bilateral landing correlation coefficients for all factors

A backwards stepwise multivariate regression model was used to assess the predictability of multiple factors on unilateral and bilateral landing PIF symmetry. This consists of all factors being combined in the statistical model at once, and removing factors based on a significance, or p value[148]. The model calculates an Akaike Information Criterion (AIC) value for each factor[149]. The AIC is an estimate of the prediction error and is used as a ranking of how significant each factor is to the model[149]. A lower value of the AIC is the better for both the model and factors trying to predict the output variable[149]. Each factor is either included or removed one at a time from the backwards regression model based on the value of its AIC. The model removes all the factors that increase the AIC and keeps only the factors that decrease the value[148]. The lowest AIC is determined by the factors in the model that are best fit to explain the predictable variable[149].

There were three different unilateral landing tasks included in this analysis, single hop (SH), triple hop (TH), and the crossover hop (CH). Two bilateral landing tasks were included in this analysis, drop vertical jump (DVJ) and stop jump (SJ). There were 9 factors able to be included in the regression model due to our sample size.

Table 3 Factors Included in Bilateral and Unilateral Regression Models

Tasks	Factors Included in Regression Models								
Unilateral Landings	Age at Surgery (years)	Sex	Time post-op (months)	Quad Strength LSI	GAD7 scores	ACL-RSI scores	MLOC internal scores	MLOC external scores	Hop distance LSI
Bilateral Landings	Age at Surgery (years)	Sex	Time post-op (months)	Quad Strength LSI	GAD7 scores	ACL-RSI scores	MLOC internal scores	MLOC external scores	Jump Height

The backwards stepwise multivariate regression model was run for each task, a total of five models were ran, and determined which factors best predicted PIF symmetry.

Results

Table 4 Patient Demographics

	n =	Sex	Age at Surgery (years)	Sx Limb	Graft Type	Time after ACLR (months)
Unilateral Landings	63	M: 35 F: 28	19.2 ± 3.06	L: 26 R: 37	BTB: 44 Quad: 19	10 ± 2.56
Bilateral Landings	69	M: 41 F: 28	19.3 ± 3.1	L: 28 R: 41	BTB: 44 Quad: 25	9.45 ± 2.37

Age at Surgery and Time after ACLR is mean ± standard deviation.

Single Hop

Four variables were determined in the initial backwards regression model for the single hop task. Together, sex (p= 0.0034), time following surgery (p= 0.16), average hop distance symmetry (p=.0004), and GAD7 scores (p= 0.037) had an R^2 = 0.3722. A final backwards regression model included only the significant factors, sex (p= 0.0009), average hop distance symmetry (p= 0.0001), and GAD7 scores (p= 0.06). These factors resulted in an R^2= 0.3512. This indicates a model that could explain 35.12% of the variance of this task's PIF landing symmetry.

Triple Hop

This model had four variables from the initial backwards regression model for triple hop PIF landing symmetry. These variables include sex (p= 0.0015), average hop distance symmetry (p< 0.0001), ACLRSI total score (p= 0.16), and MLOC external scores (p= 0.008). The R^2 = .4422. Using the significant factors only, sex (p= 0.003), average hop distance symmetry (p< 0.0001), and MLOC external scores (p= 0.005), were included in a final backwards regression model. This resulted in an R^2= 0.423. Therefore, 42.3% of the variance in this task's PIF landing symmetry could be explained by this model.

Crossover Hop

Similarly to the previous tasks, there were four variables included in the initial regression model for the crossover hop task. Sex (p= 0.01), time following surgery (p= 0.0028), GAD7 scores (p= 0.11), and MLOC internal scores (p= 0.07) were the remaining variables with an R^2 = .3017. Sex (p= 0.02) and time following surgery (p= 0.006) were included in final regression model, with a resultant R^2= .234. These factors were able to explain 23.4% of the crossover hop's PIF landing symmetry variance.

