Determining Sex-specific Differences in Gait Symmetry during Walking and Running in Participants who Have Undergone Anterior Cruciate Ligament Reconstruction at the Time of Release to Sport using a Wearable In-Shoe Sensor

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Abstract

Anterior cruciate ligament reconstruction (ACLR) is something many athletes may experience during their career due to a torn ACL. This study included ACLR athletes after their rehabilitation process, before returning to their sport to assess gait symmetry during walking and running trials using wearable in-shoe sensors to specifically measure average loading rate (ALR), peak impact force (PIF), and impulse symmetry (IMP). This study utilized 40 athletes (20 males and 20 females) from various sports, ages ranging from 14 to 21 years of age with females having 7 right limb and 13 left limb ACLRs, and males having 9 right limb and 11 left limb ACLRs. Females showed higher levels of asymmetry in their limbs that underwent ACLR during both walking and running trials compared to males. Additionally, females showed a tendency to spend less time on their surgical leg when assessing PIF during walking. Conversely, during walking and running trials assessing left limb ACLRs only, females showed higher levels of asymmetry in offloading their weight from their non-surgical limb when assessing PIF and IMP. In addition, females showed higher levels of asymmetry during average loading rates (ALRs) in both walking and running compared to males when assessing right limb ACLRs only. More research into right ACLR to left ACLR differential outcomes between males and females should be conducted in order to validate these findings, since leg dominance can play a role in the initial injury. The use of wearable technology for gait assessment should be implemented in other laboratory settings as it is a valuable and accessible tool for measuring gait symmetry. This data is valuable for any clinician involved in the rehabilitation process for the athlete. In conclusion, females tend to show higher levels of asymmetry in comparison to males after ACLR.

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Introduction

The purpose of this study was to understand the sex-specific differences in gait symmetry in walking and running exercises in athletes at the time of their release to sport after an anterior cruciate ligament repair (ACLR). These measures were collected using the loadsol® wearable technology in shoes. ACL (anterior cruciate ligament) tears are among the most sustained injuries in athletics where roughly 150,000 injuries occur yearly (Barry P. Boden, n.d.). After sustaining an ACL tear, recovery is crucial in ensuring the athlete can return to sport. Surgical interventions and extensive rehabilitation processes are often required for athletes to return to their sports. After undergoing the rehabilitation process, it is essential to assess and correct gait abnormalities to prevent future injuries.

The knee joint is comprised of two main bones: the femur and the tibia, and a smaller bone, the patella (Cleveland-Clinic, 2023). Additionally, the knee joint is comprised of other essential pieces including the meniscus and several key ligaments (lateral and medial collateral ligaments and the anterior and posterior cruciate ligaments). The knee joint is classified as a synovial joint meaning that it is comprised of a cavity in which one bone fits into the groove of another bone and is surrounded by synovial fluid. Because of this specific anatomy, it allows for synovial joints to have the most freedom in movement. The ends of the bones in synovial joints are covered in hyaline cartilage. Additionally, synovial joints have synovial membranes which are essentially fluid filled sacs that are there to lubricate and protect the given joint providing extra cushioning and decreased friction. Functionally, the knee operates as a hinge joint. All hinge joints follow the simple idea that the joint opens and closes in one direction (see Figure 1).

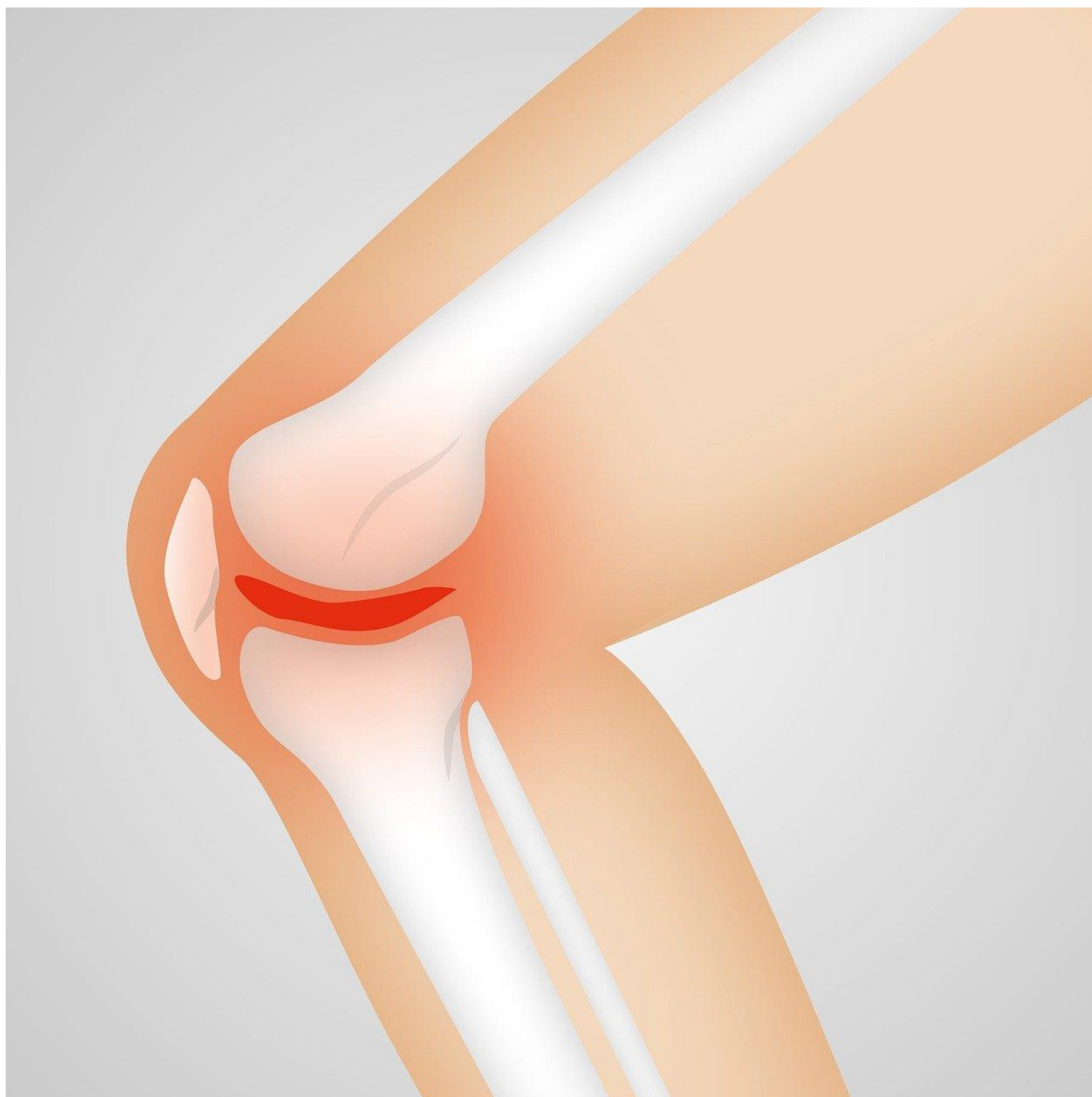


Figure 1. Figure displays a cartoon image of a human synovial knee joint (Pixabay, 2017).

The two cruciate ligaments that are found in the knee joint are the anterior cruciate ligament, or ACL, and the posterior cruciate ligament, or PCL. These go through the joint and are located on the anterior (front) and posterior (back) aspects of the joint respectively. The two ligaments cross over each other to make an “X” in order to connect the femur to the tibia. These ligaments are responsible for how the knee is controlled in a front to back movement, reducing

excessive shear forces. The ACL is particularly important for stabilizing the knee in rotational movements. ACL injuries are commonly experienced when an individual comes to an abrupt stop, changes directions too quickly, or jumping or landing in a compromised position (Mayo-Clinic, 2022). Individuals who experience a tear to their ACL often feel or hear a popping sensation. This typically leads to increased swelling to the knee joint and subsequently it is difficult for the individual to bear weight on the extremity. Athletes with ACL tears likely must undergo surgery to repair the torn ligament before returning to sport to ensure their ACL can withstand the cutting, pivoting, and jumping movement associated with sports. Surgery is then often followed by a rehabilitation process.

After an injury is sustained to the ACL, it is typical for reconstruction surgery to be scheduled 3 to 6 weeks out from the injury (Shevaun Mackie Doyle & Daniel W. Green, 2024). The reason surgeons do this is because it allows the initial inflammation in the joint to decrease and the patient can return to more normal levels of knee flexion and extension. During an ACL reconstruction surgery, surgeons often replace the ACL using a graft. Surgeons can choose between two types of grafts: autografts and allografts. A graft is tissue taken from one part of a body and used to replace injured tissue. An autograft comes from the patient's own tissue supply, whereas an allograft is tissue that is often harvested from another human donor.

To begin surgery, the surgeon makes one or two small incisions around the knee joint to allow for surgical instruments and the arthroscopic camera (Shevaun Mackie Doyle & Daniel W. Green, 2024). Once the camera is inserted, saline solution is added to the joint in order to increase space and visibility in the joint. Next, the surgeon harvests the graft of their choice, unless a donor graft is being utilized. Most commonly, surgeons will use either the patellar tendon or the hamstring tendon as the chosen graft for the reconstruction. Typically, a tunnel is drilled into both the femur and the tibia at a fifty-five-degree angle to simulate the angle of the

ACL and the graft is threaded into the knee and two screws are drilled in both ends of the tunnel, securing the graft into place. After these steps are complete, the surgeon will remove their instruments and close the incisions created. Immediately following surgery, the surgical leg is placed in a brace (see Figure 2).

