THE IMMEDIATE EFFECTS OF PLANTAR MASSAGE AND TEXTURED INSOLES ON GAIT IN PATIENTS FOLLOWING ACL RECONSTRUCTION

by

Katherine A. Collins

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Approved by:

____
Dr. Abbey Thomas Fenwick, Chair

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Dr. Tricia Hubbard-Turner

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Dr. Michael Turner

ABSTRACT

KATHERINE A. COLLINS. The immediate effects of plantar massage and textured insoles on gait in patients following ACL reconstruction. (Under the direction of Dr. ABBEY THOMAS FENWICK)

Introduction: Gait impairments, notably reduced knee flexion angle and external knee flexion moment, are common following anterior cruciate ligament reconstruction (ACLR) and may contribute to reinjury or future osteoarthritis development. Recently, plantar cutaneous sensation deficits have been reported following ACLR. It is likely that these sensory deficits influence gait and may represent a mechanism through which gait can be improved.

Objective: To examine the efficacy of two sensory interventions, plantar massage and textured insoles, at altering plantar sensation and improving gait in patients after ACLR.

Methods: Fourteen recreationally active adults with a history of ACLR participated in this study. Participants completed two testing sessions, each of which consisted of a baseline gait and plantar cutaneous sensation analysis, followed by completion of an intervention (massage or textured insole), and repeated gait and plantar cutaneous sensation assessment. Gait analysis was completed via 3D motion capture synchronized with force plate data collection while participants walked at standard gait speed (1.4 m/s ± 5%). Sagittal and frontal plane knee joint biomechanics were extracted from gait analysis using a standard inverse dynamics approach. Plantar cutaneous sensation analysis was conducted with Semmes Weinstein Monofilaments (SWM) with a 4-2-1 stepping algorithm at the plantar aspect of the head of the first metatarsal, base of

the fifth metatarsal, and the medial and lateral malleoli. The plantar massage intervention consisted of a single, five-minute massage targeting the entire plantar surface of both feet, combining effleurage and petrissage techniques. For the textured insoles intervention, the participant was given textured insoles made from coarse grit sandpaper to place into his or her neutral athletic shoes to be worn during gait analysis. Gait data were analyzed using limb X time X condition repeated measures ANOVAs. T-tests were utilized to make all *post hoc* comparisons. Plantar cutaneous sensation data were analyzed via Wilcoxon Signed Rank tests to compare differences between limbs, conditions, and time. Effect sizes were calculated using Cohen's d. Statistical analysis was performed using SPSS (v. 21, IBM SPSS, IBM Corp, Armonk, NY) and Microsoft Excel (v. 2011, Microsoft Corp., Redmond, WA). Alpha was set *a priori* at $P < 0.05$.

Results: There was a significant limb x condition interaction for sagittal plane knee rotation *Post hoc* analyses revealed no differences between limbs or conditions (P>0.05). There was a significant main effect of limb for knee frontal plane rotation, suggesting the ACLR limb was more abducted during walking than the contralateral limb (P=0.028) regardless of time or condition. No significant interactions or main effects were observed for knee joint moments. There were no statistically significant differences between pre-massage and pre-textured insoles sessions within limbs pre-intervention. Comparing sensation between limbs prior to massage, the 5^{th} metatarsal (P=0.016), medial malleolus (P=0.028), and lateral malleolus (P=0.046) demonstrated poorer sensation in the ACLR compared to the contralateral limb. Prior to receiving the textured insoles, participants demonstrated differences in sensation over the 5^{th} metatarsal (P=0.031), with the ACLR limb having worse sensation. Massage improved sensation

over the 1^{st} metatarsal head (*P*=0.026), base of the 5^{th} metatarsal (P=0.039), medial malleolus (*P*=0.035), and lateral malleolus (P=0.043) in the ACLR limb. No changes in sensation occurred as a result of massage in the contralateral limb. Following textured insoles application, sensation improved over the 1^{st} metatarsal (*P*=0.027), 5^{th} metatarsal (*P*=0.011), and medial malleolus (*P*=0.007) of the ACLR limb. No changes in sensation were observed as a result of textured insoles in the contralateral limb.

Conclusions: Plantar massage and textured insoles improved plantar cutaneous sensation in the involved limb following ACLR. Both somatosensory interventions had minimal effects on gait biomechanics. Further investigation of other sensory interventions such as visual-spatial targeted interventions, should be implemented to improve gait biomechanics following ACLR.

DEDICATION

To my parents, Debbie and Peter Collins, without whom this project would not have been possible. Thank you for your support, motivation, and enthusiasm throughout this process.

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TABLE OF CONTENTS

LIST OF TABLES x

LIST OF FIGURES xi

CHAPTER 1: INTRODUCTION 1

CHAPTER 2: REVIEW OF RELATED LITERATURE 5

2.1 Knee Joint Anatomy 5

2.3 Impaired Sensation Following Joint Injury 8

2.3.1 The ACL as a Mechanoreceptor 8

2.3.2 Sensorimotor Deficits Following ACL Injury 11

2.3.3 The Knee Joint Innervations at the Plantar Surface 13

2.3.4 Somatosensory Interventions Following Joint Injury 15

2.4 Lower Extremity Gait and Ramifications 17

CHAPTER 3: METHODS 20

3.1 Participants 20

3.2 Procedures 21

3.2.1 Patient-Reported Outcomes 21

3.2.2 Gait Analysis 22

3.2.3 Plantar Cutaneous Sensation Assessment 23

3.3 Intervention 24

3.3.1 Plantar Massage 24

3.3.2 Textured Insole 24

3.4 Data Processing 25

3.5 Statistical Analysis 25

CHAPTER 4: RESULTS 27

IKDC: International Knee Documentation Committee 27

4.1 Gait Parameters 27

4.2 Plantar Cutaneous Sensation 29

CHAPTER 5: DISCUSSION 32

5.1 Gait 32

5.2 Plantar Cutaneous Sensation 35

5.3 Effectiveness and Patient-Reported Outcomes 37

5.4 Limitations 38

5.5 Conclusion 39

REFERENCES 40

APPENDIX A: PATIENT REPORTED OUTCOMES 44

LIST OF TABLES

Table 1. Participant demographic data (mean ± standard deviation)............................... 27

Table 2. Knee joint rotations (degrees). Data are mean ± standard deviation. 28

Table 3. Knee joint moments (Nm/kg*m). Data are mean ± standard deviation. 28

Table 4. Semmes Weinstein Monofilament detection threshold (median [min, max]). ... 30

Table 5. Participant-reported intervention effectiveness (median [min, max]). 30

Table 6. Reliability of plantar cutaneous sensation assessment. 31

LIST OF FIGURES

Figure 1. Depiction of the marker set used in the present study....................................... 23

CHAPTER 1: INTRODUCTION

Approximately 200,000 anterior cruciate ligament (ACL) injuries occur in the United States each year.[1] Clinically, ACL reconstructions (ACLR) occur at a rate of 175,000 per year in the United States and result in long-term consequences, including impaired neuromuscular control and function, altered biomechanics, and osteoarthritis development, for the patient.[2]Following joint injury, there is damage to neural structures innervating the joint. This damage leads to impaired sensation at both the site of the injury and elsewhere along the nerve's pathway.[3,4] For example, with injury to the ACL, there is an implication of decreased plantar cutaneous sensation and therefore decreased afferent receptor activity.[4] Following traumatic injury, there is obvious damage to the anatomical structures of the joint itself, resulting in a loss of sensory information and therefore an impairment in motor function.[3,5-7] In order to improve cutaneous sensation and therefore stimulate afferent receptor activity and subsequent motor functions, sensory interventions must be implemented.

