Gait Analysis Post Anterior Cruciate Ligament Reconstruction Using Inertial Sensors: A Longitudinal Study

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Abstract

Altered gait patterns may persist for months or even years in patients after anterior cruciate ligament reconstruction (ACLR). The persistence of these deficits during walking or running activities is of serious concern, as they could potentially increase the risk of knee degenerative changes in the long term. Analyzing altered gait patterns in this population are commonly performed in a specialized laboratory using motion capture and force plate systems. Although those measurement systems are considered the gold standard to identify alterations in joint biomechanics, they are expensive, require extensive training, and large laboratory space. More research studies have been conducted in recent years to develop an inexpensive and practical assessment tool that can quantitively analyze patients' gait in clinical settings. In those previous studies, inertial sensors (i.e., accelerometers and gyroscopes) have been used to obtain information about lower trunk accelerations and shank angular velocity (SAV) during gait. For instance, past studies reported that patients with ACLR walked with altered trunk accelerations at 6 months post-surgery, when compared to healthy subjects. In addition, recent studies found that these patients presented with between-limb asymmetries in the sagittal plane SAV during walking at 3 months post-surgery, with lower peak SAV at the surgical limb compared to the non-surgical limb. However, it is unknown whether patients with ACLR would present with altered trunk accelerations and SAV asymmetry at faster gait speeds such as walking fast and running. In addition, the associations between these gait variables and patients' functional and psychological measures have not been investigated. Therefore, the overall goals of this dissertation project were to use inertial sensors to longitudinally quantify trunk accelerations and SAV asymmetry during gait at different speeds and to determine whether these variables are associated with functional and psychological measures in patients with ACLR.

In Chapter 2, the goal of the study was to compare changes in the acceleration patterns of the lower trunk during gait in ACLR patients over time and between ACLR patients and uninjured healthy subjects using accelerometry. Movement smoothness, calculated as normalized jerk (NJ) of trunk accelerations, during walking and walking fast was assessed at 2, 4, and 6 months after ACLR, whereas running smoothness was assessed at 4 and 6 months after ACLR. A total of 17 individuals with ACLR and 20 healthy uninjured controls participated in this study. Movement smoothness of participants was assessed during walking, walking fast, and running along a 12-meter straight walkway. A lower NJ value is indicative of a smoother gait pattern. The results showed that movement smoothness of the ACLR group during walking and walking fast improved (lower NJ) significantly across time, except for walking fast in the vertical direction. Running smoothness of the ACLR group did not improve from 4 to 6 months and was significantly less smooth than that of the healthy group. These findings suggest that the effect of the knee injury and the subsequent surgery may disrupt lower limb mechanics, which results in altered trunk accelerations during gait. Future studies with a longer follow-up period (> 6 months) should examine when running smoothness would normalize with that of healthy subjects.

In Chapter 3, the goal was to investigate whether patients with ACLR would show significant and meaningful between-limb SAV asymmetries at different gait speeds at 4 and 6 months post-surgery. A total of 15 patients with ACLR participated in the study. Peak SAV was assessed in the sagittal plane during loading response of walking, walking fast, and running. From 16 healthy subjects, the smallest meaningful between-limb difference for SAV was estimated for each gait speed. The results showed that the surgical limb had significantly smaller peak SAV during loading response of all gait speeds at 4 and 6 months post-ACLR, when compared to the non-surgical limb. In addition, between-limb differences in SAV was higher than the smallest meaningful difference at both testing times. These findings indicate that individuals after ACLR presented with significant and meaningful SAV asymmetries during walking, walking fast, and running, especially at the time when some patients may return to sports activity at 6 months after surgery. These asymmetries may be indicative of altered shank kinematics during gait.