Drop Vertical Jump

Average jump height (p= 0.063), GAD7 scores (p= 0.0022), and MLOC internal scores (p= 0.046) were included in the initial model for DVJ PIF symmetry. This model had an R^2= .2404. The final regression model included GAD7 (p= 0.0006) and MLOC internal scores (p= 0.09), which could explain 19.8% of the variance in DVJ PIF landing symmetry.

Stop Jump

MLOC internal scores (p= 0.042) was the only factor that was kept in the regression model for predicting SJ PIF symmetry. The R^2 for this model was equal to 0.06.

Discussion

The purpose of this study was to determine if psychological survey score components coupled with known risk factors for an ACL reinjury could predict PIF landing symmetry. This study looked at PIF symmetry in both unilateral and bilateral tasks. With ACL reinjury rates between 10-25%[3,10–15], there is a need to identify predictive factors to decrease this reinjury risk. This study found these psychological components are needed to understand the participant's risk holistically instead of solely performance metrics.

In unilateral landings, each initial model had a variance greater than .30. Variance between .30-.40 is considered a lower predictive model, and .41-.6 is considered a medium amount of variance when assessing psychological factors[150]. Multiple models included both typical risk factors from previous literature and psychological components. The final regression models only included factors with p values less than 0.05 to determine which factors most significantly influenced PIF symmetry. Sex was significant in each unilateral final model. Females were predicted to have greater PIF asymmetry then males in SH, TH, and CH tasks. These results indicate sex can influence levels of PIF asymmetry differently across multiple unilateral landing tasks. This aligns with previous literature stating females are at higher risks for reinjury due to greater asymmetries are associated with reinjury risk[3,4,10,29,30,40,82]. Average hop distance symmetry was factor in both the SH and TH final models. As hop distance symmetry increased during these tasks, PIF asymmetry also increased. This supports previous findings of hop distance symmetry greater than 10% asymmetry was associated with second ACL injury[86]. Time following ACLR was included in the initial models of SH and CH, but significant for only the CH. In this model, increase in time following ACLR also resulted in increased PIF asymmetry. This does not agree with previous literature[86], but may be explained by the lack of participants, 17, enrolled in the study before nine months following ACLR. The average time following reconstruction to RTS was 10 months for participants included in this analysis.

Psychological survey responses were included in each initial regression model predicting landing PIF symmetry. A final regression analysis with only significant factors from the initial model that included psychological factors in each task except the CH. These results provide evidence psychological readiness is important to consider when assessing performance in patients with

ACLR. The GAD7 scores were included in the SH and DVJ final models. Low general anxiety scores were associated with higher PIF asymmetry in SH, while the opposite was true for DVJ. These results both agree and disagree with previous literature that identified differences in typical daily activities, such as gait, based on higher levels of anxiety and depression[95,151]. Differences in tasks may influence PIF symmetry. ACL-RSI scores was included as a factor in the initial TH regression model, along with hop distance, MLOC external scores, and sex, but was not included in the final model. Previous literature determined higher ACL-RSI scores is commonly used to measure psychological readiness to RTS[33,34,115,116]. Peebles, A et al., identified ACL-RSI scores, along with graft type and jump height, to predict knee motion symmetry, which is another risk for a second ACL injury[25,87]. ACL-RSI scores may be significant depending on task. This further emphasizes the importance of including different psychological surveys when assessing patients with ACLR. Lastly, internal and external components of the M-LOC survey were included as factors in three final regression models. Internal LOC scores was a significant factor for DVJ and SJ tasks. As internal LOC scores decreased, SJ PIF asymmetry increased, while higher internal LOC scores were associated with higher PIF asymmetry in DVJ. Similar to GAD-7, these results do not completely agree with previous literature but may be due to different tasks used during assessments. External LOC was included in the final regression model for TH. Higher external LOC scores resulted in lower PIF asymmetry. This finding suggests the belief of less control over an individual's actions may contribute to similar performance between limbs following ACLR.