In patients with chronic ankle instability (CAI), a number of sensory reweighting strategies have been employed to successfully improve postural control. LeClaire et al.[3] for example, utilized plantar massage to stimulate cutaneous receptors from the metatarsal heads to the posterior aspect of the calcaneus. These authors observed significant postural control improvements, when vision was undisturbed, following a single, five-minute massage.[3] Other strategies, such as textured insoles, have also been employed with similar outcomes. Corbin et al.[8] noted postural control improvements, such as reductions in area and velocity of center of pressure (COP) excursion in bilateral stance with textured insoles. These marked improvements are attributed to heightened sensitivity of the plantar surface of the foot while wearing textured insoles, resulting in increased cutaneous afferent receptor activity.[8]

There is emerging evidence that patients with a history of ACLR experience similar deficits in sensation and perception. Perkins et al.[4] examined plantar cutaneous sensory deficits in patients post-ACLR using light touch detection thresholds via Semmes-Weinstein Monofilaments (SWM). The results suggest that patients with a history of ACLR have decreased light touch sensation compared to healthy individuals at the first metatarsal head and medial malleolus. These authors suggested that the observed deficits may be related to other sensorimotor deficits that have been observed following ACLR such as decreased postural control or altered gait.[4] However, no data are available observing the impact of the stimulation of plantar cutaneous receptors on gait in those patients with a history of ACLR.

ACL injury and subsequent reconstruction have been associated with deficits in functional performance and perception of performance by the patient.[9] Among these deficits are the aforementioned abnormal gait patterns that may contribute to joint degeneration and physical inactivity long-term.[1] Improving gait in these patients may be an important adjunct to current post-operative rehabilitation to enhance long-term outcomes. Knowing that ACLR leads to decreased cutaneous sensation and that simple and cost-effective treatments such as plantar massage and textured insoles can alter afferent input and postural control in patients with CAI, it seems logical that similar treatments could be employed in patients after ACLR to improve gait. Therefore, the purpose of this study is to examine the efficacy of two sensory interventions at improving gait in patients after ACLR.

Specific aim 1: To determine the ability of plantar massage and textured insoles to improve gait and sensation in patients following ACLR.

Hypothesis 1.1: As a result of plantar massage and textured insoles, patients will increase knee flexion angle and external knee flexion moment during gait.

Hypothesis 1.2: As a result of plantar massage and textured insoles, patients will increase plantar cutaneous sensation at the head of the 1st metatarsal and the medial malleolus.

Specific aim 2: To determine which intervention (plantar massage or textured insoles) is more effective at improving gait and sensation in patients following ACLR.

Hypothesis 2.1: Based upon the current literature, as a result of the plantar massage intervention, patients will increase knee flexion angle and external knee flexion moment during gait more than as a result of the textured insoles intervention.

Hypothesis 2.2: The textured insoles will be more effective at improving plantar cutaneous sensation in patients following ACLR.

Since the plantar surface of the foot serves as an interface between the body and the ground, it is suggested that afferent information from the plantar cutaneous receptors of the foot is crucial in maintaining efficient postural control and biomechanically correct gait.[4,6-8,10] Unfortunately, afferent input from these receptors is impaired in persons with a history of lower extremity injury. With stimulation of plantar cutaneous receptors via plantar massage and textured insoles, we hope to observe improved afferent input and, therefore, an improved observed gait pattern for those patients with a history of ACLR.

CHAPTER 2: REVIEW OF RELATED LITERATURE

The purpose of this literature review is to detail: 1) knee joint anatomy, 2) anterior cruciate ligament injury and reconstruction, 3) impaired sensation following joint injury, including the ACL as a mechanoreceptor, sensorimotor deficits following anterior cruciate ligament reconstruction, and proposed interventions to target somatosensory deficits following joint injury, and, 4) lower extremity gait and ramifications following injury and reconstruction.

2.1 Knee Joint Anatomy

Four bones form the bony anatomy of the knee joint, including the femur, tibia, fibula, and patella. The knee joint is comprised of two articulations. The first articulation is between the femur and tibia, medial condyle to medial condyle and lateral condyle to lateral condyle. The second articulation is between the patella and the patellar surface of the femur. The musculature of the knee joint can be divided into flexors and extensors of the knee. Flexors of the knee include the hamstrings (biceps femoris, semimembranosus, and semitendinosus), sartorius, and popliteus muscles. The biceps femoris muscle originates on the ischial tuberosity and linea aspera of the femur and inserts on the head of the fibula and the lateral condyle of the tibia. Semimembranosus and semitendinosus both originate on the ischial tuberosity. Semimembranosus inserts at the posterior surface of the medial condyle of the tibia, whereas semitendinosus inserts at the proximal, medial surface of the tibia. Sartorius originates on the anterior superior iliac spine and inserts at the medial surface of the tibia, near the tibial tuberosity. The popliteus muscle originates on the lateral condyle of the femur and inserts on the posterior surface of the proximal tibial shaft, causing medial rotation of the tibia and flexion at the knee. Knee extension is caused by contraction of four muscles collectively known as the quadriceps muscles: the rectus femoris, vastus lateralis, vastus medialis, and vastus intermedius. Rectus femoris originates on the anterior inferior iliac spine and superior acetabular rim of the ilium. Vastus intermedius originates on the anterolateral surface of the femur and linea aspera. Vastus lateralis originates anterior and inferior to the greater trochanter of the femur and along the linea aspera. Vastus medialis originates along the length of the linea aspera of the femur. All four knee extensors insert on the tibial tuberosity via the patellar ligament. The flexors of the knee are largely innervated by the tibial nerve, whereas the extensors of the knee are innervated by the femoral nerve.[11]

There are seven total ligaments that aid in stabilization of the knee joint. The four main ligaments of the knee joint that provide stabilization include the anterior cruciate ligament (ACL), the posterior cruciate ligament (PCL), the medial (tibial) collateral ligament (MCL) and lateral (fibular) collateral ligament (LCL). The anterior cruciate ligament (ACL) is located within the knee joint capsule and attaches the intercondylar area of the tibia to the condyles of the distal femur.[11]

There are two bundles of the ACL, the anteromedial (AMB) and the posterolateral (PLB) bundles.[12] Mochizuki et al.[13] noted that the anteromedial bundle is taut in flexion, whereas the posterolateral bundle is taut in extension, and, the two bundles can be differentiated by these differences in tautness in flexion and extension.[13] While the bundle fibers of the ACL are oriented parallel in extension, they are rotated in flexion, due to their femoral and tibial attachments.[12] The AMB and PLB experience great load sharing and contribute to maintenance of knee stability.[14] The AMB and PLB work in conjunction in order to limit the amount of anterior translation in relation to the tibia.[14] The PLB, however, resists anterior translation best as the knee extends, whereas the AMB resists anterior translation best as the knee flexes.[15] Therefore, it is suggested that the AMB and PLB work together in a complementary manner in order to limit anterior translation of the knee joint.[15]

The anterior cruciate ligament also provides stability in order to limit medial rotation about the knee joint.[11] In terms of rotation stabilization, it has been suggested that the PLB contributes more to these efforts than the AMB.[16] This suggestion has been supported by the literature comparing single and double bundle ACLR.[17]

2.2 Anterior Cruciate Ligament Injury and Reconstruction

Approximately 200,000 anterior cruciate ligament (ACL) injuries occur in the United States each year.[1] Patients with ACL injury often experience knee instability, affecting daily life activities. This impact on daily life often requires surgical intervention, such as reconstruction of the anterior cruciate ligament.[18] ACLR is performed arthroscopically and can be completed using a graft technique, typically an autograft of one of the hamstring tendons or a patellar tendon graft.[19] The two main reconstruction techniques are referred to as either single bundle or double bundle repair. Single bundle repair of the ACL reconstructs only the anteromedial bundle. Double bundle repair, however, reconstructs both the anteromedial and posteromedial bundles.[19]

Following reconstructive surgery is typically a lengthy rehabilitation program, with patients rarely returning to pre-injury levels of strength and function.[1] Patients with a history of ACLR often have low levels of satisfaction with their surgical and reconstruction processes, attributable to an incomplete return to function.[20] There are a variety of possible ramifications to follow ACL reconstructive surgery, including somatosensory deficits and abnormal gait patterns. Clinically, both of these deficits increase the risk for further injury and damage to the knee joint. An altered gait pattern similarly increases the risk for falls and related injuries, especially as the individual ages.[8] In addition, an altered gait pattern puts an individual at risk for the development of early onset knee osteoarthritis (OA).[21] Thus, eliminating aberrant gait biomechanics following ACLR seems imperative to improving patient satisfaction and long-term function.