Chapters 4 and 5 investigated the associations between gait measures and measures of patients' functional and psychological status at 6 months after ACLR. Functional evaluation was conducted by testing patients' performance on return-to-sport criteria, which include two self-reported questionnaires, isometric quadriceps strength, and 4 single-leg hop tests. Patient-reported fear of re-injury was assessed using the Tampa Scale for Kinesiophobia-11. The results showed that better walking smoothness was moderately correlated with better quadriceps strength and single-leg hop for distance test. In addition, better running smoothness was found to be moderately associated with a higher level of fear of movement/re-injury. No associations were found between movement smoothness during walking fast and running with any of the functional measures. On the other hand, greater between-limb asymmetries in SAV for all gait speeds were moderately to strongly correlated with greater between-limb asymmetries in the quadriceps strength and 4 hop tests. Moreover, running with greater SAV asymmetry was moderately correlated with a higher level of fear of movement/reinjury. Therefore, these findings, particularly the ones from SAV, may provide clinical information regarding functional and psychological status following ACLR. The results of these studies open future research opportunities to investigate the accuracy of gait smoothness and SAV when they are used to identify important biomechanical deficits such as knee flexion angles and knee extensor moments in patients with ACLR. Furthermore, whether patients who present with altered gait smoothness and/or SAV asymmetry are at risk of knee degenerative changes or ACL re-injury should also be investigated in future studies.

Acknowledgments

I dedicate this dissertation to my parents, my wife Eiman, and my son Wisam

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Chapter 1: Introduction

Statement of the problem

Anterior cruciate ligament (ACL) rupture is one of the common musculoskeletal injuries, in which up to 250,000 cases occur each year.[1, 2] Nearly half of the ACL injuries are sustained by individuals who are less than 30 years of age.[1] The most common mechanism of ACL injuries occurs during a non-contact event, such as landing, cutting, or sidestepping in a high-risk sport such as basketball or soccer.[3, 4] ACL rupture results in dynamic knee instability, which can lead to a significant disability that could impact individuals' activities of daily living and the ability to return to sports.[5] In addition, the annual health care costs after ACL injuries are estimated to exceed US$2 billion.[6] In the United States, it is estimated that more than 100,000 anterior cruciate ligament reconstruction (ACLR) surgeries are performed annually[7, 8], in an attempt to stabilize the knee joint and reduce the incidence of a second injury.[9] Although ACLR surgery is the standard practice for athletes who are willing to return to a high competitive physical activity, the outcomes are still not promising in terms of the ability to return to sport, risk of ACL re-injury, and knee degenerative changes.[10] In the next sections, the relatively low rates of returning to competitive sports, high rates of a second ACL injury, and the prevalence of knee osteoarthritis (OA) in individuals who undergo ACLR will be reviewed. In addition, their contributing factors such as quadriceps weakness[11-15] and abnormal movement patterns[16-24] as well as the feasibility of the traditional equipment to identify these factors during rehabilitation will be discussed. In the last section, the importance of using inertial sensors (i.e., accelerometers and gyroscopes) as a tool of an alternative and objective gait analysis tool to detect gait deficits and its feasibility in a clinical setting will be reviewed.

Rates of return to sports participation

In a recent systematic review and meta-analysis, Ardern et al[25] reviewed the rates of return to sport in 7556 ACLR patients at an average follow-up of 3.5 years after ACLR surgery. They reported that 81% of individuals returned to some sports activity, 65% returned to their preinjury level of participation, and 55% returned to competitive sport after surgery. Modifiable factors such as knee functional impairments and fear of re-injury are contributing factors to the low rate of return to sports participation, particularly competitive sport.[25] These finding are supported by other studies reporting that inability of ACLR patients to achieve 90% or more on the function-based measures (e.g. quadriceps strength symmetry and hop tests) are not considered to be ready to return to sport participation[26-28] and are at risk of having abnormal gait patterns that can increase the risk of a secondary ACL injury[16-22] and development of knee OA.[22, 29-31] These function-based measures are called return-to-sport criteria (RTSc) and will be discussed in details later in this chapter. Therefore, it is recommended that ACLR individuals with lower performance on RTSc may need longer supervised rehabilitation to pass the criteria.[28] In fact, the study by Ardern et al[25] found that patients who had a longer rehabilitation had a higher return-to-sport rate.

