THE RELATIONSHIP BETWEEN VIBRATORY PERCEPTION THRESHOLD, JOINT POSITION SENSE, AND LOADING RATE DURING WALKING GAIT IN ACLR INDIVIDUALS

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ABSTRACT

Sean M. Buitendorp: The Relationship Between Vibratory Perception Threshold, Joint Position Sense, and Loading Rate During Walking Gait in ACLR Individuals (Under the Direction of J. Troy Blackburn)

Anterior cruciate ligament (ACL) injury and surgical reconstruction (ACLR) increase the risk of knee osteoarthritis (OA). Heightened loading rates have been observed following ACLR and are associated with greater cartilage damage in animal models. ACLR individuals also demonstrate somatosensory deficits that may contribute to higher loading rates. However, the relationship between somatosensory function and gait biomechanics has yet to be evaluated post-ACLR. The purposes of this study were to 1) compare joint position sense (JPS) and vibratory perception threshold (VPT) between the ACLR and contralateral limbs, 2) evaluate the relationship between JPS and VPT, and 3) evaluate the relationship between somatosensory function and loading rate during gait following ACLR. JPS, VPT, and gait biomechanics were assessed in 30 ACLR individuals. JPS was assessed as the ability to reproduce a specified joint angle. VPT was assessed as the minimum detectable vibration amplitude applied to bony prominences in the lower extremity. Loading rate was assessed from force plates embedded in a walkway as the peak of the 1st time derivative of the vertical ground reaction force (vGRF). No significant between-limb differences in JPS or VPT were observed, nor were any significant correlations between JPS and VPT or between vGRF loading rate and either JPS or VPT observed. These results suggest that current ACLR and rehabilitation sufficiently restores somatosensory function following rupture.
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LIST OF ABBREVIATIONS

1st MTP – First Metatarsophalangeal Joint

ACL – Anterior Cruciate Ligament

ACLD – Anterior Cruciate Ligament Deficient

ACLR – Anterior Cruciate Ligament Reconstruction/Reconstructed

BW – Body Weight

DVJ – Drop Vertical Jump

GRF – Ground Reaction Force

HST – Heel Strike Transient

JPS – Joint Position Sense

KOOS – Knee Injury and Osteoarthritis Outcome Score

LFE – Lateral Femoral Epicondyle

LM – Lateral Malleolus

LMV – Local Muscle Vibration

MFE – Medial Femoral Epicondyle

MM – Medial Malleolus

MRI – Magnetic Resonance Imaging

OA – Osteoarthritis

PTOA – Post-traumatic Osteoarthritis

ROL – Rate of Loading

TDPM – Threshold to Detect Passive Motion

TKA – Total Knee Arthroplasty

vGRF – Vertical Ground Reaction Force

VPT – Vibratory Perception Threshold

WBV – Whole Body Vibration
CHAPTER I: INTRODUCTION

1.1 Background

One of the most common injuries to the ligamentous structures of the knee joint is a disruption of the anterior cruciate ligament (ACL). A ten-year study documenting knee injuries found that ACL tears accounted for 20.3% of all knee injuries reported and 45.4% of internal knee injuries. It is estimated that 200,000 ACL tears occur each year in the United States alone. There are currently two primary methods for treatment of ACL tears: surgical reconstruction with subsequent rehabilitation and structured rehabilitation alone. Surgical reconstruction has been the traditional treatment in the U.S., especially for younger and more physically active individuals, due to its shorter recovery periods and lower mean lifetime costs to society compared to structured rehabilitation alone. While surgical reconstruction typically accomplishes the goal of returning static stability and functional capabilities to the knee joint, it fails to restore proper joint kinematics and can leave the joint vulnerable to further injury and degenerative conditions.

There is a growing body of evidence that while ACL reconstruction (ACLR) increases long-term joint stability, it heightens the risk of developing osteoarthritis (OA). Posttraumatic osteoarthritis (PTOA) involves joint degeneration, dysfunction, and pain following joint disruptions, and unlike idiopathic osteoarthritis, frequently affects young and middle-aged adults. In a study examining female soccer players 12 years post-ACL disruption, Lohmander et al. found that 34 of 67 (51%) female soccer players displayed radiographic signs of either patellofemoral or tibiofemoral OA in the injured knee. Only 5 of 67 women displayed radiographic tibiofemoral OA in the contralateral knee (4 had known injuries), and no subjects displayed radiographic patellofemoral OA in the contralateral knee 12 years post-ACL disruption. Struwer et al. found that 73.8% of patients displayed degenerative changes associated with grade I or II OA and 17% and 6% of patients displayed grade III or IV OA respectively a mean of 13.5 years after ACLR. A later study by Struwer et al. found that degenerative changes associated with grade I (85.7%), grade II (9.2%), and grade III (5.1%) OA were present in subjects only two years post-reconstruction. Li et al. found that despite reduced joint laxity and improved activity level, 39% of
subjects displayed radiographic OA an average of 7.8 years post-ACL. More recently, Eckstein et al. 12 found that disruptions in cartilage at the knee joint were present two years post ACL injury, and a study by Culvenor et al. 13 observed signs of magnetic resonance imaging (MRI)-defined OA only one year post ACLR.

While there is substantial evidence that ACL injury and ACLR can lead to PTOA, the exact mechanisms involved are neither well defined nor understood. Some more obvious factors including obesity, concomitant meniscal injury, existing chondral lesions, and age at the time of injury have been linked to PTOA. ³,⁴,¹¹,¹⁵ However, altered knee joint loading rate may be a key factor in the development and progression of PTOA post-ACLR. Research suggests that ACLR individuals experience increased loading rates. Noehren et al. ¹⁶ and Co et al. ¹⁷ reported greater loading rates during walking gait in ACLR individuals compared to healthy controls. Similarly, Blackburn et al. ¹⁸ reported greater loading rate in the ACLR limb compared to the contralateral limb during walking gait. Biomechanical forces, and the altered response of tissues to such forces, are the primary catalysts of joint deterioration associated with the development of PTOA. ¹⁹ During the stance phase of gait, the majority of tibiofemoral joint loading is a result of ground reaction forces (GRF). ²⁰ Taylor et al. ²¹ found that said total tibiofemoral joint contact forces can reach 3.1 times body weight (BW) during normal walking gait. Particularly, high rate, or impulsive, joint loading, often seen in ACLR individuals, has been linked to OA development. ²²-²⁵ In animal cartilage explants repeated, high rate loading resulted in significantly greater surface fissuring than low rate loading. ²³ Additionally, the minimum peak stress magnitude required to elicit cartilage disruption was significantly lower for high rate loading than for smoothly arising compressions. ²⁵ Similar results have been observed in humans. Significant correlations have been reported between tibiofemoral joint deterioration and medial knee joint loading rate. ²² Furthermore, Kurz et al. ²⁴ found that greater strain rates resulted in greater mechanical cartilage damage than lower strain rates. These data support the need for continued research evaluating the causes of impulsive loading following ACLR.

There exists substantial evidence that individuals with ACL injuries possess deficits in somatosensory function. ²⁶-²⁸ Lee et al. ²⁹ found that knee joint proprioception as assessed by joint position
sense (JPS) was impaired in chronic ACL tears (> 3 months post injury) relative to both acute ACL tears (≤ 3 months post injury) and to the uninvolved knee. Fremerey et al. 30 reported greater JPS error in the ACLR knee relative to the contralateral knee at three months, six months, and an average of 3.7 ± 0.3 years. While a significant deficiency remained, there were significant decreases in the angles of deviation of the ACLR knee at each testing. Hoch et al. 31 reported impaired cutaneous sensation, a source of somatosensory information, distally in patients with ACLR. Additionally, a meta-analysis examining JPS and threshold to detect passive motion (TDPM) found deficiencies in these measures in patients with ACL injuries compared to the contralateral limb and healthy controls. 32 However, research examining somatosensory function following ACLR has produced varied results. Mir et al. 33 found no evidence of impaired JPS a mean of 11 months post-ACLR. Similarly, Reider et al. 34 reported no difference in JPS between ACLR and contralateral knees 3 weeks, 6 weeks, and 3 months postoperatively, and the injured knees performed better than contralateral knees 6 months postoperatively. Lastly, Hopper et al. 35 found no deficits in JPS 12 to 16 months post-ACLR compared to healthy controls. These data support the need for continued research evaluating somatosensory function following ACLR.