2.3 Impaired Sensation Following Joint Injury

2.3.1 The ACL as a Mechanoreceptor

Mechanoreceptors are specialized receptor cells that sense changes of mechanical forces, encapsulating afferent fibers. If stimulated, these afferent fibers generate action potentials down the length of the fiber, sending information to the central nervous system regarding joint mechanics.[22] As part of a neural network, mechanoreceptors are involved in the integration of somatosensory, vestibular, and visual inputs in the central nervous system.[23] Mechanoreceptors account for approximately 2.5% of the ACL, with the majority of these located in the femoral and tibial ends of the ligament.[24] A healthy ACL holds three types of mechanoreceptors and free nerve endings that contribute to the functional stability of the knee joint.[23] The three types of mechanoreceptors in the ACL include Ruffini-like receptors, Golgi-tendon organs and Pacini-like corpuscles.[25] Ruffini afferents are slowly adapting, low threshold fibers that are particularly sensitive to cutaneous stretching and track the movement and position of the joint. Golgi-tendon organs are high-threshold, slowly adapting receptors in the ACL that send information to the central nervous system regarding changes in tension at the joint. Pacinian corpuscles are low-threshold, rapidly adapting fibers that detect vibration and signal joint acceleration.[22,25]

It has been suggested that joint proprioception at the knee provides dynamic stability by achieving neuromuscular control via afferent signals from joint mechanoreceptors.[23] The ACL functions as a sensory organ, providing not only proprioceptive information, but also by initiating protective and stabilizing reflexes.[26] Injury to the ACL not only causes obvious mechanical instability, but also causes disruption to neuromuscular control of the knee due to loss of or damage to mechanoreceptors.[27] It has been suggested that the loss of proprioceptive feedback following an ACL injury contributes to the resultant knee instability that manifests itself in a high percentage of ACL deficient individuals.[26]

There is a suggestion of a sensory-motor arc that exists between the ACL and the surrounding knee musculature.[28] For example, mechanical loading and direct electrical stimulation of the ACL increases hamstring activation and decreases quadriceps activity. The reflex may be attributed to a feed-forward control mechanism during activity.[29] This dynamic “ACL-reflex” mechanism works in conjunction with the static stabilization of the collagenous ACL structure to fire the hamstrings and protect against increased anterior tibial translation, which may injure the ACL.[30]

The mechanoreceptors of the ACL typically provide afferent information to the central nervous system (CNS) regarding knee joint location, movement, etc.[23] If these mechanoreceptors are lost or damaged, the normal signal is lost. Following ACL rupture, arthrogenic muscle inhibition (AMI) is likely to occur, due to a lack of motor unit recruitment.[31] Without motor unit recruitment, voluntary muscle contraction is unable to occur.[31] Thus, AMI can lead to muscle atrophy, and muscle weakness.[31] Following ACL rupture, the quadriceps commonly experience AMI.[32] Even with reconstruction to the ACL, individuals may still experience 15% activation deficits in the injured limb 2 years after surgery.[32] Owing to the central nature of this impairment, Urbach et al.[32] reported activation deficits of 16% in the uninjured limb.[32]

With ACLR there are conflicting results regarding mechanoreceptor damage and regeneration. Shidahara et al.[23] determined that kinesthesia is adapted within twelve months following reconstruction.[23] The authors also suggest that sensory function and biomechanical stability are restored following anterior cruciate ligament reconstruction when comparing knee flexion angles of ACLR patients and healthy individuals.[23] Ochi et al.[33] reported that sensory regeneration is possible following ACLR, suggesting not only a return of mechanical function, but also somatosensory function to the knee.[33] Conversely, Bonfim et al.[34] examined the mechanoreceptors of the ACL and found that following reconstruction, patients showed sensory deficits, probably due to damage of the

ACL mechanoreceptors. It has been suggested that this damage may lead to reduced afferent information and therefore decreased postural control. Differences between maintenance of upright stance on the reconstructed knee, in comparison with the contralateral limb and those of the control group, was significant (*P*<0.05). This combination of functional and sensory deficits compromise motor and postural control in patients with a history of ACLR.[34] Further, Valeriani et al.[20] have suggested that although basic mechanical function of the knee may be restored to patients following ACLR, deficits in knee proprioception and somatosensory central conduction may be considered permanent.[20]

2.3.2 Sensorimotor Deficits Following ACL Injury

Following ACL injury and reconstruction, loss of proprioception is common.[35] Proprioception refers to the somatosensory afferent information that is conveyed regarding position and movement of the body.[36] Afferent information from skin receptors is vital for proprioception. If skin receptors are lost or damaged, impaired proprioception is a likely consequence.[20] Bonfim et al.[34] observed patients who had undergone ACLR and the sensory and motor behavior changes that resulted. Motor behavior changes were tested via passive knee motion, onset of hamstring muscle activation, and body sway in regard to maintenance of upright stance. Patients with a history of ACLR exhibited decreased postural control performance, decreased joint perception, and an increased threshold for detection of passive knee motion and a longer latency of hamstring muscles.[34] These sensory and motor deficits in the injured limb may be due to a lack of proprioceptive information from the ACL due to injury and reconstruction.

Kocak et al.[18] suggest that the lack of full recovery following ACLR is due to a combination of both sensory and motor behavior deficits. The authors examined the impact of a proprioceptive rehabilitation program in order to improve postural control outcomes. Proprioceptive rehabilitation, in combination with active and passive full range of motion exercises, was implemented under the supervision of a physiotherapist. Postural control was evaluated using the KAT 2000, a balance platform. When vision was disturbed there were statistically significant differences between the reconstructed and uninvolved limbs at the third and sixth months following surgery, suggesting proprioceptive deficits among patients with a history of reconstruction.[18]

Sensorimotor deficits, such as decreased postural control, have been observed in patients following ACLR. Unfortunately, there is insufficient evidence to suggest why these patients have impaired postural control. Perkins et al.[4] examined lower limb cutaneous detection threshold, comparing healthy individuals and those with a history of ACLR. Utilizing the Semmes-Weinstein Monofilaments (SWM), Perkins et al.[4] assessed patients at a 4-2-1 stepping algorithm to determine detection thresholds on the plantar surface at four locations, including the head of the first metatarsal and the base of the fifth metatarsal and the medial and lateral malleoli. The authors found statistically significant differences at the first metatarsal and the medial malleolus, P=0.018, suggesting that patients with a history of ACLR have decreased light touch sensation when compared to healthy individuals.[4] These somatosensory deficits may be associated with deficits in postural control or abnormal gait mechanics.[4] The results of Perkins et al.

[4] are in accordance with much of the current CAI literature, suggesting that following joint injury, there are existing sensorimotor deficits.[3,37,38]

As part of a follow-up study, Hoch et al.[9] examined patient-reported outcomes and postural control outcomes of individuals with and without a history of ACLR. The authors could not determine a significant difference in postural control between healthy and ACLR individuals. Post ACLR individuals (4 years post-reconstruction) demonstrated similar balance when compared to healthy individuals when utilizing the Star Excursions Balance Test (SEBT), the Balance Error Scoring System (BESS), and traditional static balance on a force platform. These individuals, however, demonstrated decreased self-reported function when utilizing the Disablement in the Physically Active Scale (DPA), The Fear-Avoidance Belief Questionnaire (FABQ), the Knee Osteoarthritis Outcomes Score (KOOS) subscales, and the Tampa Scale of Kinesiophobia (TSK-11) when compared to healthy individuals. Therefore, while these individuals may have demonstrated effective balance, perceived deficits may exist in this population when compared to healthy individuals.[9]

2.3.3 The Knee Joint Innervations at the Plantar Surface

The anterior cruciate ligament is innervated by not only a variety of mechanoreceptors, but also free nerve endings.[23] The ACL is largely innervated by the posterior articular nerve, which is a branch of the tibial nerve.[39] Not only does the tibial nerve innervate the ACL, but it innervates the knee flexors and ankle plantar flexors. The tibial nerve has three large terminal branches, including the medial and lateral plantar nerves and the calcaneal branch, which innervate the medial and lateral plantar and calcaneal areas of the foot.[40] It is logical that damage to one area of the tibial nerve would not have an isolated impact. Rather, due to the expansive reach of the tibial nerve in the lower limb, it seems that damage to one area would extend to all structures innervated by the nerve. Therefore, it is possible that damage to the ACL could lead to proprioceptive or neuromuscular control deficits in other lower limb muscles also innervated by the tibial nerve. This notion is supported by changes in nerve strain during movements of the foot and ankle. Nerve strain has been documented in the tibial and plantar nerves during movements of the foot and ankle.[41] The position of adjacent joints, such as the knee and hip, has a substantial impact on the amount of strain in the tibial and plantar nerves. For example, there is a suggestion that changes in knee flexion and extension can impact nerve strain. Strain in the tibial nerve is higher when the hip is in flexion, the knee is in extension, and the ankle is in dorsiflexion, suggesting that joint position impacts strain.[41] It is suggested that this biomechanical position pretensions the nervous system.[41] For example, in normal gait, when the hip is in flexion and the knee is in full extension at initial contact, it is suggested that strain in the tibial nerve is high. If strain of the tibial nerve can be altered, it is possible that somatosensory input in these individuals may be altered. With manipulation of somatosensory input, there may be change in gait biomechanics of the ACLR patient population.