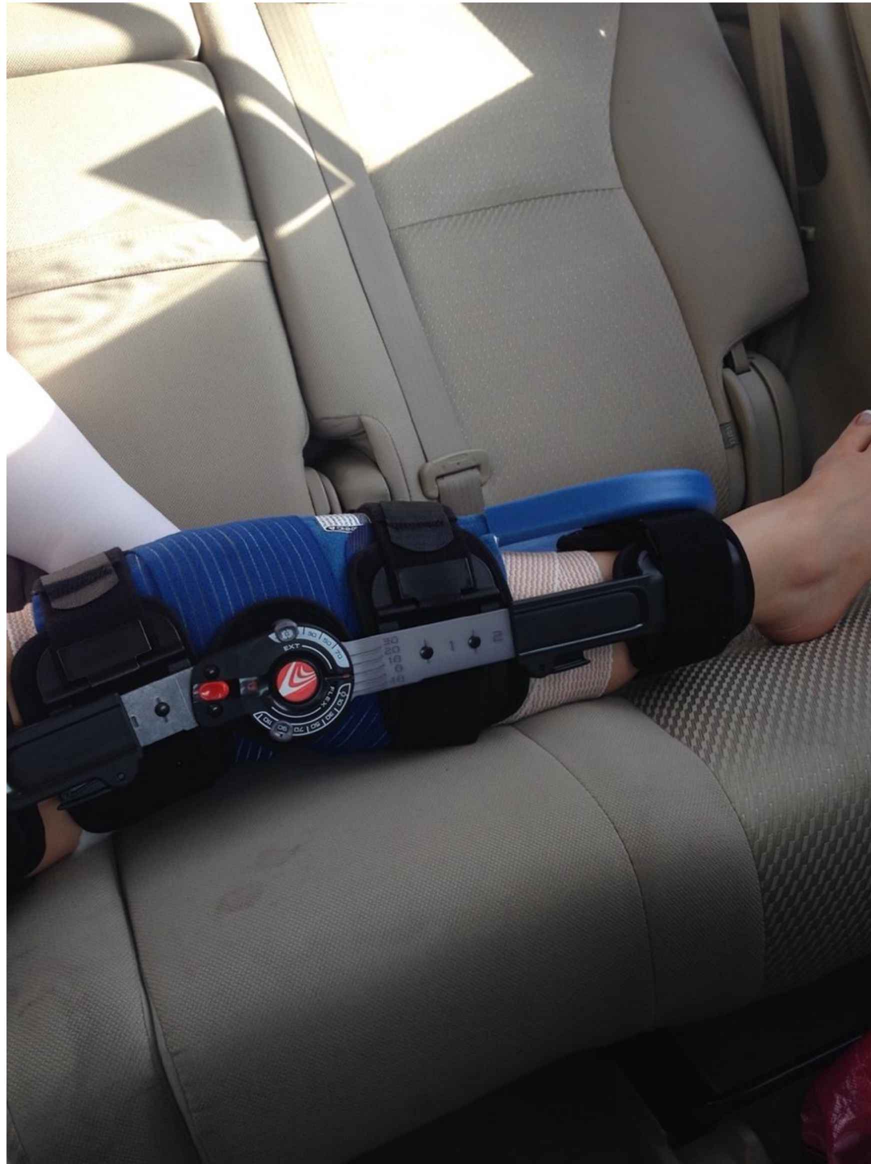


Figure 2. Figure displays a person in a full leg knee brace.

The process of rehabilitation following an ACL reconstruction often takes place over nine to twelve months (Massachusetts-General-Brigham-Sports-Medicine, 2021). Each surgeon

typically has their own protocol they want their patients to follow. Additionally, all patients heal at different rates. Consequently, it makes it difficult for there to be a true standard for recovery protocol. Typically, the rehabilitation process is sectioned into anywhere from three to six phases. Massachusetts General Brigham Sports Medicine has produced one of the most comprehensive ACL protocols in the country. It is noted that the exercises listed are not an exhaustive list and therapists should use their discretion when progressing and beginning new exercises (Massachusetts-General-Brigham-Sports-Medicine, 2021).

Phase one lasts approximately one to two weeks and usually consists of controlling the pain and decreasing the swelling (Massachusetts-General-Brigham-Sports-Medicine, 2021). During this period, it is common for patients to utilize the use of ice, elevation, and anti-inflammatory medications. Patients in this phase often begin weight-bearing with the aid of crutches and later progress to be independent of crutches. Exercises during this phase consist of gentle strengthening such as calf raises, isometric quadricep contraction, straight leg raise, etc. Phase two begins around three to five weeks after surgery (Massachusetts-General-Brigham-Sports-Medicine, 2021). During this phase of recovery, patients are encouraged to increase strength, mobility, and range of motion. Patients are progressed to more challenging strength building exercises such as squats, hamstring curls, bridges, etc. and encouraged to use a stationary bike to increase mobility and range of motion. Patients are also progressed to proprioception exercises such as balancing on the operative leg.

Massachusetts General Brigham Sports Medicine considers phase three to occur approximately six to eight weeks post-operatively (Massachusetts-General-Brigham-Sports-Medicine, 2021). Some goals for this phase of rehabilitation include gaining full range of motion and progressing intensity of cardiovascular and strengthening exercises. Patients can begin more challenging aerobic machines such as the elliptical or stair climber, as well as the use of a pool to

begin jogging. Strengthening exercises can progress to machines such as the leg press, hamstring curl machine, and the hip abductor and hip adductor machine. Other exercises can include squatting to a chair, lateral lunges, and Romanian deadlifts, as well as progression with single leg activities.

Phase four typically begins nine to twelve weeks after surgery and this phase just adds on to the existing exercise program (Massachusetts-General-Brigham-Sports-Medicine, 2021). Whereas the phases before the exercises were progressing to new exercises, this phase focuses on increasing the weights, repetitions, etc. in order to continue increasing strength. During this phase, patients begin exercises that have them training movement that replicate their sport, but at a sub-maximal level. Additionally, plyometric exercises are added into the program. Phase five generally lasts three to five months post-operatively and begins the early stages of returning to sport (Massachusetts-General-Brigham-Sports-Medicine, 2021). During this phase, patients begin an interval running program as well as progressing their plyometric and agility program. Phase six, and typically the final phase, occurs six or more months past surgery and is aimed to give patients unrestricted ability to return to sport (Massachusetts-General-Brigham-Sports-Medicine, 2021). This phase allows patients to continue with their agility and plyometric program and begin including hard cutting and pivoting movement. After these movements are completed with no pain, then patients can begin returning to practice. Typically, they begin with non-contact practice, followed by full practice, and finally the patient can return to full play.

After the rehabilitation process, athletes can still experience deficits such as gait asymmetry which can cause an imbalance in peak impact force (PIF), impulse symmetry (IMP), and average loading rates (ALRs), and may put individuals at an increased risk of reinjury. There are various ways that these deficits can be tested. Common use of technology includes force plates, high speed videos with the use of biomarkers, and sensors worn on the body or in the

shoes. In-shoe technology can be useful for athletes because it can efficiently measure the movement of the athlete in any setting and in any shoe. The loadsol® brand insole is a mobile system that is able to measure plantar force and ground reaction forces in both standing and dynamic movements (North-America-Novel, n.d.). The loadsol® consists of one flat, yet flexible, sensor that covers the bottom of the foot. The loadsol® works by measuring the force between the foot and the shoe, regardless of which part of the foot is in contact with the insole.

The purpose of this project was to assess sex differences in gait symmetries as assessed via ALR, PIF, and IMP in walking and running trials. Secondly, the purpose was to identify differences in gait symmetry depending on whether the injury occurred in a left or right leg and whether these differences were apparent in both males and females since males typically injure their dominant leg and females tend to injure their non-dominant leg in specific sports-related injuries (Van Melick et al., 2017).

Literature review

Gait symmetry

Gait is referred to as one's consecutive sequence of steps in either a walking or running pace (Merriam-Webster, n.d.). Symmetry of gait is important when understanding functionality. Gait symmetry assumes identical function between a left and right limb when walking or running (Wu & Wu, 2015). After undergoing an anterior cruciate ligament reconstruction (ACLR), a person's gait symmetry can be affected negatively, although restoration in gait symmetry is possible during rehabilitation.

Hadizadeh et al. conducted a study to measure gait patterns and their symmetries in athletes with ACL reconstructions during their rehabilitation program (Hadizadeh et al., 2016). The researchers measured components such as cadence, weight acceptance time, and velocity. After three months, the researchers used symmetry indices (SI) to assess symmetry, and no significant differences were found between the post-operative group and the healthy control group when measuring gait components. The research suggests that symmetry was restored around 12 to 13 weeks post-reconstruction. Winiarski et al. saw similar results where they conducted a study to evaluate gait kinematics and symmetry during the early stages of physical therapy after ACL reconstruction (Winiarski & Czamara, 2012). The researchers measured aspects from the participants' gait such as velocity, gait frequency, and the swing and stance phase durations. The individuals were examined using a movement analysis system during their physical therapy programs assessment of gait kinematics including the dynamic range of motion in the knee joint and gait asymmetry coefficients were evaluated. In the ACLR group, there was a statistically significant increase in the length of stance phase and the range of movement significantly improved from 25.5 degrees to 63.7 degrees. The stance time asymmetry coefficient

decreased from 68.5% to -0.4%. The researchers highlighted a significant improvement in gait in ACLR patients from week two to week twelve. Lastly, Pfeiffer et al. sought out to assess peak knee biomechanics and limb differences 6 or more months after ACLR (Pfeiffer et al., 2018). The researchers determined that essentially all associations being measured were found to be negligible and non-statistically significant, although the span of time since ACL repair ranged from 6 months to over 13 years. These associations included both asymmetries in walking gait and jump landing tasks.