JPS is a more practical measure of proprioception for the research setting, while vibratory perception threshold (VPT) is more practical for the clinical setting and may be useful for medical professionals in determining risk and/or progression of PTOA. VPT is believed to serve as an analog to direct proprioceptive testing, as both sensations travel the same type of large afferent nerve fibers, are transmitted in parallel through the dorsal columns of the spinal cord, and share some sensory bodies. 36-38 Deficits in VPT have been observed in individuals with OA, 36,38 and as with JPS, deficits in VPT have been linked to greater knee joint loading rates during gait. 39 The exact relationship between VPT, JPS, and loading rate is not known, however, and more research is needed.

Somatosensory dysfunction post-ACLR may lead to abnormal joint loading and the development of OA. 40 Proprioceptive deficits have been linked to decreased quadriceps muscle function, 41 a factor in high loading rates at the knee joint during gait. 42 Riskowski et al. 43 found that proprioceptive deficits, as assessed by TDPM and JPS, were correlated with higher loading rates during gait. Additionally, greater
VPT is linked to greater loading rates during gait in individuals with symptomatic OA.\textsuperscript{39} Furthermore, Collins et al.\textsuperscript{44} reported that improving JPS via stochastic resonance electrical stimulation and a neoprene knee sleeve reduced loading rate during gait in individuals with OA. These data suggest that somatosensory dysfunction following ACLR likely contributes to PTOA risk. However, the relationship between somatosensory function and gait biomechanics linked to PTOA development has yet to be evaluated in individuals with ACLR.

The influence of somatosensory dysfunction on gait biomechanics, joint loading, and the development and progression of PTOA in the ACLR knee joint is unknown. However, individuals with ACLR are at a heightened risk for development of PTOA,\textsuperscript{2-14} and experience proprioceptive deficits,\textsuperscript{30-32,45} and proprioceptive deficits are associated with greater loading rates\textsuperscript{41-44} and magnitudes\textsuperscript{39} during gait in individuals with OA. Therefore, it can be hypothesized that somatosensory dysfunction following ACLR may lead to alterations in gait, and thus joint loading, that contribute to the development of knee PTOA. This study will evaluate relationships between somatosensory function (JPS and VPT) and vertical ground reaction force loading rate during walking gait in individuals with ACLR. It will also evaluate the relationship between laboratory-intensive measures of somatosensory function (JPS) and a more practical clinical assessment of somatosensory function (VPT) in individuals with ACL-R.
1.2 Research Questions

- Do joint position sense (JPS) and vibratory perception threshold (VPT) differ between the reconstructed and contralateral limbs in individuals with ACLR?
  - H1: JPS error and VPT will be greater in the ACLR limb relative to the contralateral limb.

- Is there a correlation between JPS and VPT in the ACLR limb of individuals with ACLR?
  - H2: JPS error and VPT will be positively correlated.

- Is there a relationship between somatosensory function (JPS and VPT) and vertical ground reaction force loading rate during gait in the ACLR limb of individuals with ACLR?
  - H3: Individuals with poorer somatosensory function (i.e. larger JPS error and VPT values) will demonstrate greater loading rates.
CHAPTER II: REVIEW OF LITERATURE

2.1 – ACL Injury

The anterior cruciate ligament (ACL) is one of the most commonly disrupted ligamentous structures of the knee joint, accounting for 20.3% of all knee injuries and 45.4% of internal knee injuries. In the United States alone, an estimated 200,000 ACL tears occur each year. Incidences may be as high as 250,000 per year, but accurate estimates are difficult since not all individuals with ACL injuries seek medical treatment. A systematic review of literature examining ACL injuries in several countries found a median annual incidence rate of 0.03% in the general population, incidence rates ranging 0.30% to 2.14% in military populations, 0.15% to 3.67% in professional athletes, and 0.03% to 1.62% in amateur athletes. This data supports the generality that younger, physically active individuals face a heightened risk of ACL injury compared to the general population. In fact, Griffin et al. state that young athletes (15-25 years of age) represent more than 50% of all ACL injuries.

Traditionally, ACL injuries have been treated using one of two primary methods: surgical reconstruction or structured rehabilitation. Collins et al. found that less than a quarter of individuals from an older population (mean age 47) with ACL injury subsequently sought treatment via ACL reconstruction (ACLR), and that younger age was positively correlated with ACLR following ACL injury. In the United States, surgical reconstruction has predominated for younger and more physically active individuals, as its recovery periods are generally shorter and it poses a lower mean lifetime cost to society than rehabilitation alone ($38,121 vs. $88,538). While surgical reconstruction typically accomplishes the goal of returning static stability and restoring basic capabilities of the knee joint, it often fails to restore pre-injury functional levels and can leave the joint vulnerable to further injury and degenerative conditions.

Individuals who undergo ACLR face a heightened risk for the development of knee osteoarthritis (OA), with prevalence ranging between 10% and 90%. A plethora of research has linked increased risk of OA development to ACLR. Signs of OA have been observed in ACLR individuals 12 years post-reconstruction, a mean of 7.8 years post-reconstruction, and even as soon as one year post-
reconstruction. The proprioceptive deficits and altered joint kinetics experienced by ACLR individuals may play a key role in the increased susceptibility of ACLR individuals to early OA development.

2.2 – Osteoarthritis

Osteoarthritis is the most common joint disorder in the world and serves as the most common source of joint pain, loss of joint function, and chronic disability in adults in the Western world, particularly in the hip and knee. In the United States alone 27 million adults meet clinical classification criteria for OA, and the prevalence of OA among US adults increased nearly 30% in the ten years prior to 2005. A systematic review of the economic and humanistic burden of OA found that the total annual direct costs to individuals with OA ranges from $1,442 to $21,335, and that despite these steep costs, health-related quality of life in these individuals remains low. Osteoarthritis is a painful and debilitating chronic disease that affects the joint as a whole, including articular cartilage, ligament, and peri-articular muscle. There is no proven disease-modifying therapeutic intervention for OA, and surgical intervention is a common route taken by individuals with severe pain or disability. In the case of debilitating knee OA, total knee arthroplasty (TKA) is the surgical intervention of choice. Nearly 500,000 TKA were performed in 2005 in the United States alone at a total cost exceeding $11 billion. Individuals with knee OA face functional burdens in addition to the economic burden associated with the disease. The presence of OA in a weight-bearing joint such as the knee can severely limit the affected individual’s functional capacity. Individuals with OA may have great difficulty with daily activities including walking, climbing stairs, transferring, and using the bathroom. Additionally, Pereira et al. found that greater presence of radiographic features of OA was associated with greater bodily pain, pain frequency, and difficulty of activities of daily living, as well as diminished general health and physical function. Individuals with OA also face greater fall risks. In a study examining the fall risk of OA individuals prior to knee replacement, 48% of participants with OA experienced a fall in the 12 months prior to the study compared to only 30% of asymptomatic age-matched controls. Scott et al. found
that chronic knee pain associated with OA predicted a more substantial decline in knee extension strength, leg muscle quality, and whole leg strength in addition to a greater fall risk.