There is a suggestion that the reflex reactions resulting from stimulation of cutaneous nerves of the plantar surface of the foot onto the motor neurons innervating the lower leg muscles occur in a systematic, regulated manner.[42] Therefore, if there is stimulation of the tibial nerve at the plantar surface of the foot, it is logical that there would be an effect along the length of the nerve, from the ankle plantar flexors, to the musculature surrounding the knee. According to Andersen et al.,[43] when considering stimulation of the plantar surface of the foot, knee flexion is the dominant reaction.[43] Perhaps, with stimulation of the tibial nerve at the plantar surface, the observed reduced knee flexion angle of those with a history of ACLR can be corrected for.

2.3.4 Somatosensory Interventions Following Joint Injury

A somatosensory intervention not previously associated with patients with a history of ACLR is plantar massage. LeClaire et al.[3] utilized both calf and plantar massage in order to determine whether postural control would improve in patients with a history of chronic ankle instability (CAI). Results indicated that plantar massage, through stimulation of cutaneous receptors, improved postural control. LeClaire et al.[3] utilized a single, five-minute plantar massage that targeted the entire plantar surface of the foot. The objective of this massage was to stimulate the plantar cutaneous receptors from the metatarsal heads to the posterior aspect of the calcaneus. Immediate improvement of postural control was observed following plantar massage when vision was undisturbed. These results suggest that the plantar massage stimulates sensory receptors, possibly improving their sensitivity and making them more receptive to sensorimotor signals. It is also possible that the plantar massage may have stimulated afferent pathways that were previously altered or unavailable due to injury. Further, plantar massage may cause a reweighting of available sensory information. Sensory reweighting is defined as the corresponding input of each sensory system that varies depending upon environmental factors and cues.[3] LeClaire et al.[3] explain that the individual would 'de-weight' the importance of afferent information from the lateral ligaments following the massage, while placing a greater emphasis on the information from the massage-targeted area. In this case, the individual would place a greater emphasis on afferent information coming from the plantar surface of the foot.[3] If this is true for those individuals with chronic ankle instability, it is possible that this type of intervention could influence sensory inputs on the plantar surface for those with a history of ACLR. This type of sensory reweighting could contribute to the feedback mechanism used by the body during postural control, including the visual, vestibular, and proprioceptive systems.[44] Improvement in sensory inputs suggests the possibility of improvement in motor outputs, including gait biomechanics.

A second somatosensory intervention not previously associated with patients with a history of ACLR is the utilization of textured insoles. The results of Watanabe et al.[45] suggest that textured surfaces may stimulate plantar cutaneous receptors, even in healthy individuals. In addition, these results suggest that with a greater area of stimulation, there is a greater improvement in postural control.[45] If there is a possibility to stimulate the plantar surface of the foot of individuals with a history of ACLR, there is a possibility to view changes in their abnormal gait patterns via sensory reweighting of afferent information. Corbin et al.[8] observed increased afferent information input from textured insoles in healthy individuals as well. Textured insoles, created from a plastic floor matting material, were used as a shoe orthotic and postural control was tested. Postural control improved during bilateral, eyes-closed stance, suggesting that there was an increase in cutaneous afferent receptor activity while subjects stood on textured insoles. Essentially, this increase in plantar cutaneous receptor activity suggests a possible reweighting of information, placing a larger emphasis on the plantar cutaneous receptor information due to stimulation. Corbin et al.[8] suggest that afferent information from plantar cutaneous receptors is important in maintaining postural control. Postural control is vital in maintaining balance and avoiding falls during gait and other activities.[8]

2.4 Lower Extremity Gait and Ramifications

There has been a suggestion of an altered gait pattern among those with ACL deficiency and subsequent reconstruction. The aberrant gait observed among individuals with a history of ACL deficiency and reconstruction is described as a "knee stiffening strategy," formerly referred to as "quadriceps avoidance" gait.[46,47] This biomechanical model allows individuals to "avoid" placing an eccentric load on the weakened quadriceps muscles.[47] Andriacchi[46] first identified this "quadriceps avoidance" gait in ACL deficient knees; he found that in ACL deficient knees, the extension moment at heel strike was significantly greater, $P < 0.05$.[46] This suggests that ACL deficient individuals exhibit reduced knee flexion angles and external knee flexion moments[46,48] to maintain a peak extension moment during midstance[46] and limit use of the quadriceps. This altered knee joint position, however, causes changes in tibiofemoral contact that may contribute to degenerative damage to articular cartilage of the knee.[49] In addition, the weakened quadriceps are no longer able to absorb load upon impact.[50] Therefore, other structures, such as the articular cartilage of the knee, are forced to compensate and absorb this load. Repeated shock absorption by articular cartilage can lead to damage and degeneration, and, eventually osteoarthritis.[50]

Following ACLR, alterations in lower extremity joint kinetics and kinematics have been observed during gait. Ferber et al.[51] found that patients with a history of ACLR produced a markedly greater knee extensor moment during early stance compared to healthy individuals and a significantly reduced knee flexor moment for the remainder of stance compared to both healthy individuals and ACL deficient values. Moreover, patients who underwent reconstruction also had an altered hip moment pattern during early stance when compared to healthy individuals and pre-surgery values. The authors suggest that this aberrant gait could be the result of a crouched position adapted by the individual in order to prevent falls and further damage.[51] Timoney et al.[48] also recorded abnormal gait patterns in those patients with a history of ACLR. Patients had a significantly lower external knee flexion moment at mid-stance when comparing the reconstructed and contralateral limbs. Moreover, the authors found that at the time of heel-strike, there was a slower loading rate in patients with a history of ACLR than healthy individuals. This difference suggests a tendency for patients to walk in a more cautious manner in order to avoid submitting the knee joint to sudden tension and pressure.[48] Tashman et al.[52] examined rotational knee motion during running after anterior cruciate ligament reconstruction and found abnormalities in the resultant gait. Results suggested that patients with a history of ACLR were more externally rotated at the knee, P=0.001; moreover, patients were more adducted at the knee joint, P=0.009. Tashman et al.[52] suggest that these changes in gait can considerably alter the location and magnitude of stresses applied to both the cartilage and menisci at the joint.[52] These results support the abundance of evidence in literature that abnormalities in gait mechanics are associated with the progression and development of osteoarthritis (OA) and other forms of joint degeneration.[52] Specifically, increases in both knee adduction and abduction following reconstruction have been closely associated with higher prevalence and faster progression of knee OA. For example, Tashman et al.[52] found increased adduction in the ACLR knee compared to the contralateral limb of patients, suggesting an increase in lateral compartment separation and a decrease in medial compartment separation. These structural changes suggest an alteration in the location, pattern, and magnitude of stresses applied to the knee joint.[52] Butler et al.[21] recorded observations of increased peak knee-abduction moment. The peak knee abduction moment was increased by 21% in patients with a history of ACLR when compared with healthy individuals, P=0.04. This increased peak knee-abduction moment may be a contributing factor to early onset knee osteoarthritis.[21] These abnormal gait patterns, if not addressed with clinical intervention, may have life-long implications for the individual, such as decreased physical activity levels and rapid onset of knee OA.