Conversely, not all studies show gait symmetry being fully restored after ACLR. Moya-Angeler et al. conducted a study to evaluate functional status prior to, as well as after ACLR, to analyze changes in kinetic patterns of the lower limb during the gait, sprint, and three hop tests (Moya-Angeler et al., 2017). These tests were conducted at 3, 6, and 12 months after ACLR. The researchers concluded that in some measurements, symmetry restoration occurred especially in the test where the limbs had been isolated and trained individually during rehab, however symmetry was not completely restored in the drop vertical jump and vertical hop tests. This suggests that the isolation of the involved limb may be a critical component in functional rehabilitation. Similarly, Renner et al. conducted a study to understand limb asymmetries during ACLR recovery over the span of a year (Renner et al., 2018). The authors collected data from 23 post-ACLR athletes during vertical stop jump tests at the 4-, 5-, 6-, and 12-month marks of their recovery process. They measured outcomes such as peak knee flexion and extension, peak vertical ground reaction force, loading rate, and frontal plane knee and sagittal hip range of motion. By the 12-month mark post-op, limb asymmetries in peak vertical ground reaction plane force and impulse, as well as peak knee extension, were not fully restored.

What are possible causes of gait asymmetry? Blackburn et al. conducted a study in order to determine the significance of quadriceps function and gait kinetics such as peak vertical

ground reaction force and limb loading rates after anterior cruciate ligament reconstruction (J Troy Blackburn et al., 2016). The results showed a greater rate of torque in the knee was associated with lesser peak vertical ground reaction force in both linear and instantaneous loading rates. The researchers concluded that poor quadriceps function (i.e., quadricep disfunction), particularly the rate of torque development, is associated with altered gait kinetics that could be linked to negative outcomes such as cartilage degradation in individuals with ACL reconstructions. Arhos et al. went further to investigate the relationship between symmetry and isometric quadriceps strength and gait biomechanics in ACLR athletes after they began their return-to-sport training (Arhos et al., 2021). Conversely to Blackburn et al., out of the 76 participants in this study, 27 demonstrated asymmetries in quadricep strength. Additionally, 67% of participants showed asymmetry in peak knee flexion, 68% and 83% in knee excursion during weight acceptance and midstance. In addition, 74% of participants in internal peak knee extension moment as well as quadriceps muscle force, and finally 57% in medial compartment contact force. The researchers reported no significant correlations between quadriceps strength and limb symmetry for any biomechanical variable following return-to-sport training.

Consequently, different rehabilitation interventions such as perturbation, which is a type of neuromuscular training that is designed to increase knee stability, or massage, have been implemented to improve gait kinetic outcomes (Capin et al., 2019). This is generally done by placing the patient on an uneven surface while therapist perturbs either the surface or the participant to increase difficulty. Capin et al. found this to have no implications on improved walking mechanics. Some researchers have measured how gait and ground reaction forces can be altered post-ACLR after introducing measures such as plantar massage or textured shoe insoles. Collins et al.'s data suggest that the vertical ground force was lower during the first half of stance, but greater during the second half of stance in ACLR compared to the control group after

the massage, but overall neither intervention had any impact on gait kinematics (Collins et al., 2020). Therefore, more research is needed for effective rehabilitation programs to improve gait symmetry.

Vertical Ground Force

When researchers are evaluating gait symmetry, one component that is measured is vertical ground reaction force (vGRF). This essentially is measuring the force that a participants' foot is exerting on the ground in a vertical direction. Researchers, such as Blackburn et al., have conducted a cross-sectional studies in order to determine differences between limbs following ACLR in females testing impulsive loading (J. Troy Blackburn et al., 2016). In this study, participants were either classified as "Impulsive Loaders" or "Normal Loaders." The researchers based this on whether the vGRF peak immediately following heel strike was objectively classified as a heel strike in the majority of trials that were conducted. The study reported that the vGRF magnitude that immediately followed the heel strike, and instantaneous loading rates were greater in the ACLR limb. Additionally, participants who were classified as impulsive loaders showed higher vGRF linear and instantaneous loading rates between limbs. Based on the data, it is understood that greater loading rates on ACLR limbs can lead to the development of post-traumatic knee osteoarthritis and contribute to limb asymmetries.

Long term gait deviations post-ACLR can lead to functional complications in the long run. Noehren et al. conducted a study to understand these potential implications (Noehren et al., 2013). These researchers focused their study solely on female athletes and compared healthy controls to those post-ACLR. The research suggested that the post-ACLR group, during walking and running, had significantly greater initial vertical ground reaction force and loading rates. The authors noted no significant differences between inter-limb analysis in the post-ACLR group

compared to the control group. So, although there were alterations in gait mechanics, gait symmetry was restored.

In addition, Alzakerin et al. conducted a study to understand peak vertical ground reaction force and linear loading rate and how they can provide return-to-sport criterion after anterior cruciate ligament reconstruction (Alzakerin et al., 2021). Their data showed that ninety percent of the post-ACLR reconstructed limbs exhibited abnormal limb dynamics. The researchers concluded that peak ground reaction force and linear loading rate changes are often coupled together in healthy individuals indicating that participants can control the force that they are applying to the ground when running. Conversely, with the deviations found to the reconstructed limbs in post-ACLR individuals, the data suggest they are unable to properly control the force being applied to that limb. The researchers have attributed this to a possible dysfunction in neuromuscular control in individuals post-ACLR who could alter gait mechanics such as limb symmetry.

Loading rate

Another important aspect of gait symmetry after ACLR is loading rate of limbs. Loading rate refers to the speed at which force is applied on a given limb, usually measured by calculating the slope of the vGRF over time (Puddle & Maulder, 2013). Authors have conducted studies in order to understand how variations in loading rates can affect a patient's gait symmetry after ACLR. Milandri et al. conducted a cross-sectional study to investigate gait deviations in males post-ACLR (Milandri et al., 2017). In this study, the researchers noted that affected limbs compared to their control limbs showed significantly lower maximum and initial loading rates during running, but not during walking. The authors also concluded that maximum force was higher during running in the unaffected limb, which in turn showed to be associated with a higher loading rate. In conclusion, the authors determined that male ACLR participants

consistently demonstrated gait asymmetries compared to their heathy counterparts long after surgery in various aspects and loading rate may be a significant contributor.

Loading rate can also be affected based on sex-related differences. Ito et al. conducted a study to determine how sex and mechanism of injury influence knee joint loading symmetry during gait 6 months after ACL reconstruction (Ito et al., 2021). The researchers established that there was an interaction effect that consisted of sex, mechanism of injury (MOI), and limb for peak medial compartment contact force. The data suggested that men who sustained non-contact injuries walked with asymmetry that was characterized by underloading the involved limb and those men who sustained contact injuries walked with the most symmetrical loading. In the group of women, no clear pattern was determined from their mechanism of injury.

If a patient has an altered limb loading rate contributing to gait asymmetries, this can lead to larger problems later in life. If gait deviations such as elevated impact loading and loading rates in the long term, are not resolved, they may contribute to early onset joint degeneration in individuals post-ACLR (Noehren et al., 2013). Loading rate is often coupled with ground reaction force irregularities in a clinical setting. There is a universal relationship between loading rates and ground reaction forces for healthy individuals which can be used by clinicians in order to make identifying limb abnormalities easier (Alzakerin et al., 2021), where loading rate measures how quickly the force applied to the ground changes during a movement.

Landing mechanics

Landing mechanics play a crucial component in ACL recovery. If athletes are not demonstrating proper landing techniques, it can put significant stress on the ACL graft and risk re-injury (Bell et al., 2014), regardless of gait symmetry differences. Landing mechanics are not only important when walking and running, but also with jumping mechanics. Kotsifaki et al., found that at the time of returning to their sport, participants showed significant differences in

shifting their weight to the uninvolved leg, particularly in impulse symmetry in all jump tests compared to the control group (Kotsifaki et al., 2023). Additionally, peak landing force asymmetry was greater in the ACLR group compared to the control group in both the countermovement and the double leg drop jump. The authors concluded that despite ACLR participants passing the traditional therapeutic criteria for discharging, they continued to show asymmetries.

Peebles et al. also conducted a study in order to assess landing biomechanics deficits in individuals post-ACLR (Peebles et al., 2022). The study showed that the ACLR individuals had larger normalized symmetry index (NSI) for plantar force impulse during bilateral landing and knee flexion range of motion (ROM) during unilateral landing which indicates higher asymmetry. Plantar force impulse refers to the change in momentum from the bottom of the foot that occurs when force is applied to it over time (Carson et al., 2012). The study reported there were no between-group (ACLR and control) differences observed for knee frontal plane projection angle range of motion. Additionally, Heinrich et al. conducted a study in skiers, to determine the relationship between jump landing kinematics and peak anterior cruciate ligament force during a jump in downhill skiing (Heinrich et al., 2014). The researchers noted an increased lean backwards stance, increased hip flexion, knee extension, and ankle dorsiflexion. They also made a key discovery that during jump landings, an asymmetric position was related to higher peak ACL forces. Additionally, the orientation of the trunk of the skier was the most important indicator as it accounted for nearly 60% of the variance of the peak ACL force during the simulations on affected legs.