Rates of a secondary injury

The rate of incurring a second ACL injury is alarmingly high after return to sports participation. In a recent meta-analysis, it is estimated that nearly 1 in 4 ACLR subjects who return to high impact sports will sustain another ACL injury, with the highest risk of re-injury within one year after returning to sports participation.[32] The rates of a primary ACL injury are 0.6% and 0.8% in adolescents and high school basketball athletes, respectively. By comparing these rates of primary ACL injury to the 23% rate of a second ACL injury, ACLR athletes who return to competitive sports are up to 40 times at risk of suffering another ACL injury compared to uninjured individuals. This high risk of ACL re-injury can be attributed to several risk factors including age, sports type, persistent knee functional deficits and altered movement patterns after return to sport.[32] Studies have been done to investigate potentially modifiable factors that could reduce the rates of ACL re-injury. Laboute et al[33] found that ACLR patients who participated in less risky sports activities did not sustain a second ACL injury. However, activity modification may not be feasible since many patients are willing to return to their pre-injury levels of sports participation. On the other hand, it seems that focusing on decreasing knee functional asymmetries and abnormal movement patterns is a possible approach. Indeed, growing evidence indicates ACLR patients must achieve 90% or more symmetry between involved and uninvolved legs on knee strength and functional-based measures to be considered as ready to return to sports.[26-28] The key factor in preventing ACL injury and reinjury may depend on choosing the appropriate training programs. Neuromuscular training has been found to be an effective intervention in reducing the rate of primary[34, 35] and secondary[36, 37] ACL injury by improving strength and minimizing biomechanical faults in athletes.[38, 39]

Prevalence of knee OA after ACLR

One of the primary goals of ACLR is to increase knee joint stability and prevent damage to the knee joint cartilage.[40] However, there are growing concerns that the risk of developing premature knee OA is not reduced after ACLR. In a recent systematic review (number of included studies = 41), the prevalence of knee OA was reviewed involving a total of 4919 participants with an average age of 28.1 years at inclusion and 42.2 years at follow-up.[41] Of these participants, 4709 patients underwent ACLR, while the remaining participants (n = 210 or 4%) did not undergo a surgical reconstruction. The findings of this review showed that the prevalence of knee OA was between 0% and 13% for isolated ACL injuries and between 21% and 43% for combined ACL and meniscal injuries within 10 to 24 years. These results indicate an alarmingly high OA prevalence in this population when compared with 3.8% for the global age-standardized prevalence.[41] In addition, this review reported that the prevalence of symptomatic knee OA was 35% for the tibiofemoral joint and 15% for the patellofemoral joint.[41] Furthermore, knee OA prevalence remained high regardless of treatment options, as OA prevalence in patients with ACLR was ranging from 8% to 68% after 10 years post-surgery, which was compatible with 24% to 80% for those who did not undergo ACLR.[41] In patients with ACLR, OA prevalence is also high regardless of graft type (bone-patellar tendon-bone graft (2%-80%), hamstring graft (0%-73%), and synthetic graft (39%-100%)).[41] In contralateral knees, the prevalence of knee OA was ranging from 2%-38%.[41]

In this previous review, risk factors for both radiographic OA and symptomatic OA were reviewed too.[41] Risk factors for radiographic OA were older age at surgery, additional injury, loss of knee range of motion at follow-up, partial medial meniscectomy, articular cartilage injury, knee function deficits, and pain during activity. For patients with symptomatic OA, risk factors were poor self-reported knee function at two years post-ACLR and quadriceps muscle weakness between 2 and 15 years. Moreover, altered knee biomechanics during gait are considered a risk factor for knee OA in patients with ACLR.[23, 42, 43] In addition to those previous risk factors, a recent review reported that patients with non-anatomic ACLR (744/1696, 43.9%) had OA at an average follow-up of 15 years, when compared to those with anatomic ACLR (87/375, 23.2%).[44] This indicates that using anatomic ACLR may reduce the long-term risk of OA after ACLR possibly by restoring knee kinematics, when compared to non-anatomic ACLR.[44] On the other hand, the development of OA in contralateral knees is thought to be related to altered movement patterns after ACL injuries, as some patients may overuse/overload their intact knees.[41] This mechanism can result in premature OA in contralateral knees, when compared to uninjured healthy subjects.[41]

With the high risk of developing premature knee OA following ACL injury with or without surgical reconstruction, a recent study surveyed 233 patients to investigate their knowledge and beliefs about the risk of developing knee OA following ACL injury and reconstruction.[45] Most patients (n = 164 or 70%) believed that they were at a higher risk of OA compared to uninjured healthy individuals. When patients asked whether undergoing ACLR would reduce the risk of OA, two-thirds of these patients (n = 152) mistakenly believed the surgery would reduce the risk of OA, or they did not know. Further, only 62 out of 233 (27%) patients indicated that they had a discussion with their health care provider about the risk of knee OA. The authors of this review found that patients who were less informed about the risk of OA after ACL injury or surgery were men, older patients, patients with a high body mass index, and patients with a low physical activity level.[45] Interestingly, those previous factors were found as potential risk factors for knee OA after ACL injury or ACLR.[45] The authors of this study highlighted the importance of educating patients about the consequences of ACL injury (regardless of treatment options) as well as potential strategies to minimize the risk of OA.[45] It is suggested that health care providers should educate their patients about benefits of activity motivation, muscle strengthening, and maintaining healthy weight as potential strategies that may reduce the risk of OA.[45] In addition to those previous factors, altered knee biomechanics during gait should be assessed and addressed during rehabilitation to further reduce the risk of OA following ACLR.[46, 47] Unfortunately, current standard gait analysis systems are difficult to be implemented in clinical settings due to their high cost and large space requirement. As a result, those factors may limit clinicians' ability to objectively detect gait deficits following