Improvement of gait mechanics in patients after ACLR may be a pivotal addition to current post-operative rehabilitation programs. Recognizing that ACLR leads to decreased plantar cutaneous sensation and that simple, cost-effective treatments such as plantar massage and textured insoles can stimulate afferent information to improve postural control in patients with a history of CAI and healthy individuals via sensory reweighting, it seems reasonable that similar interventions could be used with patients with a history of ACLR in order to improve gait mechanics.

CHAPTER 3: METHODS

3.1 Participants

Fourteen adults with a history of ACLR were recruited to participate in this study. Our sample size estimate was calculated to attain 80% statistical power with an alpha level of 0.05. Our sample size estimate was calculated via G*Power software (version 3.9.1.2), based upon a study involving the use of plantar massage as an intervention for postural control improvement[3] and an ACLR gait analysis study.[51] LeClaire et al.[3] suggest a sample size of 8 participants with the somatosensory intervention of plantar massage. Ferber et al.[51] suggest a sample size of 10 participants. After consideration of the two recommended sample sizes, and accounting for a 20% drop out rate, we estimated our necessary sample size to be 12 total participants. All participants were recruited from the general student population at the University of North Carolina at Charlotte. To be considered eligible, participants must have sustained a single, unilateral ACL injury, followed by reconstructive surgery a minimum of 1 year prior to enrollment. Participants were also required to be recreationally active, defined as completing 30 or more minutes of physical activity at least 3 days per week. Exclusion criteria for all participants included sustaining any type of acute knee injury or other lower extremity injury within the last six months. In addition, individuals were excluded if they had ever undergone lower extremity surgery other than ACLR. In addition, participants were excluded if they reported current knee pain. After eligibility was determined, participants read and signed the university institutional review board-approved informed consent prior to participation.

3.2 Procedures

Participants in this crossover study completed two testing sessions separated by 48 hours. Participants underwent a baseline gait and plantar cutaneous sensation analysis, followed by completion of an intervention, and repeated gait and plantar cutaneous sensation assessment. Intervention order (i.e., plantar massage vs. textured insole) was counterbalanced across participants via coin flip.

3.2.1 Patient-Reported Outcomes

Participants completed two patient-reported outcome questionnaires, including the 2000 International Knee Documentation Committee (IKDC) Subjective Knee Evaluation Form and the Tegner Activity Scale. The IKDC includes self-reported questions regarding knee symptoms, sports and daily activities, and knee function.[53-55] The IKDC is scored from 0-100, with 100 indicating no symptoms or disability with activity.[53] The Tegner Activity Scale quantifies patient activity levels prior to and following ACL injury.[56] The Tegner scale ranges from 0 (sick leave/disability) to 10 (national, elite level sports competition). Participants were also asked to report efficacy of improving gait and sensation of each intervention immediately following completion of all post-tests. Effectiveness was ranked 1 through 10; 1 was categorized as no change in gait biomechanics and sensation and 10 was categorized as a completely successful change in gait biomechanics and sensation.

3.2.2 Gait Analysis

Gait data were collected bilaterally. Each participant was prepared with retro-reflective markers in accordance with the work of Thomas et al.,[1] Figure 1. The markers were attached to anatomical landmarks in order to establish limb position. All participants walked in their own neutral athletic shoe (i.e., sneakers). A single investigator attached all markers and collected all gait data. Unpublished data from our laboratory using the same methods as in the present study suggest moderate to high reliability (intraclass correlation coefficient [ICC] 0.742-0.917) when data are collected by a single investigator.

Gait analysis was completed via three-dimensional motion capture. To capture lower extremity motion, ten cameras recorded at a frequency of 200 Hz via Vicon Vantage Motion Systems (Vicon MX T40S, Oxford Metrics Ltd., Oxford, UK) and associated Nexus (Version 2) software.

Two force platforms (Bertec Corporation, Columbus, Ohio, USA) were embedded in the center of a 5-meter walkway. Participants walked such that one foot landed on each force platform during subsequent foot strikes without normal gait being disrupted. Participants were instructed to utilize standard gait speed. In this study, standard gait speed was defined as average human walking speed, 1.4 m/s ±5%. The force platforms collected ground reaction force data for use in determining joint kinetics. Ground reaction force data were sampled at 1000 Hz and synchronized with the Vicon system for simultaneous collection of lower extremity motion in order to provide a complete gait analysis.

Both pre- and post-tests were completed for this study. Each participant completed a baseline gait analysis and a post-test gait analysis following each intervention. Each participant completed three successful trials per limb. In order to obtain what was considered a successful trial, the entire foot had to strike the center of the force platform without disrupting normal gait.

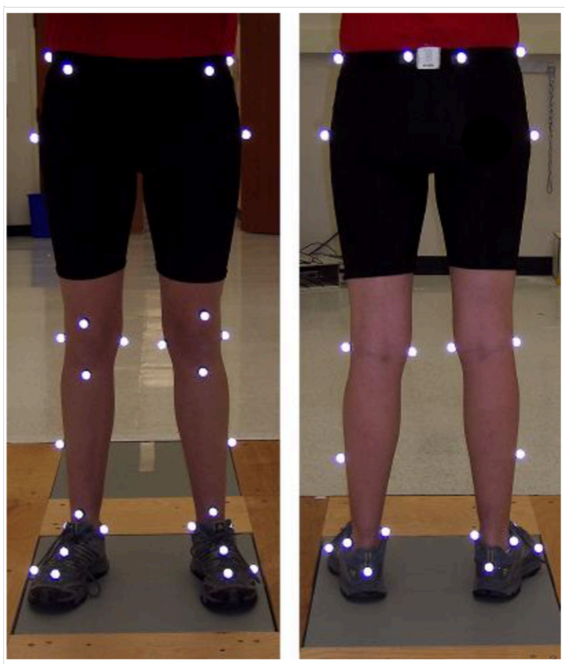

Figure 1. Depiction of the marker set used in the present study.[1]

3.2.3 Plantar Cutaneous Sensation Assessment

After the initial gait analysis was completed, we examined plantar cutaneous sensation utilizing the 20 piece Semmes-Weinstein Monofilaments (SWM). Light touch detection thresholds were assessed at the plantar aspect of the head of the first metatarsal, base of the fifth metatarsal, and the medial and lateral malleoli, in accordance with the procedures of Perkins et al.[4] Subjects were instructed to lie prone on a treatment table in a quiet laboratory setting. All testing locations were labeled prior to assessment. Utilizing the SWM, a nylon monofilament was applied perpendicular to the skin in order to create a 'C' shape. Participants stated 'yes' at the point in which a monofilament was detected. A validated 4-2-1 stepping algorithm was utilized in order to determine detection thresholds [4,6]. In accordance with the methods employed by Perkins et al.,[4] based on a positive or negative detection, the monofilament was either increased or decreased according to the algorithm until the detection threshold was identified. Testing sites were counterbalanced in order to avoid an order effect.[4]

3.3 Intervention

Participants completed a different intervention, plantar massage or textured insole, during each session. Intervention order, plantar massage or textured insole, was counterbalanced across participants via coin flip.

3.3.1 Plantar Massage

Plantar massage technique followed that of LeClaire et al.,[3] who utilized plantar massage to examine the effect of cutaneous stimulation for those with chronic ankle instability and postural control improvements. The plantar massage was a single, five-minute massage that targeted the entire plantar surface of the foot. The massage combined effleurage and petrissage techniques to stimulate the cutaneous receptors in the area.[3] Immediately following the plantar massage, gait and plantar cutaneous sensation were reassessed following identical methodology as prior to the intervention.

3.3.2 Textured Insole

For the textured insole treatment, insoles were created from a coated abrasive material (i.e., coarse grit sandpaper sheet). The sandpaper was cut into the shape of the individual participant's shoes, similar to an orthotic. The textured insoles were placed in the individual's athletic shoes.[8] Then, gait was reassessed in the same manner as described above while the individual wore the textured insoles.