Sex Differences

The ACL reconstruction and rehabilitation process has been shown in studies to have differences between men and women. These differences include knee valgus angle, strength,

hormones, and other anatomical differences. Knee valgus causes the knee to bow inward, whereas knee varus shifts the knee in an outward position (Eustice, n.d.). In some studies, such as Slater et al., researchers conducted a study to determine how sex may affect gait (specifically running) after exercise in individuals that have undergone ACL reconstruction (Slater et al., 2020). The study suggested that after exercise, females with reconstructions showed increased knee valgus (1.81 deg) and knee external rotation (2.02 deg) on their affected legs comparatively to the legs of healthy females. After exercise, males with reconstruction showed a decrease in knee varus (-4.83 deg) compared to healthy males. This information points to males with reconstructions having an increase in hip loading whereas women with reconstructions have an increase in trunk motion post-exercise.

In other studies, such as Kim et al., researchers conducted a retrospective outcome study to understand sex related differences in strength deficits 1 year after an ACLR (Kim & Park, 2015). The results showed significant differences noted between men and women with extensor muscle strength both at 60 deg/sec and 180 deg/sec. Finally, the authors concluded that women showed less extensor muscle strength compared to men and in turn showed less improvement one-year post-op. Similarly, other studies have also been conducted on comparing the limb loading characteristics and functional outcomes between sexes after ACLR (Leicht et al., 2024). These participants completed bilateral bodyweight squats in order to assess the symmetry between limbs. The results of this study revealed that nearly 64% of participants offloaded their body weight from their affected limb, reducing weight-bearing on that leg. Particularly, it was the majority of females who offloaded their ACLR limb, whereas men did not.

Other sex-related differences include hormone differences which may affect gait mechanics. Stijak et al. conducted two studies in order to understand the effect that sex hormones play on men and women post ACL rupture. Results showed female participants with ACL tears

had significantly lower concentration of testosterone, significantly lower concentrations of estradiol, and significantly lower concentrations of progesterone compared to the females without tears (Stijak et al., 2015). The researchers concluded that these decreased concentrations of estradiol, testosterone, and progesterone can potentially be a risk factor for ACL tears. Additionally, these hormones did not have an impact on joint laxity. The researchers suggest that young female athletes with low concentrations of sex hormones are more prone to ACL tears. The results for men showed that participants with ACL tears had significantly higher concentrations of testosterone, significantly higher concentrations of estradiol, and significantly higher laxity scores all compared to participants without tears. More research needs to be conducted to understand the role sex hormones and joint laxity may have on ACL tear risk.

Lastly, the other most common sex-related difference in ACL recovery individuals face are various anatomical differences. Throughout previous literature, many anatomical features of the knee have been shown to affect both the joint and ACL loading. Most of this literature has shown the sex differences on these anatomical features, but little is known on how growth and maturation are affected by these differences. Hosseinzadeh et al. conducted a cross-sectional study in order to understand sex and age-related differences in anatomical features in people who have experienced ACL injuries (Hosseinzadeh & Kiapour, 2020). On average, females in early and late adolescence displayed smaller femoral notches, steeper lateral tibial slopes, flatter medial tibial plateaus, and shorter tibial spines compared to the age-matched male participants. The authors concluded that sex-specific changes in anatomical features are linked to an ACL injury during growth and maturation.

Although some studies show women as having more exaggerated gait differences than men, other studies show males with greater altered gait. Clark et al. found that females had reduced sway compared to males in balance tests (Clark et al., 2017). In addition, some studies

show no real sex differences when testing gait patterns in individuals post-ACLR. One study conducted by Gurchiek et al., showed that gait symmetry was not significantly different between men and women when tested during fast walking (Gurchiek et al., 2019).

Right and Left Leg Differential Outcomes

Not only can there be possible differential outcomes between sexes, but there can also possibly be differences in asymmetries depending on whether the ACL injury was to a left or right leg, although the literature is limited. There have been noted differences between males and females when assessing dominant and non-dominant limbs. Van Melick et al. suggests that leg dominance plays a role in the cause of ACL injuries (Van Melick et al., 2017). Tedesco et al. conducted a study assessing gait patterns through motion sensors used by rugby athletes who have undergone ACL reconstruction and are returning to sport (Tedesco et al., 2020). When the researchers compared the post-ACLR vs. healthy participants, only the left leg showed gait cycle time and cadence having a statistical difference, but not in stance time. Conversely, analyzing only the right leg post-ACLR group vs. the healthy group, there was no statistical significance shown for any of the three measures. There were no statistically significant differences in any three measures when comparing both groups post-ACLR, left post-ACLR, and right post-ACLR, to one another.

Limb Symmetry Index (LSI)

When assessing gait symmetry, the Limb Symmetry Index (LSI) can be used to look for asymmetries. LSI is the ratio between surgical limb and dominant limb that is commonly used to assess individuals during rehabilitation (*Limb Symmetry Index: Chasing Equal Function*), thereby providing a quantifiable and objective measurement tool to assess differences between limbs. Typically, LSI is calculated by taking the affected limb value, dividing by the unaffected limb value and then multiplying by 100. Pietrosimone et al. conducted a study in order to assess

walking gait asymmetries six months following ACLR in order to predict patient reported outcomes after 12 months (Pietrosimone et al., 2018). LSI was used to normalize outcomes in the ACLR limb to that of the uninjured limb (ACLR/uninjured). The data highlighted that in individuals six months post-ACLR, a lower peak vGRF LSI demonstrated worse patient-reported outcomes at the 12-month exam. Additionally, a peak vGRF LSI greater than or equal to 0.99 six months after ACL surgery showed 13.33 higher odds of reporting acceptable patient-reported outcomes 12 months post-ACLR. Finally, the researchers concluded that participants six months post-ACLR with lesser peak vGRF LSI during walking may be a critical indicator of worse future patient-reported outcomes.

Other walking tests have been performed and studied in relation to using LSI. Luc-Harkey et al. collected walking gait data in a 60 second walk test that included gait speed, peak vertical ground reaction force loading rate, peak internal knee extension moment, and knee flexion excursion to assess these objective measurements to participant's perceived knee function deficits (Luc-Harkey et al., 2018). They measured these characteristics between the ACLR limb and the unaffected limb using LSIs. The researchers were attempting to determine the association between kinesiophobia and walking gait characteristics. After concluding their research, they discovered that kinesiophobia did not associate with any walking characteristics as indicated by the LSI.

The Limb Symmetry Index can also be used when calculating data from hop, jump, and squat related tests. The 111 participants of the Ebert et al. study were asked to perform a 4-hop test battery which included a single hop for distance, a 6-meter timed hop test, a triple hop for distance, and a triple crossover hop for distance (Ebert et al., 2018). LSI calculations revealed that the unaffected limb was significantly better than the affected limb for all tests. Only around half (47–55%) of the participants demonstrated LSIs ≥ 90% for each of the hop tests. In addition,

only 34 participants were ≥ 90% LSI for peak quadriceps, and 61 participants were ≥ 90% LSI hamstring strength.

Marrs et al. conducted their research using both load sensing insoles, as well as force plates to assess jumping mechanics (Marrs et al., 2023). Participants were instructed to perform 10 bilateral stop jumps while landing on two force plates, then the test repeated using the load sensing insoles. The researchers then analyzed the data, and the participants were either categorized as either symmetrical or asymmetrical for each primary outcome based on an 85% LSI symmetry cutoff. Out of 29 participants, 25 participants (86%) had asymmetrical peak knee extension LSI. 24 participants (83%) had asymmetrical impulse LSI measured through a force plate, and 21 participants (72%) had asymmetrical impulse LSI measured through load sensing insoles. Finally, Leicht et al. conducted a cross-sectional study which sought to compare the limb loading characteristics during squats using the LSI (%) in order to calculate the normalized peak force (Leicht et al., 2024). Limb Symmetry was calculated to show that a majority of the participants offloaded their body weight from their affected limb, decreasing weight bearing on that leg. This highlights the usefulness of using LSI to assess limb imbalances and possibly predict reduced patient outcomes including re-injury. As useful as the LSI is for individual limb differences, it is only one of several measures that should be used in determining return to play criteria, since evidence shows that even with LSIs >90%, there can still be deficits compared to healthy controls (Gokeler et al., 2017).

Conclusion and Project Aims

Based on the evidence presented, this project aims to investigate sex differences in individuals post-ACLR. Specifically investigating gait asymmetries using %LSI to determine if males and females have differences in their average loading rate (ALR), peak impact force (PIF), and impulse (IMP) outcomes while both walking and running using loadsol® collected

technology. Secondarily, the investigation looked to see if within sexes, there were differences in symmetry measurements if it was a right leg injury or a left leg injury. Lastly, the investigation sought to determine if there were differences between males and females if it was their right or left leg that was injured.

Methods and Materials

Participants

Participants were selected as part of a larger study on lower extremity biomechanics after ACL reconstruction (ACLR) that is being conducted as a multi-site study at Virginia Tech and University of North Carolina. The participants were between the ages 14 to 21 years of age, both men and women, and had undergone ACL reconstruction and rehabilitation (see Table 1). All participants participated in athletics prior to their injury, and at the time of data collection were cleared to return to their respective sports.