Individuals with OA face challenges both financially and functionally, and while OA typically affects an older population in a chronic manner, individuals with traumatic joint injuries are susceptible to accelerated OA development at younger ages. Studies of OA development in young people with traumatic joint injury presents an opportunity to uncover new information potentially pertinent to OA sufferers of all ages.

2.3 – Post-traumatic Osteoarthritis

Unlike idiopathic OA, which is a chronic, often age-related condition without any one specific cause, post-traumatic osteoarthritis (PTOA) arises following direct trauma to a joint and/or its surrounding structures. The joint degeneration, dysfunction, and pain associated with PTOA have an acute onset and an accelerated development. In fact, individuals with PTOA are an average of 10.4 years younger at the time of diagnosis than individuals with idiopathic OA. PTOA of the hip, knee, and ankle accounts for 12% of the overall incidence of symptomatic OA in the United States and represents a total direct financial burden of $3.06 billion. As stated before, PTOA develops in response to a traumatic joint injury. An estimated 6.6 million knee injuries occurred in the ten-year period from 1999-2008 at a rate of 2.29 knee injuries per 1,000 people in the population. Of all age groups, people age 15-24 had the highest rate of knee injury. The ACL is the most commonly disrupted ligamentous structure of the knee joint, accounting for 20.3% of all knee injuries and 45.4% of internal knee injuries. As such, ACL injury is the most relevant knee joint disruption in terms of OA development.

Signs of OA, as defined by magnetic resonance imaging (MRI) have been found as early as two years post ACL injury. ACLR, while increasing static stability and functional capability, fails to reduce PTOA risk and may actually enhance risk. In a 14-year follow up study, 57% of ACLR individuals developed OA in the reconstructed knee while only 18% developed OA in the healthy contralateral knee; a more than three fold increase in prevalence. Struwever et al. found that degenerative changes
associated with grade I (85.7%), grade II (9.2%), and grade III (5.1%) OA were present in subjects only two years post-reconstruction. More recently, Culvenor et al. observed signs of MRI-defined OA only one year post ACLR. Clearly, PTOA associated with ACL injury and ACLR poses a significant financial and functional challenge to patients and medical professionals. However, the underlying causes of PTOA development are not well known, and early detection is difficult outside of the clinical research setting. More research investigating the mechanisms and potential indicators of PTOA development post ACLR is needed.

2.4 – Altered Loading Rate at the Knee Following ACLR

Individuals with ACLR experience lingering biomechanical alterations despite the increased structural support gained from surgical repair. Despite displaying better biomechanics than ACL deficient (ACLD) individuals, ACLR individuals possess significant extension deficits throughout the stance phase of walking gait relative to healthy controls. ACLR individuals also experience flexion deficits during gait. In a study assessing various aspects of gait biomechanics in 40 ACLR athletes, White et al. found significant asymmetries of knee flexion angles and moments during gait 1 year post ACLR. Gait asymmetries were seen in all subjects regardless of whether they had been cleared to return to activity. Research also indicates that ACLR individuals experience tibial rotational offsets throughout the gait cycle. A study performed by Scanlan et al. examined tibial rotation during gait in ACL reconstructed individuals. Of 26 subjects, 22 displayed an offset towards tibial external rotation throughout stance phase of gait. Additionally, Andriacchi et al. found that ACLR individuals display an offset of the tibia towards internal rotation during swing phase of gait, which was correlated with smaller knee flexion moment during weight acceptance in stance phase. The altered gait biomechanics, including altered tibial rotation and flexion/extension deficits, may result in abnormal patterns of cartilage loading, which can lead to cartilage degeneration and OA.

There is a significant amount of research indicating that post-ACLR individuals experienced altered patterns of joint loading. Traditionally, studies often focused on jump-landing mechanics in
assessing joint loading rates and magnitudes in ACLR individuals. Paterno et al.\textsuperscript{67} tracked 14 female athletes at a mean of 27 months post-ACLR and 18 healthy female controls to assess whether limb asymmetries in landing and jumping exist post-ACLR. Subjects performed a drop vertical jump (DVJ) onto two force plates and vGRF was used to determine loading rates. The researchers found that vGRF and loading rate were actually elevated in the uninvolved limb compared to both the reconstructed limb in the ACLR subjects and the healthy controls.\textsuperscript{67} However, subjects may have been consciously favoring their uninvolved limb during the DVJ testing. Mohammadi et al.\textsuperscript{68} observed significantly greater peak vGRF and loading rate in the uninvolved limb compared to the involved limb and healthy controls during both the landing and takeoff phases of a drop jump test in thirty ACLR athletes.

While there is value to assessing loading rates associated with jump-landing mechanics in ACLR individuals, this practice sheds little light on the influence of altered loading rates in ACLR individuals during tasks of daily living. Analysis of loading rates and magnitudes during walking gait provides a valuable assessment of the day-to-day impact that the altered biomechanics associated with ACLR have on joint degeneration. Hadizadeh et al.\textsuperscript{69} performed a study in which vGRF was measured during walking gait in 22 ACLR athletes and 15 healthy athletes 4-5, 8-9, and 12-13 weeks post-ACLR. By the third testing session, there were no significant differences in the average vGRF magnitude during stance phase between reconstructed knees and healthy controls. However, significant vGRF asymmetries between injured and contralateral knees still persisted at the third testing. Co et al.\textsuperscript{17} found higher heel strike transient forces in both limbs of individuals with ACL-R compared to healthy controls. The heel strike transient (HST) is the force immediately following ground contact during gait, and is separate from and occurs prior to the peak vGRF. The HST has been used to discriminate between normal and impulsive loaders during gait following ACLR.\textsuperscript{18} However, there were no significant differences in the HST between ACLR individuals’ involved and contralateral limbs.\textsuperscript{17} The lack of a difference between limbs may have been limited by small sample size (n=10). Similarly, in a study consisting of 20 ACLR and 20 healthy control females, Noehren et al.\textsuperscript{16} found significantly greater initial vertical impact force and loading rate in ACLR individuals compared to healthy controls during both walking and running gait.
However, no significant between limb differences in initial vertical impact force or loading rate were observed in the ACLR cohort. This may be explained by the fact that this study calculated the linear/average loading rates rather than instantaneous loading rates immediately following heel strike.\textsuperscript{18} These limitations were attenuated in a study performed by Blackburn et al.\textsuperscript{18} examining inter-limb differences in impulsive loading during walking gait in 29 female subjects with unilateral ACLR an average of 48 ± 41 months post surgery. While the overall peak vGRF and its linear loading rate during the first 50\% of gait did not differ between subjects’ reconstructed and healthy limbs, the instantaneous loading rate was significantly greater in ACLR limbs. The researchers also found significantly greater peak vGRF and associated instantaneous loading rate immediately following heel strike in subjects’ ACLR limbs compared to their healthy limbs.

Clearly, individuals who undergo ACL reconstructions experience altered joint loading during walking gait. Research indicates that altered knee joint loading rates and magnitudes may result in cartilage breakdown and can lead to PTOA development. Chen et al.\textsuperscript{25} subjected canine cartilage explants to both repeated blunt impacts and smoothly arising compressions in order to assess the impact of joint loading on cartilage. The results indicated that mechanical cartilage damage is dependent on peak stress, stress rate, and loading duration. Significant cartilage disruption was reached at a lower peak stress (2.5 MPa) via repeated blunt impacts than via smoothly applied compression (10 MPa). In fact, significant changes were seen in the cartilage matrix water content at a peak stress as small as 2.5 MPa for only 2 minutes.\textsuperscript{25} Similarly, Ewers et al.\textsuperscript{23} found that high rate of loading to rabbit retropatellar cartilage produced significantly more surface fissuring than low rate loading, suggesting that chronic injury mechanisms and outcomes may be significantly dependent on the rate of impact loading.