ACLR. Therefore, future studies should investigate whether commercially available inertial sensors can be used as an inexpensive and practical objective gait assessment tool to identify ACLR patients with altered gait patterns.

Return to sport criteria

With the high rates of reinjury within one year after return to sports participation, there are legitimate concerns over the decision-making criteria that are used to release ACLR patients safely to fully return to functional activity. It is often that these patients are discharged to sports activity within 6 months after surgery. However, growing concerns have questioned discharging patients based on time alone[48] and encouraged the use of objective criteria to support decision-making.[28, 49, 50] The return to sport criteria (RTSc) have been promoted as markers to determine the readiness of ACLR patients to return to sports participation.[26-28] These criteria consist of a battery of tests, including 2 self-reported questionnaires, quadriceps strength, and 4 single-leg hop tests. Assessment of quadriceps strength and hop tests are used to detect limb-to-limb asymmetries, whereas the questionnaires are used to assess global knee function. ACLR patients who failed to pass RTSc demonstrated limb-to-limb asymmetrical gait patterns when compared to those who passed RTSc.[51, 52] In addition, ACLR patients who passed RTSc had a higher rate of return to the preinjury level of functional activity compared to those who failed.[53] More recently, patients who pass RTSc had 72% lower risk of any knee injury, 75% lower odds of any ACL injury, and 78% lower odds of ACL graft rupture, when compared with patients who failed to pass RTSc.[54] Therefore, RTSc have been suggested to be used to inform clinical decision-making.[50-52]

Quadriceps strength is considered a key variable in the RTSc. Quadriceps weakness of the injured leg, when compared to the uninjured leg, has been found to be associated with poor knee functional stability and asymmetric loading patterns.[11-15] The weakness of quadriceps strength has been found to be persistent in the short- and long-term follow-up after return to sports in patients with ACLR.[13, 49, 55, 56] Since quadriceps are the main active stabilizer of the knee joint during gait, their deficits have been found to altered knee kinematics and moments during gait.[15, 57] Therefore, quadriceps strength deficits of the injured leg are of clinical concerns because of its association with increased incidence of reinjury, poor functional performance, and early onset post-traumatic osteoarthritis after ACLR.[32, 55, 58-62] Several methods have been used to objectively quantify quadriceps strength. The quadriceps limb symmetry index (Q-LSI) is the common method that has been used to assess quadriceps strength after ACLR.[26-28] The Q-LSI is used to compare the strength of the injured leg relative to the uninjured leg. In the normal population, up to a 10% difference on the Q-LSI can be expected and greater than a 20% difference is considered abnormal.[63] However, the current evidence suggests that scoring 90% or more on the Q-LSI is considered a sign of good quadriceps strength and one of the important measures in RTSc after ACLR.[26-28, 64] In addition to having good quadriceps strength, ACLR patients must achieve 90% or more on the other tests in RTSc to be considered as ready and safe to return to sports participation.[20-22]

However, these criteria are not without limitations. For instance, some of RTSc tests may not be appropriate for some patients with residual impairments, fear of reinjury, or pain. In addition, these tests are time-consuming for both patients and clinicians. Furthermore, not every clinic is equipped with the electromechanical dynamometer, expensive testing equipment that is commonly used to measure quadriceps strength. Therefore, future studies should identify or develop a novel screening tool that can provide an objective assessment, accessible to clinicians, easily administered in a short time, and linked to the performance on RTSc.