Limb Loading Assessment Technology

The data were collected using loadsol® (Novel Electronics Inc., Pittsburg, PA) technology in the participants' shoes as they completed walking and running tests. The loadsol® sensors are selected to fit each individual participants' shoes based on their shoe size. Each participant wore Nike Pegasus shoes to ensure consistency between trials and participants. The sensors consist of two parts, the plantar part which fits inside the shoe and the pack that extends on the outside of the shoe and clips on to the laces (see Figure 3). This pack stores the battery as well as the technology that collects and transmits the data via Bluetooth. The loadsol® is then calibrated using the loadsol® specific app. The loadsol® technology has been validated as an effective method of assessing gait mechanics (Peebles et al., 2018). In addition, Renner et al. showed high between-day reliability for both walking and running trials ($p > 0.76$) using the loadsol® technology (Renner et al., 2019). Peebles et al. found that the loadsol® sampling rate can impact the validity and reliability of the loadsol® during dynamic movements and Renner et al. found that the 200 Hz

insoles had improved validity compared to the 100 Hz data (Peebles et al., 2018; Renner et al., 2019). This study used a 200 Hz sampling rate.

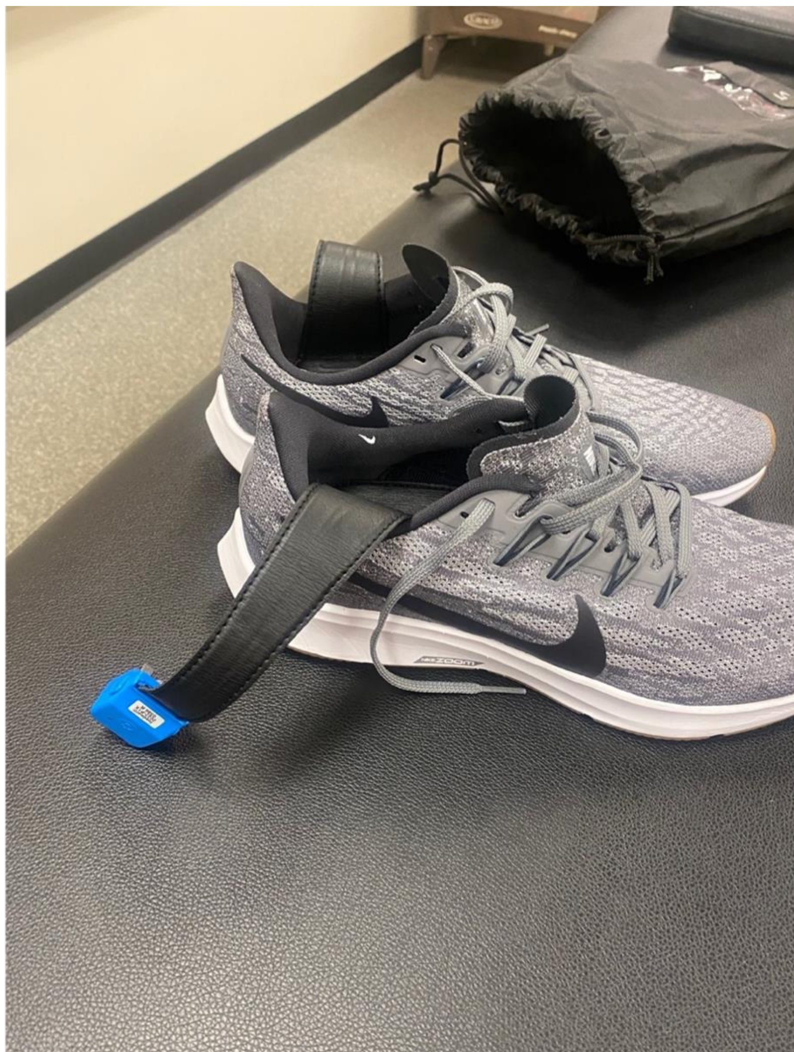


Figure 3. Figure displays tennis shoes on a table with the loadsol® insert placed inside.

Data Collection

Each participant completed three walking trials and three running trials. The participants were asked to walk and run at their own pace for six meters in each trial. Gait symmetry was assessed using peak impact force symmetry (PIF), average loading rate symmetry (ALR), and impulse symmetry (IMP) (see Figure 4). The in-shoe sensor collected participant's data points

using Bluetooth and created a text file with these points. The text files were loaded into the analysis software, Loadsol Analysis Program (LAP) (Granata Lab, Blacksburg, VA) which is a custom Matlab code (MathWorks, Natick, MA). Once the file was loaded into the software, the patient's body mass and non-surgical limb were added. For walking trials, percent of GC (ground contact) for impulse was set to 99/100 and percent of GC for impact peak was set to 50/100 to capture the peak present in the first 50% of their stance. For running trials, percent of GC for impulse was set to 99/100 and percent of GC for impact peak was set to 99/100. This setting measures 99% of the data points collected during ground contact for each foot individually. The code requires at least three data points from toe-off to properly compute the data. In the last frame of the running trial, occasionally the participants do not have those three points from toe-off because the time their foot is spending on the ground is so little. To account for this, both settings were adjusted to 98/100 to attempt obtain those three data points. If the data continued to not compute properly, the settings would decrease by one each time until there were enough data points for the data to run correctly.

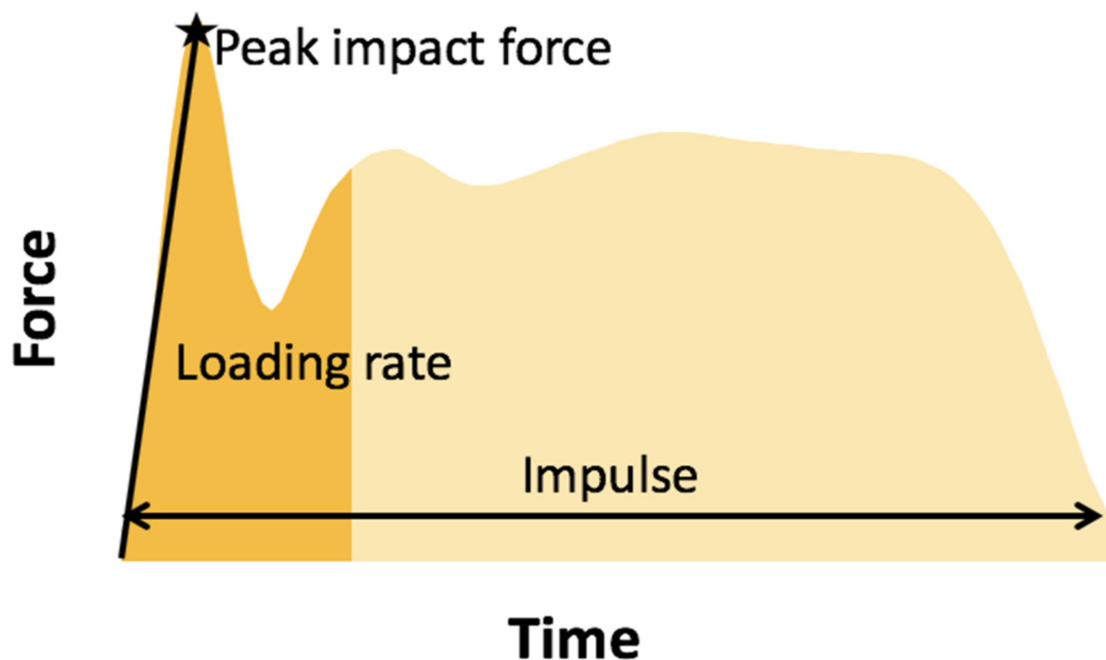


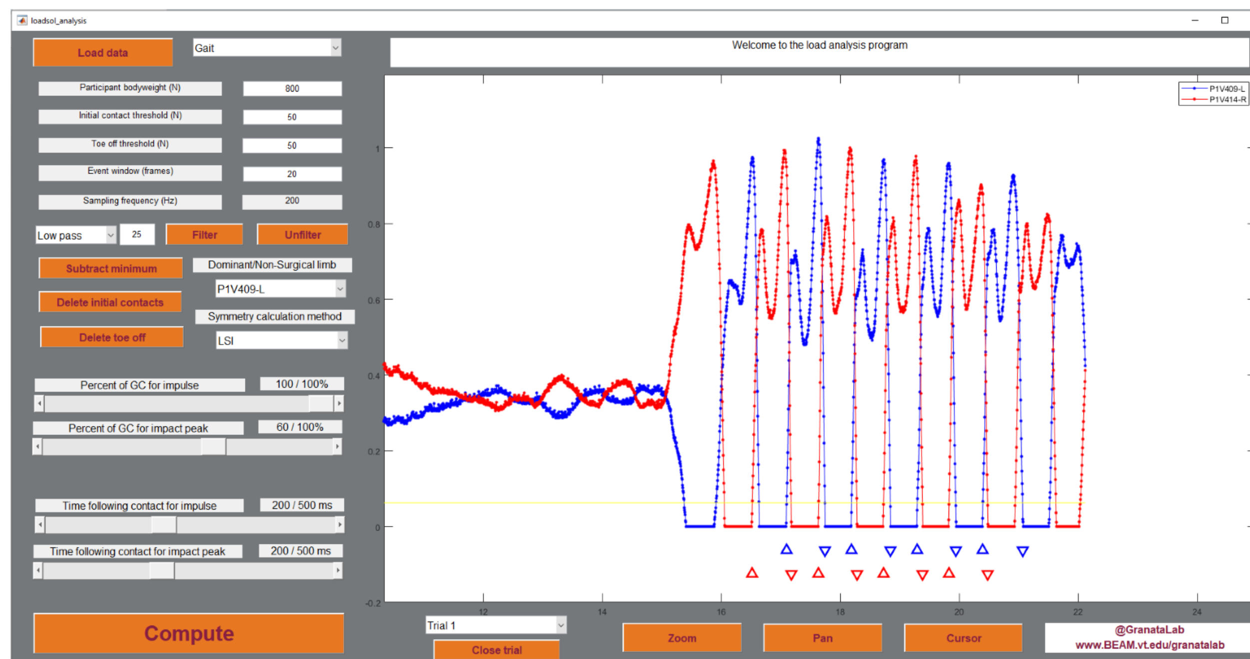
Figure 4. Figure from Pebbles et al. shows force over time to show peak impact force, loading rate, and impulse (Peebles et al., 2018).