3.4 Data Processing

In accordance with Thomas et al.,[1] the 3-D marker trajectories to be recorded during gait analysis were processed by Visual 3-D software (Version 3.9, C-motion, Inc., Rockville, MD, USA) based upon the three-dimensional coordinates of the retro-reflective markers.[1] Joint rotations were calculated utilizing a Cardan rotation sequence. Joint rotations were defined relative to the participant's neutral position.[1]

Simultaneously collected, 3-D ground reaction force data and kinematic data were filtered with a fourth order, zero-lag, low pass Butterworth with a 12Hz cutoff frequency. Biomechanical data were collected over the entire gait cycle and time normalized to 100% of stance for visualization purposes. Joint moment data were calculated as external joint moments and normalized to body mass and height (Nm/kg*m).[1] Knee and hip flexion angles and moments were extracted at the instance of peak vGRF.[1]

3.5 Statistical Analysis

Dependent variables for this study included knee joint sagittal and frontal plane rotations and moments during walking and plantar cutaneous sensation. Independent variables in this study were: limb (ACLR and contralateral), time (pre- and post-intervention), and condition (textured insoles and massage). Gait data were analyzed using limb X time X condition repeated measures ANOVAs. T-tests were utilized in order to make all *post hoc* comparisons. Plantar cutaneous sensation data, differences in Tegner score pre- to post-injury, and intervention effectiveness were analyzed via

Wilcoxon Signed Rank tests to compare differences between limbs, conditions, and time. Intervention effectiveness was determined via Mann Whitney U tests. Effect sizes were calculated using Cohen's d. Intrarater reliability of plantar cutaneous sensation assessment was determined using an ICC(2,1) for absolute agreement. Cutoff values were as follows: strong (ICC>0.8), moderate (ICC 0.5-0.8), and weak (ICC<0.5). Statistical analysis was performed using SPSS (v. 21, IBM SPSS, IBM Corp, Armonk, NY) and Microsoft Excel (v. 2011, Microsoft Corp., Redmond, WA). Alpha was set *a priori* at $P < 0.05$.

CHAPTER 4: RESULTS

Fourteen (n=4 female) individuals enrolled in our study. Participant demographic data are located in Table 1. Tegner score was lower following ACLR than prior to injury (*P*=0.007).

Table 1. Participant demographic data (mean ± standard deviation).

Age (yrs.)	BMI (kg/m^2)	IKDC	Time Since Injury (mos.)	Time Since Surgery (mos.)	Tegner (median [min, max])
20.43±1.70	26.08±4.83	85.80±12.23	45.36±28.50	43.71±27.32	7 [4,10]

IKDC: International Knee Documentation Committee

4.1 Gait Parameters

There was a significant limb x condition interaction for sagittal plane knee rotation (Table 2). *Post hoc* analyses revealed no differences between limbs or conditions (*P*>0.05). There was a significant main effect of limb for knee frontal plane rotation, suggesting that regardless of time or condition, the ACLR limb was more abducted during walking than the contralateral limb (*P*=0.028). The effect size for knee frontal plane rotation of the ACLR limb was -0.10 following massage and and -0.11 following textured insoles, suggesting minimal clinical significance. No significant interactions or main effects were observed for knee joint moments (Table 3).

Table 2. Knee joint rotations (degrees). Data are mean ± standard deviation.

	Massage						Orthotic					
	ACLR			Contralateral			ACLR			Contralateral		
	Pre	Post	ES	Pre	Post	ES	Pre	Post	ES	Pre	Post	ES
Knee extension/ flexion	-12.7±6.8	-13.6±5.6	0.15	-13.6±12.2	-14.6±11.6	0.08	-14.3±5.6	-15.2±5.5	0.17	-11.5±11.3	-13.9±10.8	0.21
Knee adduction/ abduction	-1.6±4.1*	-1.2±4.4	-0.10	0.9±3.6	0.4±3.5	0.13	-1.3±3.6	-0.9±3.7	-0.11	0.9±3.7	1.1±3.0	-0.07

The joint angle listed first is positive. ES= effect size
*Indicates significant main effect of limb (P=0.028)

Table 3. Knee joint moments (Nm/kg*m). Data are mean ± standard deviation.

	Massage						Orthotic					
	ACLR			Contralateral			ACLR			Contralateral		
	Pre	Post	ES	Pre	Post	ES	Pre	Post	ES	Pre	Post	ES
Knee extension/ flexion	-0.41±0.13	-0.42±0.14	-0.01	-0.37±0.24	-0.37±0.31	0.00	-0.41±0.25	-0.45±0.15	-0.18	-0.39±0.28	-0.42±0.24	-0.14
Knee adduction/ abduction	-0.26±.070	-0.26±0.10	0.07	-0.34±0.14	-0.31±0.26	-0.18	-0.28±0.09	-0.28±0.07	-0.04	-0.32±0.11	-0.30±0.13	-0.11

The joint moment listed first is positive. ES= effect size

4.2 Plantar Cutaneous Sensation

There were no statistically significant differences in plantar cutaneous sensation prior to the start of either intervention (Table 4). Comparing sensation between limbs prior to massage, the 5th metatarsal (*P*=0.016), medial malleolus (*P*=0.028), and lateral malleolus (*P*=0.046) demonstrated poorer sensation in the ACLR compared to the contralateral limb. Prior to receiving the textured insoles, participants demonstrated differences in sensation over the 5th metatarsal (*P*=0.031), with the ACLR limb having worse sensation. Massage improved sensation over the 1st metatarsal head (*P*=0.026), over the base of the 5th metatarsal (*P*=0.039), the medial malleolus (*P*=0.035), and the lateral malleolus (*P*=0.043) in the ACLR limb. No changes in sensation occurred as a result of massage in the contralateral limb. Following textured insoles application, sensation improved over the 1st metatarsal (*P*=0.027), 5th metatarsal (*P*=0.011), and medial malleolus (*P*=0.007) of the ACLR limb while no changes were observed in the contralateral limb. Participant reported effectiveness following each intervention was high but not significantly different between the massage and the textured insoles conditions (*P*=0.087, Table 5).

Table 2. Semmes Weinstein Monofilament detection threshold (median [min, max]).

	Massage				Orthotic			
	ACLR		Contralateral		ACLR		Contralateral	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post
1st metatarsal	3.73 [2.83, 4.74]	3.61† [2.83, 4.74]	3.61 [2.83, 4.31]	3.61 [2.83, 4.74]	3.96 [3.22, 4.74]	3.61† [2.83, 4.74]	3.61 [3.22, 4.74]	3.61 [2.83, 4.08]
5th metatarsal	4.08* [3.61, 4.31]	3.61† [3.61, 4.08]	3.61 [3.22, 4.08]	3.61 [3.22, 4.08]	4.08* [3.61, 4.17]	3.61† [3.61, 4.08]	3.73 [3.22, 4.31]	3.61 [3.22, 4.17]
Medial malleolus	4.08* [4.08, 5.07]	4.08† [3.61, 4.74]	4.08 [2.83, 4.74]	4.08 [2.83, 4.74]	4.17 [4.08, 4.93]	4.08† [3.22, 4.74]	4.08 [3.61, 4.74]	4.08 [3.61, 4.74]
Lateral malleolus	4.56* [3.61, 5.18]	4.20† [3.61, 4.74]	4.24 [3.61, 4.93]	4.08 [3.61, 4.93]	4.24 [3.61, 4.93]	4.20 [3.61, 4.93]	4.17 [3.61, 4.74]	4.13 [3.61, 4.74]

*Indicates significant difference between limbs (P<0.05)
†Indicates significant difference from pre-intervention (P<0.05)

Table 5. Participant-reported intervention effectiveness (median [min, max]).

Massage	Textured Insole
8 [6,9]	7 [4,9]

Reliability analysis revealed moderate to strong reliability for the majority of testing sites (Table 6). The exceptions to this were involved limb 5th metatarsal and uninvolved limb medial malleolus.

Table 3. Reliability of plantar cutaneous sensation assessment.

	ACLR		Contralateral	
	ICC	P-value	ICC	P-value
1st metatarsal	0.780	<0.001	0.546	0.013
5th metatarsal	0.267	0.167	0.671	0.027
Medial malleolus	0.788	<0.001	0.167	0.263
Lateral malleolus	0.724	0.001	0.611	0.010

CHAPTER 5: DISCUSSION

The purpose of this study was to determine which somatosensory intervention, plantar massage or textured insoles, was more effective at improving gait and plantar sensation in individuals with a history of ACLR. Contrary to our hypotheses, there were minimal changes in gait following both interventions.