The only final models with variance greater than .30 were SH and TH. Therefore, the CH, DVJ, and SJ may not provide strong, translatable results. This was surprising because a previous study found multiple factors predicting knee motion during a SJ task[25], and these tasks were chosen based on popular RTS performance tasks[34,72,86,104,111]. Therefore, the first hypothesis was not supported. The models obtained for CH, DVJ, and SJ did not produce a high enough variance to be an effective predictive model. However, the second hypothesis was somewhat supported. While quadricep strength was not a factor to predict PIF symmetry, each psychological component was included in an initial regression model, and in both final models with good variance. We hypothesized differences in psychological components between unilateral and bilateral tasks due to task difficulty but observed this difference within each unilateral task. The

GAD-7 score was a final factor in SH, while external LOC score was a factor included in the TH final model. This may be due to greater involvement needed to perform the TH compared to the SH. The results of this study are incredibly important because it is clear there are psychological components that influence landing symmetry, which is ultimately a risk factor for an ACL reinjury. This also presents opportunities for clinicians to be able to predict asymmetry during SH and TH tasks without needing expensive equipment to collect load. Understanding relationships between biomechanical and psychological data can improve rehabilitation for patients with ACLR and potentially help clinicians better individualize their clinical care.

Limitations

There are limitations within this study that must be addressed upon the interpretation of the results. Unilateral and bilateral PIF data was calculated using different symmetry indexes. One of the most common symmetry indexes used in biomechanics literature is the LSI, while the NSI is a modification of the SI. Calculating symmetry is the quantifying differences in a metric between limbs. However, this is typically done when both limbs perform a movement at the same time. The bilateral landings were calculated using the NSI because the PIF symmetry can be calculated at the same time, making it a true symmetry comparison. Unilateral landings occur at separate instances, and symmetry indexes can be used to quantify the limb differences. The LSI equation is used more often during rehabilitation and in clinical settings to compare limb differences. Therefore, to quantify the limb differences using symmetry, the LSI equation was used. Additionally, jump height was calculated using flight time[152]. Lastly, the results of this analysis must be repeated. Repeatability of these results would provide strong evidence of the predictive behavior.

Conclusion and Future Directions

All in all, this study found GAD7, ACL-RSI, and M-LOC surveys can be included in a backwards multivariate stepwise regression model to predict PIF symmetry in unilateral landings. These results provide evidence that incorporating psychological surveys are an important component in understanding movement and assessing injury risk following an initial ACLR. There is a need to assess performance which includes psychological readiness. Future studies should investigate different components of psychological surveys that target specific emotions, such as fear and confidence. Additionally, more sport-like tasks can be included in future studies to assess GRF symmetry and psychological components.

Chapter 5: Conclusions

Over 200,000 ACL reconstruction surgeries are performed each year[2,6–9]. An ACL injury has become one of the most common knee injuries, specifically in athletes[1–4]. Athletes experiencing ACL injuries has been increasing over the last 20 years[4], and that likelihood of that injury can change based on numerous factors. Following the initial injury, the reinjury rate increases to 10-25%[3,10–15]. This rate can be impacted by similar factors as the first injury, including age[11,49,79,83,89,90], sex[3,4,10,14,29,30,40,82], graft type[22,29,73], time following ACLR before RTS[46,47,69,74], and activity level[3,42,48,49,73,75,103]. In addition, there has been a recent increase in studies assessing psychological readiness following the initial ACL injury. Psychological readiness refers to the athlete's ability to respond to the stimulus presented in sport[142]. Previous literature has found relationships between specific emotions or beliefs, such as confidence[18,91–94], fear[24–27], and locus of control[61,100]. Few studies have included psychological components when identifying predictive factors of second ACL injuries. There are many different psychological surveys measuring different ideas and emotions that have yet to be included in studies investigating their implications on patients with ACLR upon RTS. While incorporating both physical and psychological factors when assessing performance has improved, there is an aspect of ACL injury research that many studies overlook. The interpretation of and the actual results are based on how data is collected and processed. Many of the methods and techniques commonly used are based on assumptions made by the biomechanics scientific community. These assumptions are often based on research involving healthy control participants. Data processing methods, such as normalization, have been proven not to skew data, but this has not been done within clinical populations. Patients with ACLR are a heavily researched clinical population that often use analysis methods that have only been assessed using healthy individuals. The overall goal of this research is to translate results to clinicians, surgeons, and patients to decrease injury risk and improve rehabilitation outcomes. Yet, without understanding if the assumptions surrounding common data processing methods, data may be less accurate and not interpretable. Not only is there a need to include more psychological factors when assessing performance following an initial ACLR, but identifying analysis methods that may differ within clinical populations is imperative to the continued advancement of communicating translatable, reliable research.