As seen in Figure 5a, the LAP software separated the limbs by color, the left limb being blue and other right being red. Figure 5a also shows an up triangle, and a down triangle for each step on each limb. These triangles indicate the initial contact (heel strike), and the toe-off for each step. The first two steps, and the last two steps were removed to ensure a consistent walking speed throughout the trial. This was done in order to account for the participant accelerating and decelerating. Any additional steps that did not look the same as the steps that were selected, were removed as well. It was important to always have an even pair of steps to ensure symmetry was being analyzed equally between both legs. Once the steps were identified, the initial contact and the toe off for the removed steps were deleted. When only the desired steps were left with triangles, the mean Limb Symmetry Index (LSI) and standard deviation for the outcome

variables was computed (see example in Figure 6). LAP calculated the LSI developed by Peebles et al., 2018 as seen in Equation 1.

Equation 1. $Limb\ Symmetry\ Index\ (LSI) = \frac{Injured\ Limb}{Uninjured\ limb} * \ 100$

a.



b.

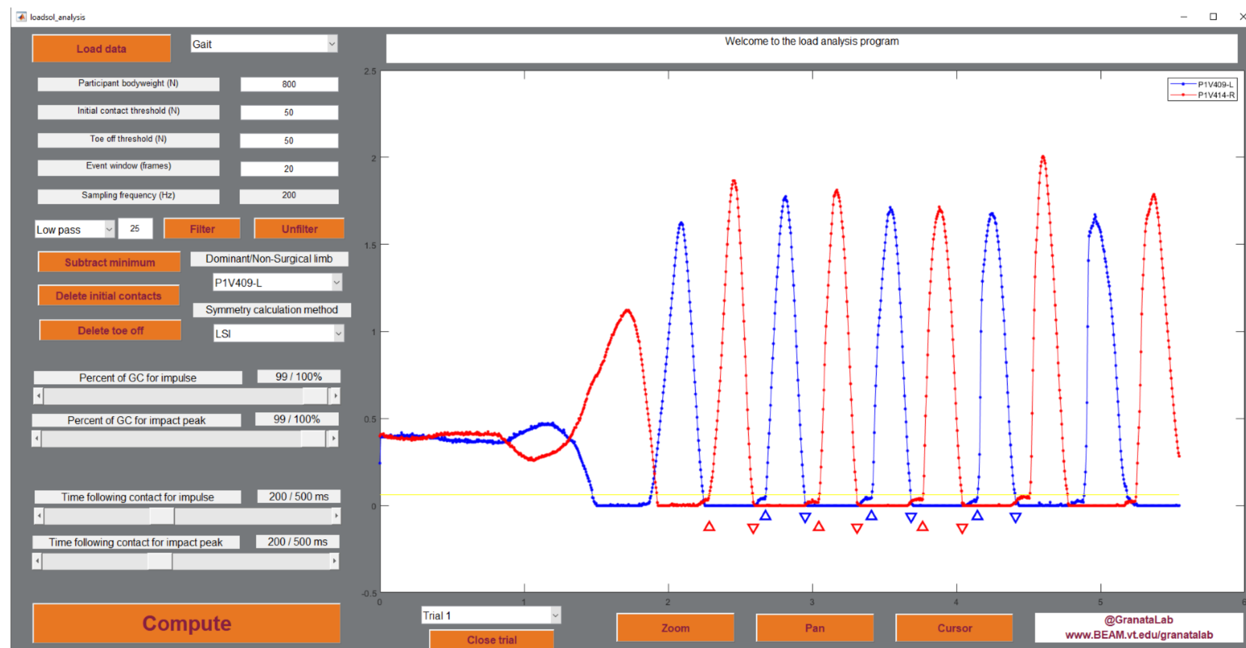


Figure 5a and b. LAP screenshots of walking and running collected data. **a.** Screenshot shows a walking trial. The blue indicates the left leg, and the red indicates the right leg. The figure shows four pairs of steps highlighted for computation, eight steps total. The first two, and last two steps do not have triangles, therefore were not included in the analysis. The upward facing triangles indicate initial contact, and the downward facing carrots indicate the toe-off. Participants' body mass in newtons, as well as the nonsurgical dominant limb were both added to each figure. **b.** Screenshot shows a running trial. Like the walking trial, the first two and last two steps were excluded from the analysis, along with one additional step to ensure step pairs for the symmetry analysis. Screenshot shows three pairs of steps and six steps total.

Lap	Step	PIF_L	PIF_R	PIF_Symm	PPF_L	PPF_R	PPF_Symm	ILR_L	ILR_R	ILR_Symm	ALR_L	ALR_R	ALR_Symm	IMP_L	IMP_R	IMP_Symm
1	1	1.772006706	1.819799418	102.6970954	1.772006706	0.325578659	18.37344398	16.3289315	22.4287521	137.3559078	12.18908	13.38490044	109.8105882	0.359433031	0.37978133	105.6612211
1	2	1.716861269	1.897003029	110.4925054	1.716861269	0.365430429	21.28479657	45.93835475	29.96529514	65.22936073	10.30541585	14.10561454	136.8757432	0.368847681	0.405775124	110.0115699
2	3	1.724213994	1.764653981	102.3454158	1.724213994	0.493044322	28.59530917	15.16720096	28.01388194	184.7004072	11.46976069	11.16320108	97.32723621	0.369803241	0.390767845	105.6691239
2	4	1.764653981	1.874944855	106.25	1.764653981	0.384988677	21.81666667	41.64583395	30.24911032	72.63418079	12.47022146	15.05511276	120.7285115	0.366011294	0.40134474	109.6536491
3	5	1.735243081	1.709508544	98.51694915	1.735243081	0.145583953	8.389830508	17.9406488	15.14073115	84.39344262	11.90553219	10.33646069	86.82065217	0.361971266	0.377880062	104.3950441
3	6	1.724213994	1.790388518	103.8379531	1.724213994	0.430281462	24.95522388	46.26922738	27.74183112	59.95741165	13.37624057	11.12761389	83.18939718	0.372688156	0.379761551	101.8979393
0	Mean	1.739532171	1.809383057	104.0233198	1.739532171	0.357484584	20.5692118	30.54836622	25.58993363	100.7117851	11.95270846	12.52881724	105.7920214	0.366459111	0.389218442	106.2147579
0	StDev	0.023183442	0.069886351	4.043196209	0.023183442	0.118672073	6.912051376	15.52338957	5.84015077	49.74221935	1.029482584	1.909766623	20.72626082	0.005007925	0.012088194	3.123848741

Figure 6. The Excel workbook that is produced after computing the data. The data is shown for each step, as well as the mean and standard deviation. The highlighted rows show which data were being utilized for this study (PIF, ALR, IMP).

Statistical Analysis

Statistical differences in PIF, ALR, and IMP symmetry differences for males and females were analyzed using GraphPad Prism (Graphpad Software, La Jolla, CA). Mean differences were assessed for both walking and running trials with an unpaired two-tailed t-test with a p value ≤ 0.05.

A power analysis was conducted using a sample size calculator (https://clincalc.com) for sample size estimation, based on pooled data from Bruce Leicht et al., Pietrosimone et al., Pfeiffer et al., and Luc-Harley et al., who compared male and female limb symmetry index (LSI) differences after ACL reconstruction (Leicht et al., 2024; Luc-Harkey et al., 2018; Pfeiffer et al., 2018; Pietrosimone et al., 2018). The LSI means ranged from 0.875 to 1.0 with a standard deviation range from 0.01- 0.04. With a significance criterion of $\alpha = .05$ and power = .80, the minimum sample size for a continuous endpoint two independent sample study would be an N = 42 (21 in each group), given a mean of 0.99 for one sex and 0.96 for the other sex with a standard deviation of 0.035. Current data collection allowed for 20 females and 20 males available for analysis in this study, which is in line with the estimated power calculation.

Results

Twenty females and twenty males were assessed for gait asymmetries. There was no statistical difference in their ages, with an average age of 19.12 ± 2.76 years. Males and females were significantly different in their height in meters (m) and body mass in newtons (N) with an average height of 1.74 ± 0.10 m and an average body mass of 727.78 ± 148.66N (see Table 1).

Table 1. Demographics for ACLR Participants.