Morgenroth et al.\textsuperscript{22} demonstrated a similar effect in humans, as significant correlations were observed between tibiofemoral joint degeneration, as assessed by MRI, and greater knee adduction moment loading rate, an indicator of medial knee joint loading, during walking gait. Kurz et al.\textsuperscript{24} found that greater strain rates resulted in greater peak stress levels and mechanical cartilage damage than lower strain rates. Additionally, compression at high strain rates led to significantly decreased proteoglycan and
total protein biosynthesis, leading the researchers to conclude that cartilage subjected to compression at high strain rates does not display the same anabolic response typical of low-amplitude, cyclic mechanical loading.\(^{24}\)

Biomechanical forces, and the altered response of tissues to such forces, are the primary catalysts of joint deterioration associated with the development of PTOA.\(^{19}\) Research investigating how altered biomechanics, and thus altered joint loading rates, develop will be beneficial not only to ACLR individuals, but also to other sufferers of joint injuries and other individuals at risk for OA.

2.5 – Proprioceptive Deficits Post ACLR

It is well established that afferent proprioceptive mechanoreceptors, including Ruffini endings, Pacinian corpuscles, and Golgi-like endings, as well as free nerve endings, exist in the intra-articular structures of the knee joint, including the ACL and its attachment sites.\(^{70-73}\) These mechanoreceptors are the first link in the afferent chain signaling positional changes at the knee joint, and thus play a major role in knee joint proprioception.\(^{70-73}\) ACL tears not only disrupt the mechanical stability of the knee joint, but also the neuromuscular control due to damage to or loss of mechanoreceptors.\(^{74}\)

Whether individuals with ACL injuries experience proprioceptive deficits has been extensively studied, with varied results. While the most common treatment for ACL tears is surgical reconstruction, some individuals elect to remain ACLD and undergo conservative treatment and rehabilitation. Barrack et al.\(^{26}\) found that between-limb differences in threshold to detect passive change in position, a measure of proprioception, were significantly greater in ACLD individuals (25% mean between limb variation) compared to healthy controls (2% mean between limb variation). Multivariate analysis directly attributed this proprioceptive deficiency to ACLD rather than other variables including age, time from injury, and degree of rehabilitation. Additionally, Lee et al.,\(^{29}\) in a study examining knee joint proprioception in 48 individuals with acute (≤ 3 months post injury) ACL tears and 28 individuals with chronic (> 3 months post injury) ACL tears, found that JPS was impaired in the involved knee in individuals with chronic tears relative to both acute ACL tears and to the uninvolved knee. Furthermore, Fremerey et al.\(^{30}\) found
significant between-limb deficiencies in proprioception, as measured by JPS, in ACLD individuals with acute anterior knee instability at all testing intervals.

However, there is also research that suggests ACLD individuals do not experience proprioceptive deficits. In a study examining standing JPS in ACLD individuals, Good et al.\textsuperscript{75} found no significant real (magnitude and direction) or absolute (magnitude only) error between-limb differences in passive-active JPS. Furthermore, no significant real error between-limb differences were observed in active-active JPS, or in any measure at flexion angles less than 45°. Good et al.\textsuperscript{75} concluded that standing JPS does not change after ACL injury. Additionally, Ozenci et al.\textsuperscript{28} compared TDPM and JPS in ACLD, ACLR autograft, ACLR allograft, and healthy controls. No significant differences in TDPM were observed between autograft and allograft ACLR groups, nor were there significant differences between either of the ACLR groups and healthy controls. The only significant differences in TDPM observed were between ACLD individuals and all other groups. No significant differences in JPS were observed between any of the groups. This suggests that ACLR does a sufficient job in restoring proprioception.

The research investigating proprioception following ACL injury has produced variable results. However, in a meta-analysis examining JPS and TDPM, Relph et al.\textsuperscript{32} found significant deficits in these measures between patients with ACL injuries and healthy controls. The study also found significant differences in JPS between ACLR and contralateral knees. On the whole, proprioceptive deficiencies were observed more clearly with JPS than with TDPM, indicating that JPS may be a more significant problem after ACL injury and should be given rehabilitative priority.

ACLR is the most common intervention for ACL injuries. Just as the research on whether ACLD individuals experience proprioceptive deficits has produced varied results, research investigating whether proprioceptive deficits persist post-ACLR is seemingly inconclusive. Several studies have reported a lack of proprioceptive deficits post-ACLR. Mir et al.\textsuperscript{33} found no evidence of impaired JPS in weight-bearing situations in 12 ACLR subjects a mean of 11 months post-reconstruction. No significant between-limb differences were observed, nor were significant differences observed between ACLR individuals’ involved knees and healthy controls. However, this study may have been limited by a small sample size.
Similar to Reider et al. \(^{34}\) found no significant difference in JPS between ACLR individuals’ injured and contralateral knees 3 weeks, 6 weeks, and 3 months postoperatively, and the injured knees performed better than contralateral knees 6 months postoperatively. Additionally, by 6 months post-reconstruction, there was no significant difference in TDPM between injured and contralateral knees. \(^{34}\) These results suggest that ACLR sufficiently restores proprioceptive deficits within 6 months.

Furthermore, Hopper et al. \(^{35}\) found no significant deficit in weight-bearing JPS either to extension or to flexion in nine subjects 12 to 16 months post-ACLR. However, this study may be limited by small sample size. Additionally, the authors postulate that the weight-bearing condition may have played a role in the lack of JPS difference. Other sources of neuromuscular feedback, such as muscle spindles, may have compensated for decreased JPS.

Contrary to the previously mentioned research, several studies have found that proprioceptive deficits persist after ACLR. Fischer-Rasmussen et al. \(^{27}\) assessed TDPM and JPS in ACLD, ACLR, and healthy control individuals. Significant between-limb differences in TDPM were observed in both the ACLD and ACLR groups, while no significant differences were observed in the healthy controls. Significant between-limb impairments in JPS were observed in both the ACLD and ACLR groups, but only when the starting position was 60 degrees of flexion. No significant differences were observed when the starting position was full extension. Likewise, significant between-limb differences were not observed in healthy controls. \(^{27}\) Additionally, Fremerley et al. \(^{30}\) found significant between-limb differences in JPS in ACLR individuals with chronic knee instability at three months, six months, and an average of 3.7 ± 0.3 years post-reconstruction. While there were significant decreases in JPS error in the ACLR knee at 6 months and 3.7 ± 0.3 years compared to 3 months, proprioceptive ability in the injured limb did not reach the level of the healthy limb. Furthermore, Hoch et al. \(^{31}\) reported impaired cutaneous detection, a source of somatosensory input, distally in patients with ACLR.
2.6 – Proprioceptive Deficit Influence on Loading Rates

Proprioception is the awareness of the position of body segments and joints in space. It has been theorized that altered proprioception after ACLR leads to altered knee joint loading rates during gait, which can lead to cartilage deterioration and OA development. Altered awareness of the relative positions of the segments of the lower limbs during gait may leave the knee joint ill prepared for the impact loading experienced at heel strike.\[43\]