5.1 Gait

Regardless of time or condition, the ACLR limb was more abducted during walking than the contralateral limb. Results of previous investigations examining frontal plane knee joint angle during a variety of tasks are conflicting. Tashman et al.,[52] for example, observed greater knee adduction angles during downhill running in the ACLR limb[52] while other researchers have found similar knee adduction in the ACLR compared to the contralateral limb.[57] When examining frontal plane angles in ACLR compared to healthy individuals, Georgoulis et al.[58] reported greater knee adduction after ACLR with no differences between ACLR and ACL deficient individuals. Our results are similar, however, to those of Hewett et al.,[59] who reported that individuals with a history of ACL injury had 8.4° greater knee abduction at initial contact during dynamic tasks than uninjured individuals.[59] The larger magnitude of differences in knee frontal plane angles between the study by Hewett et al.[59] and ours is likely due to differences in tasks. The previous study utilized jump landing while we examined biomechanics during over ground walking. It is important to note that the effect size for frontal plane rotation data in the present study was small, -0.10, suggesting that the magnitude of difference observed has limited clinical importance. More dynamic tasks should be incorporated into future investigations as these may allow for increased frontal plane movement and, thus, greater differences to be observed.

There was a significant limb x condition interaction for sagittal plane knee rotation. However, *post hoc* analyses demonstrated no differences in joint angles between limbs or conditions. In fact, the largest difference between limbs/conditions was approximately 2.5° between the pre- and post-textured insoles application. This corresponded to a small effect size of 0.21, suggesting minimal clinical significance. Likely, without improved plantar cutaneous sensation of both the involved and uninvolved limbs, there will be limited influence on gait biomechanics.

There may have been limited observations in changes in gait biomechanics due to pre- and post- data processing points. Joint rotations and moments were extracted at peak vertical ground reaction force (vGRF). At this point in the stance phase, it is suggested that there is a high prevalence of ACL injuries. At peak vGRF, roughly twenty percent of stance, an individual is in double limb support. While sensation was successfully manipulated at the ACLR limb, sensation was not changed on the contralateral limb. A lack of changes in sensation and gait in the contralateral limb may have precluded any possible changes to gait in the ACLR limb, particularly during periods of double support. Future investigations should consider examining gait while in single-limb support period of the ACLR limb.

Stimulation of peripheral sensory receptors at the plantar surface did not influence gait as expected. There is a loss of plantar cutaneous sensation following ACL injury and subsequent reconstruction.[4] However, there are additional losses that may outweigh the manipulated sensory input following a somatosensory intervention such as plantar massage or textured insoles. While we manipulated plantar cutaneous receptors, we did not manipulate visual or vestibular fields, which influence postural control and gait in individuals. Further, changes in brain activation have been reported following ACLR.[60,61] Grooms et al.[60] first documented changes in brain activation during knee movement in a case study of an individual with a history of ACLR. Specifically, the individual demonstrated decreased activation of the ipsilateral cerebellum and increased activation of the ipsilateral secondary somatosensory cortex and contralateral lingual gyrus, cerebellum, and premotor area during ACLR knee movement.[60] Increased activation of the lingual gyrus suggests a need to employ higher-level cortical processing to plan motion following injury due to its role in visual processing.[60,62] Increased activation of the premotor area additionally suggests the necessity to incorporate higher-level cortical processing to plan motion following injury. Increased activation of the secondary somatosensory area suggests processing and encoding of sensory information following injury.[60] Grooms et al.[61] suggest that individuals with a history of ACLR had a motor activation profile indicative of a shift toward a visual-motor strategy, as opposed to a sensory-motor strategy during knee flexion-extension motion representing the motion of walking. We likely did not see improvements in motor output in patients with a history of ACLR because our manipulation of sensory information was peripheral stimulation that was likely not sufficient to change activation of the secondary somatosensory area, among other cortical areas. Manipulating visual-spatial information may be more successful at improving gait biomechanics in this population.

5.2 Plantar Cutaneous Sensation

Prior to intervention, sensation between limbs was poorer at the 5th metatarsal, medial malleolus, and lateral malleolus in the ACLR compared to the contralateral limb. Perkins et al.[4,63] recently observed deficits in the ACLR limb compared to healthy, matched individuals at the head of the 1st metatarsal and the medial malleolus. The previous study did not compare data between limbs within the ACLR group. Collectively, our study and that of Perkins et al.[4] suggest changes in somatosensation with ACLR. The ACL is innervated by a branch of the tibial nerve.[39] The tibial nerve has three large terminal branches at the plantar surface including the medial and lateral plantar and calcaneal branches, which innervate the plantar surface of the foot in the medial, lateral, and calcaneal areas respectively.[40] The plantar surface of the head of the first metatarsal is largely innervated by the medial plantar nerve and the plantar surface of the base of the fifth metatarsal is largely innervated by the lateral plantar nerve.[40] The lateral malleolus is innervated by the sural nerve, another subsequent branch of the tibial nerve.[64] Given that these areas are innervated by branches of the same nerve as the ACL, it seems plausible that altered afference stemming from a torn ACL could disrupt afference throughout the tibial nerve's network. The area of medial malleolus, however, is innervated by the saphenous nerve, a branch of the femoral nerve. [65] It seems that altered sensation over the medial malleolus may be more likely to result from the surgical reconstruction process than the injury itself. In fact, peripheral nerve damage is associated with autograft type.[63,66,67] Individuals who have undergone hamstring autograft [66,67] and patellar-tendon autograft [68] reconstructions may have somatosensory deficits at the knee joint. These somatosensory deficits may have ramifications throughout the lower extremity due to tibial and saphenous nerve innervations.

Following each somatosensory intervention there was improvement in sensation. Due to the moderate to strong reliability of our measures obtained over most testing sites, we are confident these changes are due to the intervention itself. These changes are likely due to targeted stimulation of the saphenous and tibial nerves at the plantar surface. While we improved plantar cutaneous sensation of the involved limb, textured insoles and plantar massage had limited influence gait biomechanics. Similar techniques, such as textured surfaces and plantar massage, have improved postural control in healthy and other populations but gait was not assessed in these previous studies. [3,8] In order to observe improvements in joint biomechanics within this population, future studies should investigate the utility of visual-spatial interventions at improving gait as has been suggested in recent literature.[60,61]

There is also a suggestion that loss of mechanoreceptors at the ACL following rupture and reconstruction may lead to loss of somatosensory information in the lower extremity.[69] Loss of plantar cutaneous sensation may be due to impaired innervation of the ACL following injury and reconstructive surgery.[69] The ACL contains free nerve endings and mechanoreceptors, including Ruffini-like receptors, Golgi-tendon organs, and Pacinian-like corpuscles that collectively sense changes in tension, vibration, and movement. [24,25,27] Loss of mechanoreceptors and subsequent disruption of afferent transmission is common following ACL injury and reconstruction. [23,27,26,69] With functional and sensory impairments, the central nervous system receives compromised information from the knee following injury. Somatosensory information from the knee and afferent information from the contralateral lower extremity are integrated in the central nervous system to provide an individual with a sensorimotor profile.[69] Following ACL injury and reconstruction, however, there may be cortical remapping, and, therefore, sensorimotor deficits in both the ACLR and contralateral extremities.[60,61,69] This suggestion of neural plasticity following ACLR emphasizes increased activation of the lingual gyrus, premotor area, and the secondary somatosensory area. [60,61,69] Perhaps, activation of these brain areas following injury is indicative of the need to employ higher level cortical areas to process and plan motion, notably incorporation of visual-processing areas.[60,61] Future studies may benefit from incorporation of visual-spatial interventions in order to improve the aberrant gait patterns of this population.

5.3 Effectiveness and Patient-Reported Outcomes

The effectiveness scale was administered to quantify self-reported clinical effectiveness of each intervention. Participants rated both the massage and textured insole interventions as highly effective at improving both gait biomechanics and plantar cutaneous sensation. Despite the participant's confidence in the interventions, objective data do not support their use in improving gait following ACLR.