The first purpose of this study was to identify whether a common normalization technique resulted in different outputs when compared between patients with ACLR and healthy controls.

This was done looking at multiple symmetry metrics between participant groups. Previous literature has identified timing differences in patients with ACLR during bilateral landings that are greater than healthy controls[133]. Using a stop jump task, PIF, LR, impulse, and time to peak was calculated for each limb. Each metric was calculated using percent stance and time independent normalization. The results of this analysis concluded there were differences between the methods and groups. Normalizing to percent stance increased average asymmetry in patients with ACLR in all PIFs, LRs, and impulse metrics. The time independent method may report more accurate symmetry percentages across multiple metrics. This information is incredibly important for clinicians when assessing performance of a patients with ACLR wanting to RTS. Many times, their clinical decisions are based on symmetry, and using percent stance normalization may show lower asymmetry values, which can lead to an athlete being released to RTS earlier and have a higher risk for reinjury. Identifying methods that most accurately depict results of a clinical population is important when translating and interpreting findings to clinicians, surgeons, and patients.

The second purpose of this study was to include psychological components, GAD7, M-LOC, and ACL-RSI surveys, coupled with known risk factors for a second ACL tear to predict landing PIF symmetry in unilateral and bilateral landings. The risk factors included age at surgery, sex, graft type, quadricep strength symmetry, average jump height symmetry, and average hop distance symmetry. A backwards multivariate stepwise regression model was used to determine only unilateral landing predictive models could explain an adequate amount of variance within the PIF landing symmetry. Each task had final regression models that included four factors to predict the respective task's PIF symmetry. Sex, average hop distance symmetry, and GAD7 scores explained 35% of the variance in SH PIF symmetry. Sex, average hop distance symmetry, and M-LOC external scores explained 42% of the variance in TH PIF symmetry. The results from this analysis determined the psychological components coupled with known risk factors influences PIF landing symmetry across different unilateral tasks. Overall, psychological components contribute to predicting movement changes following an ACLR which may be able to reduce injury risk. This can be beneficial for clinicians and surgeons when assessing performance and identifying risk factors of patients with ACLR wanting to RTS. Clinical settings can predict PIF symmetry in SH and TH without expensive, laboratory equipment typically needed.

Limitations within this study include the different sampling rates of loadsol data. The first purpose of the study sampled at 100Hz, while the second purpose sampled at 200Hz during quick, high-load movements. In addition, participants in both aims of the study did not span wide ranges in certain qualities. The first aim's healthy control population had only right limb dominant participants, and the second purpose did not have many participants that RTS between five to nine months following ACLR. Despite these limitations, the findings of this study provide evidence to ensure data analysis assumptions are tested within different clinical populations and that psychological components can influence landing symmetry within these clinical populations.

Future studies should compare the normalization methods using force plates that can record at higher sampling rates. This would increase the amount of evidence that clinical populations may not adhere to the same assumptions as healthy control participants. In addition, future studies should repeat this study and could include additional psychological surveys or components that measure different emotions. More information how different emotions can influence movement can help clinicians individualize rehabilitation in clinical settings and potentially result in improved rehabilitation outcomes.

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