The relationship between proprioception and joint loading has commonly been studied in healthy individuals. Riskowski\[76\] performed a study in which fifteen young, healthy women performed gait training using a knee brace that offered audible feedback (to augment proprioception) in response to subjects’ knee flexion and vertical acceleration. Proprioception was measured pre and post-test via TDPM and JPS. Rate of loading (ROL) was also measured pre and post test. Significant improvements in TDPM and improvements (not significant) in JPS were observed, as well as significant reductions in ROL after training with the brace.\[76\] These results indicate that there may be a relationship between improved proprioception and decreased loading rates. Furthermore, Riskowski et al.\[43\] performed a study examining proprioception, gait kinematics, and rate of loading during walking in thirty-eight young, healthy women. Proprioception was assessed by TDPM and JPS, and ROL was determined from the vGRF. A significant correlation was observed between proprioception and ROL, with poorer proprioception associated with greater loading rates.\[43\]

The relationship between proprioceptive deficits and greater joint loading has also been studied in individuals who have already developed OA. In a study examining the relationship of vibratory perception to dynamic joint loading, Shakoor et al.\[39\] found that diminished vibratory perception threshold (VPT), as assessed using a biothesiometer, at the metatarsophalangeal joint was directly correlated with dynamic knee joint loading during gait in individuals diagnosed with OA. However, no significant relationships between VPT and knee joint loading were found at the other anatomical sites tested (medial and lateral malleoli, medial and lateral femoral condyle).\[39\]
Furthermore, improvements in proprioception have been found to reduce knee joint loading in individuals with OA. Collins et al. found that stochastic resonance electrical stimulation and a neoprene sleeve improved knee joint position sense (JPS), a measure of proprioception, in individuals with minimal to moderate medial compartment knee OA. This stimulation also reduced HST and GRF loading rates relative to a control condition. The researchers concluded that enhanced JPS resulted in decreased impulsive loading.

While a significant volume of research has been performed investigating the relationship between proprioception and loading rates in healthy individuals and individuals who already have OA, there is little research on this relationship in ACLR individuals. Given that ACLR individuals face an increased risk of PTOA, research evaluating the effects of proprioceptive deficits on joint loading in this population is needed. This research may facilitate a better understanding and possibly solutions to the development of PTOA and OA in general, and may facilitate development of interventions.

2.7 – Vibratory Perception Threshold and Joint Position Sense

Vibratory perception threshold is believed to serve as an analog to direct proprioceptive testing, as vibratory sense is believed to travel the same type of large afferent nerve fibers as proprioceptive sense. The two sensations are transmitted in parallel through the dorsal columns of the spinal cord and share some sensory bodies. However, the VPT pathway is similar, yet distinctly separate from proprioception.

VPT, as assessed using a biothesiometer, is a relatively quick, portable, and reliable measure with a high degree of reproducibility. The physical test of VPT is technically simpler than proprioceptive JPS testing, and is easier on the patient. Additionally, confounding factors including patient memory, coordination, and reaction time that are often associated with proprioceptive tests are mitigated in VPT testing. Given its reliability and relative simplicity compared to proprioceptive measures, VPT may be a valuable tool to evaluate proprioceptive deficits in the clinical setting. JPS testing is simply not feasible in most clinical settings.
Deficits in VPT have been observed in individuals already diagnosed with OA. Shakoor et al.\textsuperscript{36} performed VPT testing at five lower extremity sites (first metatarsophalangeal joint, medial and lateral malleoli, and medial and lateral femoral condyle) in 27 individuals with OA (22 women, 5 men) and 14 healthy controls (9 women, 5 men). VPT was significantly higher at all five test sites in subjects with OA compared to healthy subjects. This significant difference persisted when older OA subjects and younger healthy subjects were excluded to eliminate the possible confounding factor of age.\textsuperscript{36} However, Thorlund et al.\textsuperscript{38} found that ACLD individuals performed better during VPT tests at the medial malleolus and medial femoral condyle than did matched controls.

VPT may be particularly valuable in the clinical setting in determining if proprioceptive deficits, which have been linked to greater loading rates, are present in individuals post ACLR. Early clinical recognition of proprioceptive deficits may be useful in preventing the onset of PTOA following ACLR and OA in general.

More research is needed on the relationship between VPT and JPS and whether JPS is a valid analog to proprioceptive testing. Additionally, research investigating whether VPT is deficient in ACLR individuals is needed.
CHAPTER III: METHODS

3.1 – Subjects

Thirty-four individuals between 18-35 years of age who underwent unilateral ACLR within 6 months to 5 years prior to participation were recruited for this investigation. Exclusion criteria included a history of ACL graft rupture or revision surgery, neurological disorder, and/or injury to either leg (other than the initial ACLR) within 6 months prior to participation. Additionally, subjects were required to possess quadriceps dysfunction (i.e. Central Activation Ratio < 95%) and Knee Injury and Osteoarthritis Outcome Score (KOOS) self-report survey Pain subscale score > 53.1 and Symptom subscale score > 44.9. High scores on these measures indicate less pain and fewer symptoms. These surveys were used to screen out subjects who were “too low” to participate. Finally, subjects had to be cleared by a physician for return to physical activity and be currently physically active, participating in at least 20 minutes of physical activity at least 3 times per week. All subjects provided written informed consent prior to participation.

3.2 – Experimental Design

The data presented here are part of randomized control trial evaluating the effects of whole body vibration (WBV) and local muscle vibration (LMV) on gait biomechanics, quadriceps function, and somatosensory function following ACLR. The present study involved a cross-sectional analysis of the pre-intervention somatosensory function and gait kinetics data.

3.3 – Procedures

Upon arrival to the laboratory, subjects completed a 5-minute warm up on a cycle ergometer at a self-selected pace. During this time, the subjects were given an overview of the testing procedures and the general topics being investigated.
3.4 – Joint Position Sense

Proprioception at the knee joint was evaluated via an active joint position sense (JPS) task in a closed kinetic chain, partial weight-bearing position. Subjects were fitted with 4 electromagnetic motion tracking sensors placed bilaterally on the lateral aspect of the mid-thigh and the anterior aspect of the shank to assess knee joint motion.

Subjects were positioned supine on a sliding platform inclined 70° relative to the vertical. The sliding platform and partial weight-bearing orientation allowed unrestricted knee motion while also controlling for extraneous factors that influence JPS during weight bearing such as postural sway and trunk position. A wedge was placed under the testing limb, placing the ankle in a slightly plantarflexed position to minimize sensory cues derived from tension in the calf musculature created by dorsiflexion.

Each trial began with the subject’s knee in full extension. Prior to each trial, a target reference angle was randomly selected by the investigator (20°, 25°, or 30° of flexion). The subject then actively flexed the knee while the investigator viewed the joint angle in real time on a computer monitor and verbally indicated when the subject reached the target angle. Once the target angle was reached (within ± 2.5°), the subject pressed an electronic trigger to provide a time stamp for the kinematic data before returning to the starting position for 5 seconds. During this time, the subject was fitted with a blindfold and headphones providing white noise to eliminate visual and auditory cues. The subject then attempted to recreate the target angle by flexing the knee, and pressed the electronic trigger to indicate when he/she perceived that the target angle was reached. Subjects performed 5 trials per limb. Kinematic data were sampled at 200 Hz via the Motion Monitor motion capture system and low-pass filtered at 10 Hz. The
absolute difference between the reference angle and the subjects’ reproduced angle were calculated via custom software (LabVIEW) and averaged across the 5 trials for statistical analysis.

3.5 – Vibratory Perception Threshold

Vibratory perception threshold (VPT) was evaluated using a biothesiometer. This device consists of a vibrating tip that oscillates at 120 Hz. The tip is placed on a bony landmark, and a manual dial is used to adjust the vibration intensity. In the present study, the intensity was initially set at 0, and was then increased at a rate of 1 V/s. The subject was instructed to verbally indicate the point at which he/she first sensed the vibration, and the corresponding voltage was recorded as the VPT.