Knee kinematics during gait

Abnormal gait patterns are frequently reported to persist for months or even years following ACLR.[16-24] A recent meta-analysis reviewed 34 studies and reported that the most consistent findings after ACLR are altered knee flexion angles and moments during walking.[23] Specifically, patients with ACLR in the early postoperative stage (<6 months) presented with greater knee flexion angles and, in turn, higher flexion moments during walking when compared to uninjured contralateral knees and healthy subjects. These alterations are linked to several factors including joint swelling, pain, and muscle weakness. After 6 months post-ACLR, however, it has been found that ACLR patients may walk with lower knee flexion angles and moments compared to contralateral knees and healthy subjects. These impairments have been linked to altered quadriceps muscle activation in individuals >6 months post-ACLR. Reduced knee flexion angles during gait are of clinical concern since they may initiate degenerative changes in the knee joint. In fact, early patellofemoral joint osteoarthritis has been identified 1 year after ACLR, which may be partially attributed to decreased knee flexion angles.[23] Therefore, identifying abnormal gait patterns during the early stage of rehabilitation is imperative to delay or even prevent the progression of degenerative changes associated with ACLR. However, it should be noted that the standard method to identify abnormal knee movement patterns during gait after ACLR required having a motion analysis laboratory, which requires expensive equipment and highly trained personnel. Therefore, more research studies are needed to develop an inexpensive gait assessment tool that can be used in clinical settings to identify patients with gait deficits following ACLR.

Psychological factors

In recent years, there is mounting evidence to suggest that psychological factors play a major role in the outcome following ACLR. Factors such as fear of movement/reinjury were found to be associated with a lower level of return to activity/sport, lower functional performance, and the risk of ACL re-injury. A study by Lentz et al[65] found that patients who reported a low level of fear of re-injury, assessed by the Tampa Scale for Kinesophobia-11, at 6 months post-ACLR were able to return to sport at 1 year postoperative, when compared to those who reported a high level of fear. In addition, those patients who reported a low level of fear and return to sport showed significantly greater quadriceps strength, when compared to those with a high level of fear and did not return to sport.[65] Those findings are supported by a recent study that found patients with a high level of fear were 4 times more likely to report a low level of activity, 7 times more likely to show asymmetry in the single-leg hop for distance test, and 6 times more likely to show asymmetry in quadriceps strength.[66] Furthermore, patients who reported a high level of fear at the time of return to sport (an average of 8 months post-ACLR) were 13 times at risk of suffering an ipsilateral second ACL within 2 years from the return to sports.[66]

In line with these findings, it is plausible that fear of movement/reinjury may contribute to altered gait patterns following ACL injury and surgery. To our knowledge, only one study thus far has investigated the association between altered gait patterns and psychological factors in patients with ACLR.[67] In this recent study, walking with less knee flexion angles at initial contact and at peak knee flexion were significantly correlated with lower psychological readiness to return to sport (as assessed by Anterior Cruciate Ligament-Return to Sport questionnaire) in patients at 6 months following ACLR.[67] However, the associations between fear of movement/reinjury and other gait deficits, such as altered shank kinematics and trunk acceleration during gait at different speeds, have not been investigated. These gait variables can be assessed via inertial sensors to potentially identify altered gait patterns.

Can inertial sensors be used to identify gait deficits?

As mentioned earlier, gait alterations after ACLR can lead to future complications. The lack of objective measurements to identify these alterations during rehabilitation is of clinical concern. In clinical practice, clinicians usually assess gait of patients subjectively via visual observation, which makes it difficult to identify and address gait deficits before discharging patients to pre-injury level of functional activity. Therefore, it is imperative to evaluate gait, using objective gait assessment tools, on a regular basis during rehabilitation after ACLR in order to help clinicians to monitor gait as well as to guide, enhance, and accelerate the rehabilitation program. However, there are several factors that prevent health care providers from using current gait analysis techniques. Primarily, even though the current standard gait analysis techniques (such as motion capture system) provide accurate kinematics and kinetics data, these techniques are expensive, provide complex and extensive database, time-consuming, and are difficult to implement in clinical settings. With the recent advancement of inertial sensors in recent years, accelerometers and gyroscopes have been used as an inexpensive and alternative gait assessment tool that can be easily administered and feasible to clinicians. Specifically, measures of trunk accelerations and shank angular velocity during gait via accelerometers and gyroscopes, respectively, may help in identifying patients with abnormal gait patterns.