Participant Demographics			
Sex	Males	Females	
Participants (n)	20 (50%)	20 (50%)	P=1.0
Affected limbs	9 right limbs 11 left limbs	7 right limbs 13 left limbs	
Average age in years	19.75 ± 3.01	18.5 ± 2.39	P=0.15
Average height meters (m)	1.79 ± 0.08	1.69 ± 0.10	P<0.01
Average body mass newtons (N)	784.9 ± 132.2	670.7 ± 144.9	P<0.05

Gait symmetry outcomes included the average loading rate (ALR), peak impact force (PIF), and impulse (IMP) symmetry during both walking and running tests, expressed as % Limb Symmetry Index (%LSI). A %LSI over 100% would indicate that the participant is shifting their weight off their surgical limb compared to their non-surgical limb, under 100% would indicate favoring their non-surgical limb, and 100% would indicate perfect symmetry between the two limbs. When comparing ALR between males and females, females showed statistically significant differences than males with higher %LSI during both walking and running trials at 114.7% and 118.3%, respectively. This was compared to males whose %LSI was 99.7% and

97.5%, respectively (see Figure 7a and b). There were no sex differences in PIF or IMP in either the walking or running tests (see Table 2).

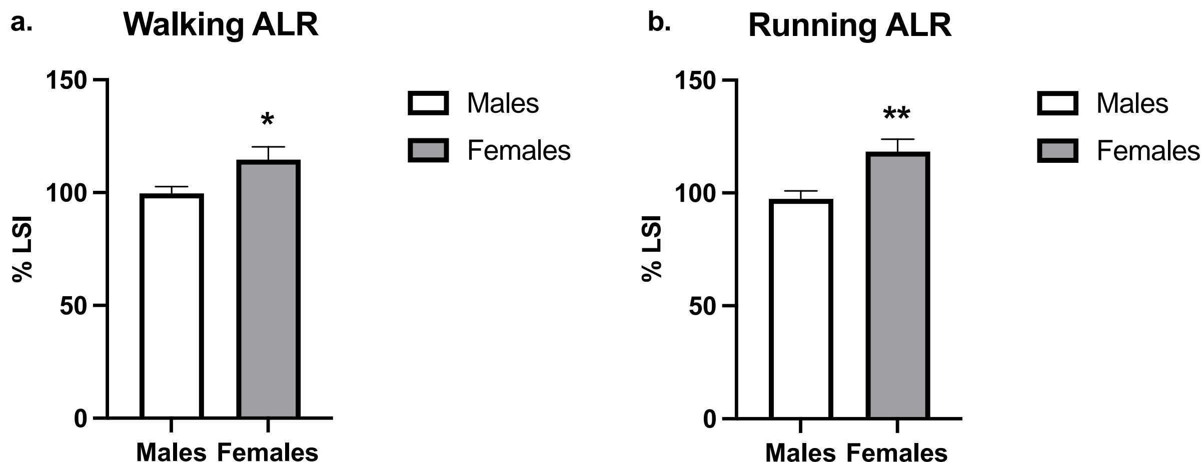


Figure 7a and b. Comparison of the average loading rate (ALR) symmetry between males and females during **a.** walking and **b.** running. The y-axis shows % of limb symmetry. * p<0.05 and ** p<0.01.

Table 2. Walking and running trials assessing average loading rate, peak impact force, and impulse symmetry in males and females depicted in % Limb Symmetry.

	Males	Females
Walking ALR (%LSI)	99.7%	114.7%
Running ALR (%LSI)	97.5%	118.3%
Walking PIF (%LSI)	98.9%	101.7%
Running PIF (%LSI)	96.0%	97.0%
Walking IMP (%LSI)	98.4%	101.2%
Running IMP (%LSI)	95.4%	97.0%

Participants had a mix of ACL injuries to both their left or their right leg. As seen in Table 1, 9 females tore their right ACL, and 11 females tore their left ACL. In addition, 7 males tore their right ACL, and 13 males tore their left ACL. We next investigated whether there were

differences in symmetry if it was a right leg ACL repair or a left leg ACL repair. As seen in Figure 8a and b, peak impact force (PIF) during walking showed that when it was a right leg ACL repair, they tended to favor the surgical leg more (105.6 %LSI). However, when it was a left leg ACL repair, PIF indicated that they tended to favor the non-surgical leg more on both the walking and running trials (95.9% and 91.2% LSI, respectively). Women with a left leg ACL repair, also showed significant asymmetry during the running trial assessing impulse (IMP) symmetry, favoring the non-surgical leg (91.1% LSI). A similar trend was seen with IMP for walking but did not reach significance (see Figure 8c and d). No average loading rate (ALR) asymmetries were detected in females if it was a right leg or left leg ACL repair in walking (118.5 and 109.0% LSI) or running (120.0% and 115.8% LSI). The data shows that there were ALR asymmetries favoring the surgical limb, regardless of the leg repaired. No significant symmetry differences were noted for males between a right leg ACL repair or a left leg ACL repair in walking or running trials (see Table 3).

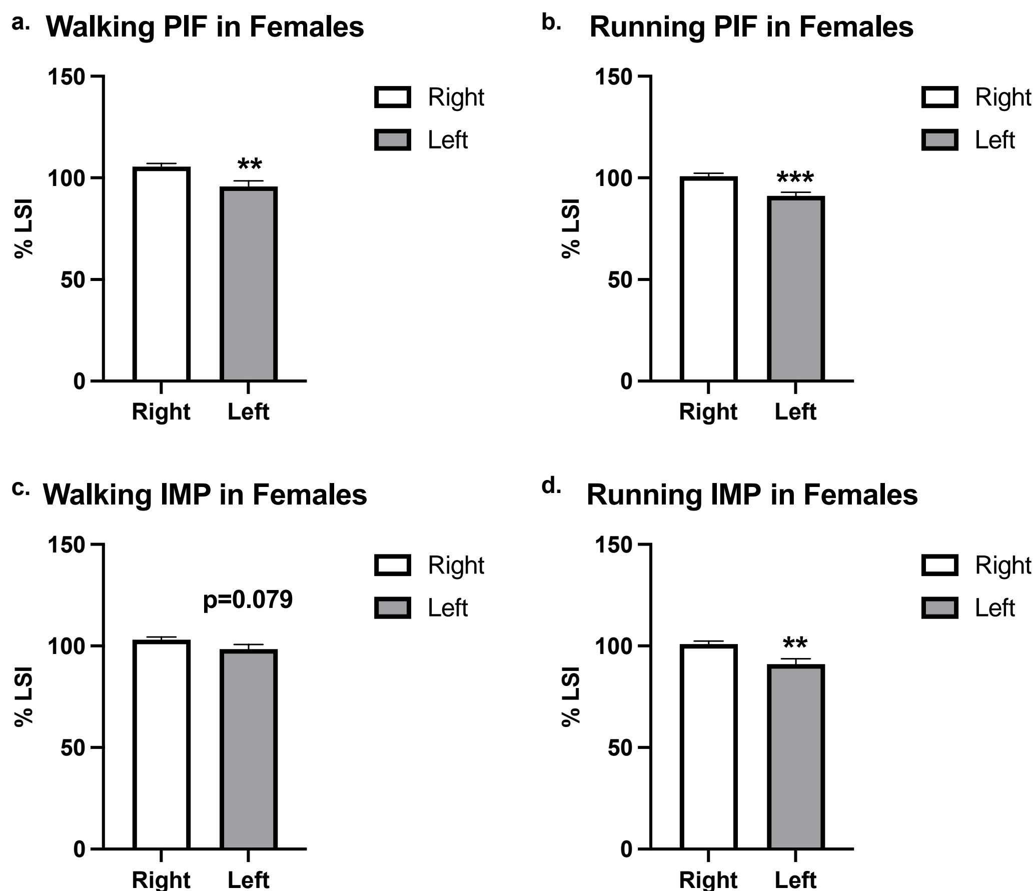


Figure 8a-d. The peak impact force (PIF) symmetry for **a.** walking and **b.** running in females. Impulse symmetry (IMP) in **c.** walking and **d.** running in females comparing right leg anterior cruciate ligament (ACL) repairs to left leg ACL repairs. The y-axis depicts % of limb symmetry. Right denotes a right leg ACL repair and left denotes a left leg ACL repair. ** $p<0.01$ and *** $p<0.001$.

Table 3. Walking and running trials in males assessing average limb loading rate, peak impact force, and impulse symmetry in right leg anterior cruciate ligament repairs compared to left leg ACL repairs depicted in % Limb Symmetry.

	Right Leg ACL Repair	Left Leg ACL Repair
Walking ALR (%LSI)	99.6%	99.9%
Running ALR (%LSI)	96.2%	99.0%
Walking PIF (%LSI)	97.8%	100.2%
Running PIF (%LSI)	97.4%	94.4%

Walking IMP (%LSI)	97.3%	99.7%
Running IMP (%LSI)	98.0%	92.2%

Next, we sought to investigate whether there were sex differences among only right leg ACL repairs and whether there were differences in only left leg ACL repairs. When assessing asymmetries between sexes in right leg ACL repairs only, females showed higher levels of asymmetry during average loading rates (ALRs) in both walking and running (118.5% and 120.0% LSI, respectively), compared to males (99.6% and 96.2% LSI, respectively) (see figure 8a and b). Additionally, females showed significantly higher levels of asymmetry during walking when assessing peak impact (PIF) (105.6% LSI), compared to males (97.8% LSI), but not during running (100.8% LSI females and 97.4% LSI males) (see figure 8c and d). Lastly, impulse symmetry (IMP) was higher in females during walking trials (103.1% LSI) compared to males (97.3% LSI), but not during running (101.0% LSI females and 98.0% LSI males) (see figure 9e and f). No significant symmetry differences were seen between males and females if it was a left leg ACL repair (see Table 4).