Prior to testing, the biothesiometer was applied to the subject’s hand to familiarize him/her with the vibratory sensation to be expected during testing. Subjects were first positioned side-lying on a padded examination table. The biothesiometer was then applied uniformly to four lower extremity bony landmarks (medial and lateral epicondyles and medial and lateral malleoli) of the ACLR and contralateral limbs with the weight of the device serving as the only source of pressure. A fifth bony landmark, the base of the first metatarsal, was assessed with the subject seated at the edge of the padded examination table with the legs hanging over the side and the feet resting flat on a box or stool. The bony landmarks of both limbs accessible in each side-lying position (i.e. subject lying on his/her left/right side) were measured in a cyclic pattern such that each landmark was tested twice with at least 60 seconds between each measurement. The VPT of the two trials at each site were averaged for statistical analysis.

Figure 2: Subject positioning for VPT assessment.
Additionally, “total knee” and “total ankle” values were calculated as the averages of the mean medial and lateral femoral epicondyle measures and mean medial and lateral malleoli measures respectively.

3.6 – Gait Biomechanics

Three–dimensional gait biomechanics were assessed via an electromagnetic motion capture system (Ascension trakSTAR) interfaced with force plates (Bertec 4060) and electromyography (DelSys Bagnoli-8) to provide comprehensive kinematic, kinetic, and neuromuscular assessment. Only kinetics are reported here. Subjects walked barefoot at a comfortable, self-selected “fast” speed along a 6m (~20 ft.) walkway embedded with three force plates staggered such that one trial provided data for both limbs. Subjects walked a minimum of 3 m via 3-5 steps prior to making contact with the first force plate and took a minimum of 2 steps following contact with the second plate. Subjects performed a minimum of 5 practice trials to determine the average preferred gait speed and to ensure subjects could consistently strike the force plates without noticeably altering their gait (i.e. without “aiming” for the force plate). Gait speed was monitored via an infrared timing system to ensure each trial was within ±5% of the preferred speed and that the entire foot made contact with the force plate (i.e. the trial was valid). Trials that did not satisfy these criteria were repeated. Kinetic variables were averaged from 5 completed valid trials.

Ground reaction forces were sampled at 1,200 Hz and low-pass filtered at 75 Hz. The outcome variable of interest was the peak instantaneous loading rate (first time derivative) of the vertical ground reaction force (vGRF) during the first 50% of the stance phase of gait. Stance phase was defined as the period of time between heel strike (vGRF ≥ 20N) and toe off (vGRF ≤ 20N). All biomechanical analyses were performed using custom software (LabVIEW). The vGRF rate was normalized to body weight (xBW/s).
3.7 – Statistical Analysis

Prior to analysis, data were screened for normality and outliers (i.e. 2.5 SD beyond the mean). JPS and VPT were compared between ACLR and contralateral limbs via paired samples t-test. The relationship between JPS and VPT in the ACLR limb was evaluated via simple Pearson r correlations. The relationships between the peak instantaneous vGRF loading rate and JPS and VPT in the ACLR limb, respectively, were evaluated using partial correlations (Pearson r) controlling for gait speed. All analyses were conducted with an *a priori* alpha level of 0.05.
CHAPTER IV: RESULTS

Four subjects were identified as outliers (i.e. $\geq 2.5$ SD beyond the mean) for VPT, JPS, and/or vGRF loading rate, and were excluded from the statistical analysis. Thus, of the 34 subjects to undergo testing, 30 subjects were used for statistical analysis. Demographic data for those retained subjects is presented in Table 1.

4.1 – Between-Limb Comparisons of JPS and VPT

There were no significant differences in measures of somatosensory function between the ACLR and contralateral limbs. No significant differences in JPS error were observed (ACLR = 2.82 ± 1.15 vs. Contralateral = 2.37 ± 1.13, $p = 0.137$), nor were there any significant differences in VPT at any of the sites tested (MFE $p = 0.806$, LFE $p = 0.909$, MM $p = 0.783$, LM $p = 0.169$, 1MTP $p = 0.313$, Total Knee $p = 0.937$, Total Ankle $p = 0.491$). (See Table 2)

4.2 – Relationship Between JPS and VPT

There was no significant correlation between JPS error and VPT at any of the sites tested in the ACLR limb: MFE ($r = -0.037$, $p = 0.846$), LFE ($r = -0.176$, $p = 0.352$), MM ($r = -0.100$, $p = 0.600$), LM ($r = -0.070$, $p = 0.714$), 1MTP ($r = -0.143$, $p = 0.450$), Total Knee ($r = -0.139$, $p = 0.465$), Total Ankle ($r = -0.092$, $p = 0.628$). (See Table 3)

4.3 – Relationships Between Peak Instantaneous vGRF Loading Rate and JPS and VPT

There was no significant correlation between the peak instantaneous vGRF loading rate and either JPS error ($r = -0.269$, $p = 0.158$), or VPT at any of the sites tested in the ACLR limb: MFE ($r = 0.177$, $p = 0.358$), LFE ($r = 0.108$, $p = 0.577$), MM ($r = -0.079$, $r = 0.682$), LM ($r = 0.040$, $p = 0.835$), 1MTP ($r = -0.337$, $p = 0.073$), Total Knee ($r = 0.191$, $p = 0.322$), Total Ankle ($r = -0.029$, $p = 0.881$). (See Table 4)
### Table 1  Demographics of Subjects Included in Analysis

<table>
<thead>
<tr>
<th></th>
<th>ACLR Limb</th>
<th>Contralateral Limb</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>19.9 ± 1.5</td>
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<tr>
<td>Mass (kg)</td>
<td>68.3 ± 18.4</td>
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<tr>
<td>Height (m)</td>
<td>1.7 ± 0.09</td>
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<tr>
<td>Time Since ACLR (months)</td>
<td>26.2 ± 14.0</td>
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<td></td>
</tr>
<tr>
<td>Gender (number of subjects)</td>
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<td>Male</td>
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<td></td>
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<tr>
<td>Female</td>
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<td></td>
</tr>
<tr>
<td>Graft Type (number of subjects)</td>
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<td></td>
<td></td>
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<tr>
<td>Hamstring</td>
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<tr>
<td>Patellar Tendon</td>
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<td>Quadriceps Tendon</td>
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<tr>
<td>Cadaver</td>
<td>4</td>
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</tbody>
</table>

### Table 2  Bilateral Comparisons of Somatosensory Characteristics (mean ± sd)

<table>
<thead>
<tr>
<th></th>
<th>ACLR Limb</th>
<th>Contralateral Limb</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint Position Sense (°)</td>
<td>2.82 ± 1.15</td>
<td>2.37 ± 1.13</td>
<td>0.137</td>
</tr>
<tr>
<td>Vibratory Perception Threshold (V)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medial Femoral Epicondyle</td>
<td>13.50 ± 3.56</td>
<td>13.30 ± 3.68</td>
<td>0.806</td>
</tr>
<tr>
<td>Lateral Femoral Epicondyle</td>
<td>12.52 ± 3.41</td>
<td>12.62 ± 4.06</td>
<td>0.909</td>
</tr>
<tr>
<td>Medial Malleolus</td>
<td>9.87 ± 2.17</td>
<td>9.78 ± 1.71</td>
<td>0.783</td>
</tr>
<tr>
<td>Lateral Malleolus</td>
<td>9.18 ± 1.65</td>
<td>9.53 ± 1.89</td>
<td>0.169</td>
</tr>
<tr>
<td>1st Metatarsophalangeal</td>
<td>4.85 ± 1.18</td>
<td>4.67 ± 0.98</td>
<td>0.313</td>
</tr>
<tr>
<td>Total Knee (Mean MFE &amp; LFE)</td>
<td>13.01 ± 2.63</td>
<td>12.96 ± 3.19</td>
<td>0.937</td>
</tr>
<tr>
<td>Total Ankle (Mean MM &amp; LM)</td>
<td>9.53 ± 1.80</td>
<td>9.65 ± 1.61</td>
<td>0.491</td>
</tr>
</tbody>
</table>
Table 3  Correlations Between JPS and VPT in ACLR Limb