Assessment of trunk accelerations during gait via an accelerometer

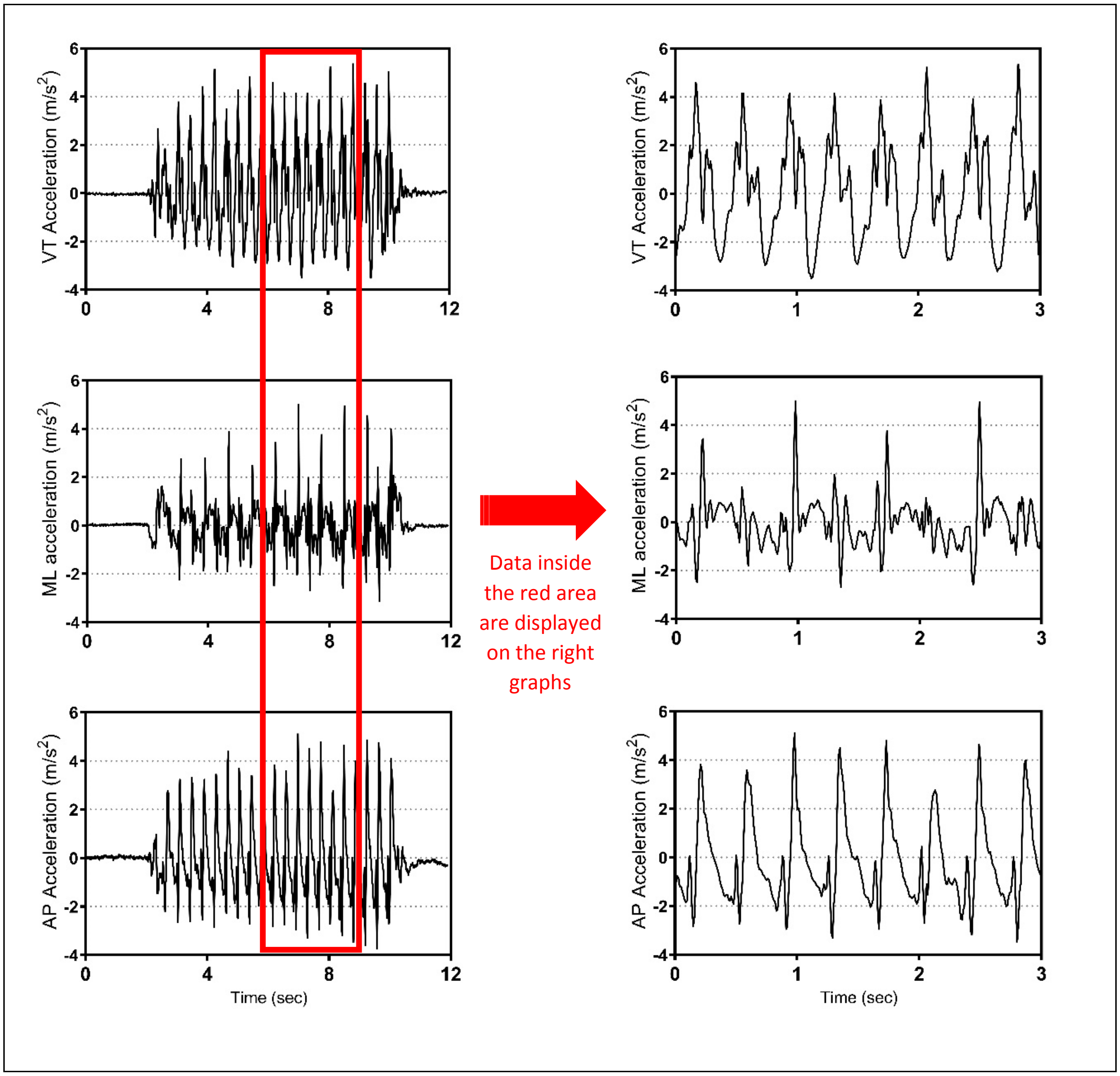

Figure 1. 1. Typical raw accelerations in the vertical, mediolateral, and anteroposterior directions of the lower trunk (at the level of L3 lumbar spine) of a healthy young subject during a self-selected walking speed. In the left graphs, the continuous line at the beginning and at the end of each direction represent the standing still. The signals between the continuous lines illustrate the trunk accelerations during a 12-meter walking. On the right graphs, the lower trunk accelerations in each direction for 4 strides are shown.