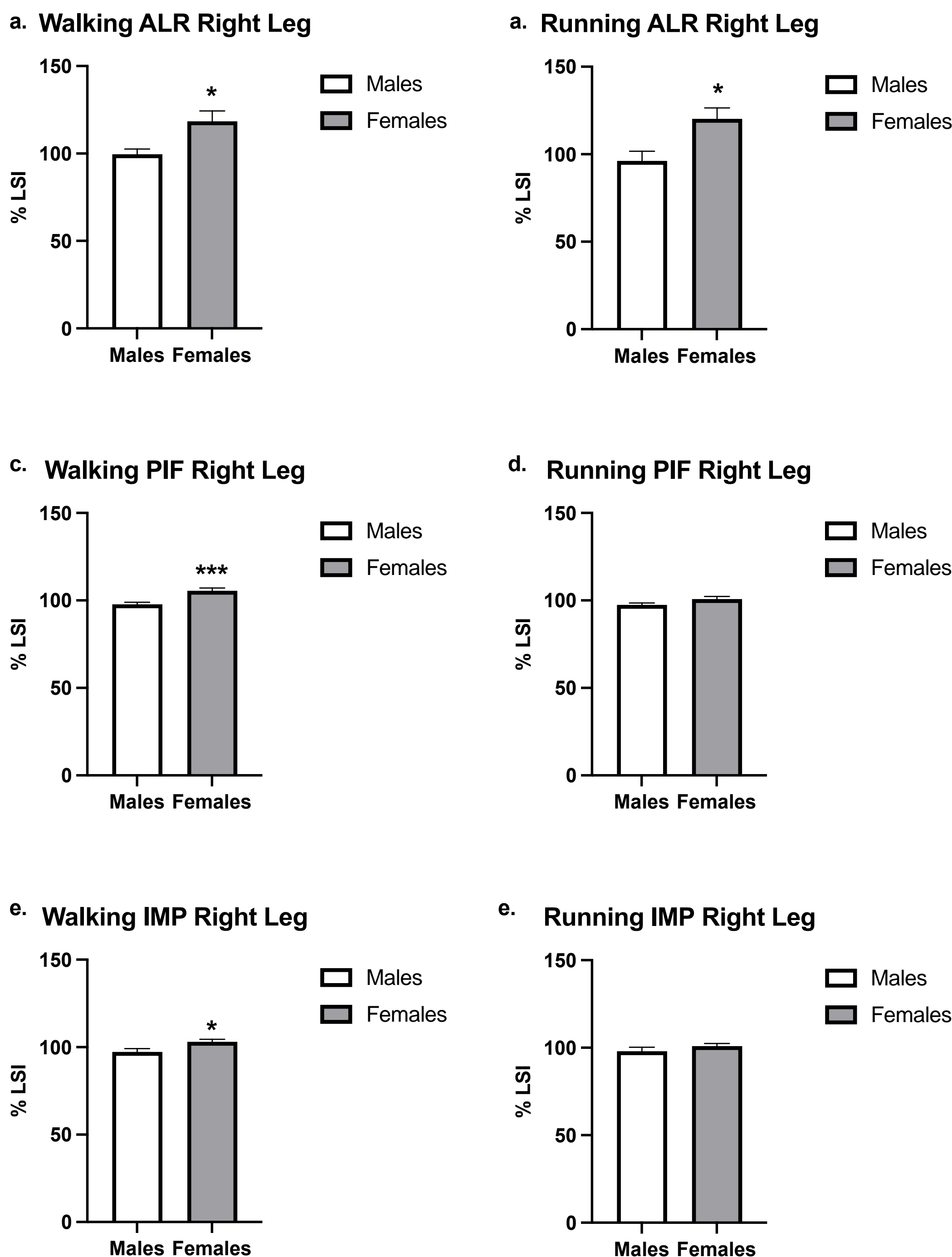


Figure 9a-e. Sex differences in average loading rate (ALR) in **a.** walking and **b.** running, peak impact force (PIF) in **c.** walking and **d.** running, impulse (IMP) symmetry in **e.** walking and **f.** running in right leg anterior cruciate ligament repairs only. The y-axis depicts % of limb symmetry. * p<0.05 and *** p<0.001.

Table 4. Walking and running trials assessing average limb loading rate, peak impact force, and impulse symmetry in left leg anterior cruciate ligament repairs in males compared to females depicted in % Limb Symmetry.

	Males	Females
Walking ALR (%LSI)	99.9%	109.0%
Running ALR (%LSI)	99.0%	115.8%
Walking PIF (%LSI)	100.2%	95.9%
Running PIF (%LSI)	94.4%	91.2%
Walking IMP (%LSI)	99.7%	98.5%
Running IMP (%LSI)	92.2%	91.1%

Discussion

The purpose of this study was to determine and understand any sex related differences that may occur post anterior cruciate ligament reconstruction surgery (ACLR). This was done by completing walking and running trials, and then analyzing average loading rate, peak impact force, and impulse symmetry. When comparing males to females in walking and running trials, females showed more asymmetry than males, especially in running trials. Some research, such as Slater et al., Kim & Park, Leicht et al., and Hosseinzadeh & Kiapour, have supported the idea that females typically show more asymmetry compared to males post-ACLR (Hosseinzadeh & Kiapour, 2020; Kim & Park, 2015; Leicht et al., 2024; Slater et al., 2020). However, the data has not all been supported in the same way. Where this data shows asymmetries in average loading rate for females, Slater et al. shows asymmetries in women with knee angles and increase trunk motion (Slater et al., 2020). Kim & Park showed asymmetry in females post-ACLR by highlighting strength deficits (Kim & Park, 2015). Leicht et al. assessed similar outcomes as it relates the sex differences by measuring limb loading (Leicht et al., 2024). Although this research was similar to the one conducted here, this research utilized bodyweight squats, whereas the current investigation assessed walking and running. Their research supports this study showing that women have more asymmetries in favor of their non-surgical limb. Although not all research has supported this theory, where Clark et al. showed women having more control during balance tests (Clark et al., 2017), however Hosseinzadeh & Kiapour highlight that females may be at more risk for ACL injury due to anatomical differences including smaller femoral notches, steeper lateral tibial slopes, flatter medial tibial plateaus, and shorter tibial spines (Hosseinzadeh & Kiapour, 2020). Additionally, Gurchiek et al. suggest from their study

that there are no real differences between males and females as it related to gait symmetry, which contradicts the data findings here (Gurchiek et al., 2019).

When comparing right leg post-ACLR to left leg post-ACLR, participants with a right leg ACLR favored their surgical limb in peak impact force during walking trials. However, the opposite was observed where participants with a left ACLR were shown to favor their non-surgical leg in both walking and running trials when assessing peak impact force. This is likely due to favoring their dominant limb, regardless of which leg had the ACL repair. This seems to be supported by Tedesco et al. where researchers noted significance in asymmetry on participants with left leg ACLR, but not on the right (Tedesco et al., 2020). More research needs to be conducted when assessing right leg ACLRs compared to left leg ACLRs specifically in males and females as current research on this is limited.

Lastly, the research assessed if there were sex differences with symmetry in only left leg ACLR and only right leg ACLR. This research was novel, as there were no other sources found that analyzed similar outcomes. There was no significant data that was presented from those with left leg ACL repairs. However, when analyzing those with right leg ACL repairs, average loading rate in females showed significant asymmetry in walking and running trials favoring the surgical limb, compared to males. Females also showed a statistical increase in peak impact force and impulse symmetry, favoring their surgical limb in the walking trials, compared to males. Milandri et al. noted that males consistently showed gait asymmetries regarding loading rates, which contradicts the research collected here (Milandri et al., 2017). Similarly, Ito et al. also showed loading rates affecting males, but having no clear effect on females (Ito et al., 2021). Asymmetries in average loading rate in females compared to males across the board showed relatively significant data, even with a larger standard deviation for each trial. Again, the current research in this outcome is limited and should be further investigated.

Strengths and Limitations

This study was conducted with some limitations. First, the study only assessed walking and running trials as it was part of a larger study being conducted. The data analyzed was only a small portion of the larger data points collected for this study. Next, the loadsol® sensors had some issues with calibration, which caused some trials not to be usable. Some trials did not collect data from any steps. Typically, there should be three trials for walking and three trials for running, but because of calibration issues, some participants only had one or two working trials. Additionally, there were significant differences in height and body mass between males and females. Another limitation occurred was not having data prior to injury and surgery. Because of this, it had to be assumed that the participants were 100% symmetrical prior to injury.

While this study was presented with limitations, it also had a number of strengths. The data were collected from two different sites which allows for greater geographical demographics and the use of the loadsol® technology allowed this data to be collected in a more natural way instead of being hooked up to camera systems, reflective markers, or using force plates. Also, the data were collected from a variety of sports, with plenty of participants with left ACLRs and right ACLRs. Finally, this study was novel in assessing sex differences while comparing asymmetries in right leg ACL repairs compared to left leg ACL repairs.

Conclusion

Measuring sex related differences in walking and running trials can be beneficial to understanding symmetry in athletes. Utilizing wearable technology can allow for more practical data collection outside of a laboratory setting. This study showed that there are sex related differences in average loading rate during walking and running trials, particularly for females. Furthermore, while some data was presented on sex differences in left ACL repairs compared to

right ACL repairs, more data should be collected to understand the true implications it may have. In almost every trial conducted and every outcome assessed, females were the group that showed the most significant asymmetry. This includes isolating left leg ACLR participants versus right leg ACLR participants, for average loading rate, peak impact force, and impulse symmetry.

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