<table>
<thead>
<tr>
<th>Joint Position Sense</th>
<th>Correlation Coefficient (r)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medial Femoral Epicondyle</td>
<td>-0.037</td>
<td>0.846</td>
</tr>
<tr>
<td>Lateral Femoral Epicondyle</td>
<td>-0.176</td>
<td>0.352</td>
</tr>
<tr>
<td>Medial Malleolus</td>
<td>-0.100</td>
<td>0.600</td>
</tr>
<tr>
<td>Lateral Malleolus</td>
<td>-0.070</td>
<td>0.714</td>
</tr>
<tr>
<td>1st Metatarsophalangeal</td>
<td>-0.143</td>
<td>0.450</td>
</tr>
<tr>
<td>Total Knee</td>
<td>-0.139</td>
<td>0.465</td>
</tr>
<tr>
<td>Total Ankle</td>
<td>-0.092</td>
<td>0.628</td>
</tr>
</tbody>
</table>

Table 4  Partial Correlations Between ACLR Limb Loading Rate and Somatosensory Function

<table>
<thead>
<tr>
<th>Joint Position Sense</th>
<th>Correlation Coefficient (r)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint Position Sense</td>
<td>-0.269</td>
<td>0.158</td>
</tr>
<tr>
<td>Medial Femoral Epicondyle</td>
<td>0.177</td>
<td>0.358</td>
</tr>
<tr>
<td>Lateral Femoral Epicondyle</td>
<td>0.108</td>
<td>0.577</td>
</tr>
<tr>
<td>Medial Malleolus</td>
<td>-0.079</td>
<td>0.682</td>
</tr>
<tr>
<td>Lateral Malleolus</td>
<td>0.040</td>
<td>0.835</td>
</tr>
<tr>
<td>1st Metatarsophalangeal</td>
<td>-0.337</td>
<td>0.073</td>
</tr>
<tr>
<td>Total Knee</td>
<td>0.191</td>
<td>0.322</td>
</tr>
<tr>
<td>Total Ankle</td>
<td>-0.029</td>
<td>0.881</td>
</tr>
</tbody>
</table>

Partial correlations after accounting for the influence of gait speed.
CHAPTER V: DISCUSSION

The primary findings of this study were that JPS error and VPT were not significantly different between the ACLR and contralateral limbs, that there was no significant correlation between JPS error and VPT in the ACLR limb, and that there were no significant correlations between instantaneous vGRF loading rate and either JPS error or VPT in the ACLR limb. These findings are inconsistent with the experimental hypotheses. It was hypothesized that individuals with ACLR would demonstrate significant deficits in JPS error and VPT in the ACLR limb relative to the contralateral, that JPS error and VPT would be positively correlated in the ACLR limb, and that the instantaneous vGRF loading rate would be positively correlated with JPS error and/or VPT in ACLR limb. Our findings suggest that current ACL reconstruction and rehabilitation processes may adequately restore somatosensory function to the ACLR limb, and that while altered gait kinetics following ACLR may be implicated in OA development, somatosensory deficits do not directly contribute to greater loading rates.

Our finding that neither JPS error nor VPT were significantly different between the reconstructed and contralateral limbs of individuals with ACLR is supported by previous research. Several studies indicate that significant differences in JPS are not present even in ACLD individuals. Good et al. performed a study comparing active JPS in an upright, non-weight bearing position between ACLD and contralateral limbs in 18 subjects a mean of 6 weeks post injury. No significant differences in absolute error were observed between injured and contralateral limbs at joint angles less than 45° of flexion. There were, however, significant differences at angles greater than 45° of flexion. These results coincide with our failure to observe a significant between-limb difference in JPS error at the relatively small knee flexion angles (20°, 25°, and 30°) associated with walking gait. In a study examining JPS and TDPM in ACLD, ACLR autograft, ACLR allograft, and healthy controls, Ozenci et al. found no significant differences in JPS between any of the groups. The only significant difference in TDPM was between ACLD and all other groups, suggesting that ACLR sufficiently restores proprioceptive sensation. JPS was assessed via a passive JPS test using a Cybex Norm dynamometer with the knee initially in full extension.
Our finding is also supported by previous research examining JPS in the ACLR individual. Mir et al.\textsuperscript{33} found no evidence of impaired active JPS in weight-bearing positions in 12 ACLR subjects a mean of 11 months post-reconstruction. No significant between-limb differences were observed, nor were significant differences observed between ACLR individuals’ involved knees and healthy controls regardless of starting knee angle. Additionally, Hopper et al.\textsuperscript{35} found no significant deficit in weight-bearing JPS either to extension or to flexion in nine subjects 12 to 16 months post-ACLR. The full weight-bearing condition may have played a role in the lack of JPS difference in these two studies, as greater recruitment of other sources of neuromuscular feedback, such as muscle spindles, and balance/equilibrium sensations may have compensated for decreased afferent ACL signals. Furthermore, Reider et al.\textsuperscript{34} found no significant difference in JPS between 26 ACLR individuals’ injured and contralateral knees 3 weeks, 6 weeks, and 3 months postoperatively, and the injured knees performed better than contralateral knees 6 months postoperatively. These results suggest that ACLR and subsequent rehabilitation sufficiently restores proprioceptive deficits within 6 months.

Clearly, there is significant research to suggest that JPS error is not significantly different between ACLR and contralateral limbs. However, these studies, and the present study, have several limitations. Each study examined JPS a mean of no more than 26.2 months postoperatively (present study). The previously mentioned studies examined JPS at either 6 weeks post-injury\textsuperscript{75} or at a maximum of 25.6 months,\textsuperscript{28} 11 months,\textsuperscript{33} 12-16 months,\textsuperscript{35} or 6 months\textsuperscript{34} postoperatively, respectively. The between limb JPS error differences pertinent to the development and/or acceleration of OA following ACLR may develop more slowly, over the course of several years. Furthermore, each of the studies cited had relatively small sample sizes: 30 in the present study and 18,\textsuperscript{75} 12,\textsuperscript{33} 9,\textsuperscript{35} and 26,\textsuperscript{34} respectively. Larger samples sizes may have revealed a more representative relationship. Additionally, the majority of studies reporting no significant differences in JPS error between limbs investigated individuals with ACLR rather than ACLD. This may indicate that ACLR and subsequent rehabilitation sufficiently restores proprioceptive sensation following an ACL rupture, at least to a functional level.
Our finding that VPT is not significantly different between the ACLR and contralateral limb is partially supported by a study by Thorlund et al.\textsuperscript{38} comparing VPT in individuals with ACL injuries and healthy controls. In this study, individuals with ACL injury performed better during VPT tests at the medial malleolus and medial femoral condyle than did matched controls. Subjects were 39 ACL-injured individuals with mean time since injury of 21.9 ± 21.6 months for ACLD or mean time since surgery of 13.9 ± 19.3 months for ACLR. Again, this study may be limited by the time frame of investigation.