Overall, participants reported high levels of efficacy and low levels of disability following ACLR. IKDC scores were 85.80±12.23, indicative of reasonably high levels of functionality, and minimal limitations in day-to-day and sport activities, and, symptoms associated with ACLR. Tegner Activity Scale was reported to be 7 [4,10] following ACLR, suggesting an active group of participants. A reported activity level of 7, out of a possible 10, suggests an individual who participates in competitive sports and/ or recreational sports regularly. These elevated activity levels, combined with a lack of symptoms, could account for the lack of change observed in gait biomechanics. If individuals did not perceive that they had deficits in biomechanics of over-ground walking, this may have limited the effectiveness of the somatosensory interventions in order to improve gait.

5.4 Limitations

This study was not without limitations. First, time since surgery varied greatly among the participants, ranging from 10 months to 93 months since ACLR. While this limits standardization to a specific group of ACLR patients, it does improve generalizability to the whole ACLR patient population. Second, graft type was not available from all participants. Graft type may be associated with somatosensory deficits at the knee, which may influence where somatosensory differences at the ankle present.[66-68] Third, there was an unequal distribution of males (n=10) and females (n=4) in the present study. Previous research suggests that frontal plane knee joint angles differ between males and females, with females demonstrating greater knee abduction.[70,71] However, no differences between males in females for other gait variables, including sagittal plane knee angles or ground reaction force have been observed.[71,72] Thus, considering that both males and females injure their ACL, inclusion of both sexes helps improve the generalizability of our findings. Future studies may benefit from investigating sex-specific differences in sensory reweighting interventions to improve gait following ACLR. Finally, we did not assess how much force was applied during plantar cutaneous sensation assessment. SWM are applied by touching the skin and applying pressure until the monofilament bends into a “C” shape.[6] Each monofilament is calibrated to bend at a specific magnitude of force application. Pre-intervention sensation was not different across days for any of the testing sites. Additionally, with the exception of the uninvolved medial malleolus and involved 5th metatarsal, intrarater reliability (ICC[2,1]) was moderate to strong. Thus, we are confident similar magnitudes of force were applied and data were collected consistently across trials and testing sessions.

5.5 Conclusion

Plantar massage and textured insoles improved plantar cutaneous sensation in the involved limb following ACLR. Both somatosensory interventions, however, had minimal effects on gait biomechanics. Peripheral somatosensory manipulation does not appear to be sufficient to change gait biomechanics. Further investigation of other sensory interventions such as visual-spatial targeted interventions, should be implemented in order to improve gait biomechanics following ACLR.

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APPENDIX A: PATIENT REPORTED OUTCOMES

2000 IKDC SUBJECTIVE KNEE EVALUATION FORM

Your Full Name____

Today's Date: ______/______/______ (Day / Month / Year)   Date of Injury: ______/______/______ (Day / Month / Year)

SYMPTOMS*:
*Grade symptoms at the highest activity level at which you think you could function without significant symptoms, even if you are not actually performing activities at this level.

1. What is the highest level of activity that you can perform without significant knee pain?

❑Very strenuous activities like jumping or pivoting as in basketball or soccer
❑Strenuous activities like heavy physical work, skiing or tennis
❑Moderate activities like moderate physical work, running or jogging
❑Light activities like walking, housework or yard work
❑Unable to perform any of the above activities due to knee pain

2. During the past 4 weeks, or since your injury, how often have you had pain?

	0	1	2	3	4	5	6	7	8	9	10	
Never	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑	Constant

3. If you have pain, how severe is it?

	0	1	2	3	4	5	6	7	8	9	10	
No pain	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑	Worst pain imaginable

4. During the past 4 weeks, or since your injury, how stiff or swollen was your knee?

❑Not at all
❑Mildly
❑Moderately
❑Very
❑Extremely

5. What is the highest level of activity you can perform without significant swelling in your knee?

❑Very strenuous activities like jumping or pivoting as in basketball or soccer
❑Strenuous activities like heavy physical work, skiing or tennis
❑Moderate activities like moderate physical work, running or jogging
❑Light activities like walking, housework, or yard work
❑Unable to perform any of the above activities due to knee swelling

6. During the past 4 weeks, or since your injury, did your knee lock or catch?

❑Yes ❑No

7. What is the highest level of activity you can perform without significant giving way in your knee?

❑Very strenuous activities like jumping or pivoting as in basketball or soccer
❑Strenuous activities like heavy physical work, skiing or tennis
❑Moderate activities like moderate physical work, running or jogging
❑Light activities like walking, housework or yard work
❑Unable to perform any of the above activities due to giving way of the knee

Page 2 – 2000 IKDC SUBJECTIVE KNEE EVALUATION FORM

SPORTS ACTIVITIES:

8. What is the highest level of activity you can participate in on a regular basis?

❑Very strenuous activities like jumping or pivoting as in basketball or soccer
❑Strenuous activities like heavy physical work, skiing or tennis
❑Moderate activities like moderate physical work, running or jogging
❑Light activities like walking, housework or yard work
❑Unable to perform any of the above activities due to knee

9. How does your knee affect your ability to:

		Not difficult at all	Minimally difficult	Moderately Difficult	Extremely difficult	Unable to do
a.	Go up stairs	❑	❑	❑	❑	❑
b.	Go down stairs	❑	❑	❑	❑	❑
c.	Kneel on the front of your knee	❑	❑	❑	❑	❑
d.	Squat	❑	❑	❑	❑	❑
e.	Sit with your knee bent	❑	❑	❑	❑	❑
f.	Rise from a chair	❑	❑	❑	❑	❑
g.	Run straight ahead	❑	❑	❑	❑	❑
h.	Jump and land on your involved leg	❑	❑	❑	❑	❑
i.	Stop and start quickly	❑	❑	❑	❑	❑

FUNCTION:

10. How would you rate the function of your knee on a scale of 0 to 10 with 10 being normal, excellent function and 0 being the inability to perform any of your usual daily activities which may include sports?

FUNCTION PRIOR TO YOUR KNEE INJURY:

Cannot perform daily activities	0	1	2	3	4	5	6	7	8	9	10	No limitation in daily activities
	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑	

CURRENT FUNCTION OF YOUR KNEE:

Cannot perform daily activities	0	1	2	3	4	5	6	7	8	9	10	No limitation in daily activities
	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑	

TEGNER ACTIVITY LEVEL SCALE

Please indicate in the spaces below the HIGHEST level of activity that you participated in <u>BEFORE YOUR INJURY</u> and the highest level you are able to participate in <u>CURRENTLY</u>.

BEFORE INJURY: Level__________ CURRENT: Level___________

Level 10	**Competitive sports- soccer, football, rugby (national elite)**
Level 9	**Competitive sports- soccer, football, rugby (lower divisions), ice hockey, wrestling, gymnastics, basketball**
Level 8	**Competitive sports- racquetball or bandy, squash or badminton, track and field athletics (jumping, etc.), down-hill skiing**
Level 7	**Competitive sports- tennis, running, motorcars speedway, handball** **Recreational sports- soccer, football, rugby, bandy, ice hockey, basketball, squash, racquetball, running**
Level 6	**Recreational sports- tennis and badminton, handball, racquetball, down-hill skiing, jogging at least 5 times per week**
Level 5	**Work- heavy labor (construction, etc.)** **Competitive sports- cycling, cross-country skiing,** **Recreational sports- jogging on uneven ground at least twice weekly**
Level 4	**Work- moderately heavy labor (e.g. truck driving, etc.)**
Level 3	**Work- light labor (nursing, etc.)**
Level 2	**Work- light labor** **Walking on uneven ground possible, but impossible to back pack or hike**
Level 1	**Work- sedentary (secretarial, etc.)**
Level 0	**Sick leave or disability pension because of knee problems**

Y Tegner and J Lysolm. *Rating Systems in the Evaluation of Knee Ligament Injuries*. <u>Clinical Orthopedics and Related Research</u>. Vol. 198: 43-49, 1985.

Effectiveness Assessment

Directions: Rank the overall effectiveness of the intervention on improving both gait and plantar sensation on the scale below. A score of 1 indicates no change and 10 indicates successful change in both gait and sensation.

1 2 3 4 5 6 7 8 9 10

Plantar Massage
Date: ________

1 2 3 4 5 6 7 8 9 10

Textured Insole
Date: ________