While several studies support our findings related to JPS error, there is a substantial body of evidence that suggests JPS error is significantly different between-limbs following ACL injury and reconstruction. Lee et al.,\textsuperscript{29} in a study examining knee joint proprioception in 48 individuals with acute (≤ 3 months post injury) ACL tears and 28 individuals with chronic (> 3 months post injury) ACL tears, found that JPS was impaired in the involved knee in individuals with chronic tears relative to both acute ACL tears and to the uninvolved knee. However, unlike the present study, JPS was assessed passively with the subject seated on isokinetic dynamometer with hips and knees flexed to 90°. The target angle of 45° of knee flexion was larger than the angles used in the present study (and those seen in walking gait), and closer to the midrange of knee joint range of motion. Some proprioceptive receptors, such as articular receptors, are less effective in the mid-ranges regardless of injury, and this may have played a role in the differences observed. Fremerey et al.\textsuperscript{30} found significant between-limb deficiencies in proprioception, as measured by JPS, in ACLD individuals with acute anterior knee instability (within first 12 days following injury) at all target angle intervals (extension 0-20°, mid range 40-60°, and flexion 80-100°), with the greatest deviation in flexion and smallest deviation in extension. This study also found significant between-limb differences in JPS error in ACLR individuals with chronic knee instability at three months (all intervals), six months (mid range), and an average of 3.7 ± 0.3 years post-reconstruction (mid range).

The finding that JPS improved over time supports the notion that ACLR and subsequent rehabilitation sufficiently restores proprioceptive sensation. Furthermore, significant differences were only found in the mid range angles (40-60° of flexion) beyond 6 months postoperatively.\textsuperscript{30} These knee angle ranges are less typical for walking gait and were not included in the present study. Again, some proprioceptive receptors
are less effective in the mid-range of motion regardless of injury. In a meta-analysis examining JPS and TDPM, Relph et al.\textsuperscript{32} found significant deficits in these measures between patients with ACL injuries and healthy controls. The study also found significant differences in JPS between ACLR and contralateral knees. However, the study included both ACLD and ACLR individuals and found that the proprioception of ACLR subjects was significantly better than those who did not undergo reconstruction.\textsuperscript{32} This finding is consistent with the notion that, while ACLD individuals may possess between limb differences in JPS, ACLR tends to improve and sufficiently eliminate these deficits. Finally, Fischer-Rasmussen et al.\textsuperscript{27} assessed JPS in ACLD (\(n = 20\)), ACLR (\(n = 18\)), and healthy control (\(n = 20\)) individuals. Significant between-limb impairments in JPS were observed in both the ACLD and ACLR groups, but only when the starting position was 60° of flexion, a joint angle not typically associated with walking gait. No significant differences were observed when the starting position was full extension, as in the present study.

The present study is the first, to our knowledge, to investigate the relationship between instantaneous \(v\)GRF loading rate and JPS and VPT in ACLR individuals. Previous research has examined these relationships in healthy individuals and individuals who already have OA. Riskowski et al.\textsuperscript{43} assessed proprioception (JPS) and loading rate in 38 young, healthy women. A significant correlation was observed between proprioception and loading rate, with poorer proprioception associated with greater loading rates. JPS was tested at 45° and 70° of extension, with only the 70° test significantly correlated with ROL. A later study by Riskowski et al.\textsuperscript{76} found significantly improved proprioception and significantly reduced loading rates in fifteen young, healthy women following gait training using a knee brace that offered audible feedback (to augment proprioception) in response to subjects’ knee flexion and vertical acceleration. The findings that proprioception and loading rate are significantly correlated and that improved proprioception is associated with improved loading rates provided part of the basis for the present study. However, no such correlations were found in the ACLR individual.

Previous studies have also found significant correlations between somatosensory information and loading rate in individuals who already have OA. Shakoor et al.,\textsuperscript{39} using the same procedure as in the
present study, found that diminished VPT at the metatarsophalangeal joint was directly correlated with dynamic knee joint loading during gait in 31 individuals diagnosed with OA. However, no significant relationships between VPT and knee joint loading were found at the other anatomical sites tested (medial and lateral malleoli, medial and lateral femoral condyle). Additionally, Collins et al. found that stochastic resonance electrical stimulation and a neoprene sleeve improved knee JPS via similar procedures as in the current study in individuals with minimal to moderate medial compartment knee OA. This stimulation also reduced HST and GRF loading rates relative to a control condition. Similar relationships were not observed in the present study.

Despite similar sample sizes and JPS and VPT testing procedures, our findings suggest that somatosensory information is not significantly correlated with loading rate in the same manner as has been observed in healthy and OA individuals. Afferent somatosensory signaling directly affected by ACL disruption may be present, but may be compensated for via other sources of information from the knee and surrounding musculature in ways that do not manifest themselves via the testing procedures used.

Our investigation into the direct relationship between VPT and JPS was the first of its kind to our knowledge. VPT is believed to serve as an analog to direct proprioceptive testing, as vibratory sense is believed to travel the same type of large afferent nerve fibers as proprioceptive sense. The two sensations are transmitted in parallel through the dorsal columns of the spinal cord and share some sensory bodies. However, the VPT pathway is similar, yet distinctly separate from proprioception. Previous research had linked both JPS and VPT to increased loading rate following ACLR, and our investigation sought to determine if VPT could be used as a reliable clinically practical analog for JPS, a more practical laboratory test of proprioception. Our finding that JPS and VPT are not positively correlated suggests that this is not the case. However, our study may have been limited by sample size and time frame.

On the whole, our findings suggest that ACLR sufficiently restores somatosensory sensation following disruption of the ACL and that somatosensory function is not directly related to increased loading rates. This is not to suggest that somatosensory sensation is not a factor in increased loading rate
or that impulsive loading is not a factor in the development of OA following ACLR. Somatosensory deficits may actually be present following ACL rupture, and if left unresolved may significantly alter gait kinetics in a manner that accelerates OA development. However, the present study and previous research suggests that ACLR and subsequent rehabilitation restores somatosensory sensation at least to the level of the contralateral limb, and that this restored somatosensory sensation is not directly implicated in increased loading rate at the knee. ACL tears not only disrupt the mechanical stability of the knee joint, but also neuromuscular control due to damage to or loss of mechanoreceptors. Generally, the loss of these mechanoreceptors should result in some degree of diminished somatosensory sensation at the knee. However, our findings indicate that this is not the case. Several factors may explain this conclusion. First, other sources of afferent somatosensory signal in the joint and surrounding musculature may be naturally compensating for the afferent signals lost with ACL disruption. Second, the current rehabilitation paradigm following ACLR may already sufficiently facilitate compensatory mechanisms. Finally, ACLR may provide the platform for reafferentation of the mechanoreceptors disrupted by the rupture, if given enough time. Barrack et al. found evidence of reinervation of mechanoreceptors in patellar tendon ACLR 6 months postoperatively in canine models. Additionally, Tsuda et al. reported evidence of the return of the ACL-hamstring reflex arc in two of three subjects at a range of 37 to 80 months following reconstruction, further indicating the possibility of reinervation following ACLR. There is still substantial evidence that ACLR individuals possess greater loading rates in the reconstructed limb than healthy controls and/or the contralateral limb. However, other factors, such as persistent quadriceps dysfunction following ACLR, may play a greater role in the development of greater loading rates than somatosensory deficits.

Future research should further investigate whether JPS and VPT differ between ACLR and contralateral limbs and whether somatosensory information is correlated with loading rate following ACLR. However, future investigations should include larger sample sizes and should also seek to investigate these variables in subjects farther removed from ACLR, as the somatosensory deficits and loading rates leading to OA may develop later. Additionally, as research to date suggests that ACLR and
the current postoperative rehabilitation paradigm is sufficient in restoring somatosensory function, future research should investigate which components of the current paradigm influence this restoration. For example, clinical trials evaluating the effects of graft type or rehabilitation focus (muscular strength restoration, functional balance/coordination, etc.) are warranted. Finally, future research should further investigate the relationship between JPS and VPT with larger sample sizes and farther removed from ACLR to determine whether VPT can serve as a clinically practical analog for JPS.
REFERENCES