In the last decade, accelerometry has become a popular alternative gait assessment tool because of its applicability in clinical gait analysis. Compared to the standard gait analysis techniques, accelerometry has many advantages including its low cost, small size and lightweight, and wireless capabilities that would enable patients to walk freely without restrictions. One of the popular uses of accelerometry is to assess the overall gait patterns using information from the acceleration patterns of the lower trunk, which is an area that in proximity to the body's center of mass.[68, 69] In comparison to motion capture system, the use of a single wireless accelerometer attached to the lower back during gait has shown to a reliable and valid method to quantify the acceleration patterns of the lower trunk during gait.[70, 71] The use of accelerometry to quantify the acceleration patterns of the lower trunk during gait has been widely used in the last decade in healthy subjects and in patients with pathological gait. During normal walking, trunk accelerations in all three directions of motion (vertical, mediolateral, and anteroposterior) are characterized by rhythmic and repeatable patterns throughout the gait cycles[72] (Figure 1.1).

In healthy subjects, the acceleration patterns of the lower trunk in the vertical (VT) and anteroposterior (AP) directions are characterized by a repeatable, bi-phasic pattern over one stride.[73] In both directions, positive peaks represent heel-strike events, whereas the negative peaks represent loading phase. In contrast, lower trunk accelerations in the ML direction exhibit a mono-phasic pattern over one stride[73] (Figure 1.1). During the support phase on one limb, the lower trunk accelerates medially (positive peaks) toward the opposite limb.

In recent years, cumulative evidence indicates that altered trunk accelerations during gait are a sign of pathological gait. Specifically, patients with pathological gait were found to present with altered trunk accelerations when compared to healthy subjects. For instance, trunk acceleration patterns during walking were found to be different between older adult fallers and non-fallers and between older adults and young adults.[74-77] In addition, patients with diabetic peripheral neuropathy[78], Parkinson's disease[79], ataxia[80], multiple sclerosis[81], and stroke[82] exhibited abnormal trunk acceleration patterns during walking when compared to healthy subjects. In orthopedic populations, patients with different musculoskeletal disorders such as hip osteoarthritis and arthroplasty[83, 84], knee osteoarthritis[85], ankle fracture,[86] unilateral lower-limb amputation[87, 88], and ACLR[89] demonstrated altered trunk acceleration patterns during walking compared to healthy subjects. These studies support the use of trunk accelerometry as an alternative and inexpensive method to identify patients with gait deficits.

Gait analysis in subject with ACLR via accelerometry

During the early stance phase of gait, the knee joint plays a major role in absorbing shocks and reducing gait-related accelerations that resulted from the foot contact with the ground before they reach the upper body segments. Therefore, it is likely that injuries to the knee joint may compromise its ability to attenuate gait-related accelerations. This notion was investigated in patients after ACL injury and subsequent surgery. Tsivgoulis et al[89] assessed lower trunk accelerations in the mediolateral and anteroposterior directions during normal walking in patients prior to and after ACLR. In their study, 20 patients and 20 healthy participants were asked to walk at a self-selected speed along a 40-meter straight walkway. Irregularity of lower trunk acceleration signals was quantified using differential entropy. A higher differential entropy value is indicative of a higher irregularity in lower trunk acceleration signals. Before surgery, the results showed that patients had higher differential entropy values in the mediolateral and anteroposterior directions, when compared to the same patients at 6 months after ACLR. When compared to healthy subjects, patients at 6 months post-ACLR showed similar differential entropy values in the anteroposterior direction, but higher values in the mediolateral direction. The authors concluded that although stabilizing the knee joint after ACLR surgery was a factor that might have contributed to reducing irregularity of lower trunk accelerations during walking when compared to before surgery, such improvement was only observed in the anteroposterior direction when compared to healthy subjects.

Differential entropy used in the study by Tsivgoulis et al[89] requires complicated calculations and larger data sets, which may limit its feasibility in a clinical setting. Therefore, this dissertation evaluated lower trunk accelerations during gait using jerk-based analysis. Jerk analysis involves a simple and fast method that does not require a large data set and thus can be used in clinical settings. In addition, lower trunk accelerations in the present work were not only assessed during walking, but also during activities that produce high impact forces with the ground such as walking fast and running.

Normalized Jerk as a measure of trunk accelerations during gait

In this dissertation, normalized jerk of lower trunk accelerations during gait was used to evaluate movement smoothness. A movement that occurs without any interruption is perceived to be smooth.[90] Balasubramanian et al[31] defined movement smoothness as "a quality related to the continuity or non-intermittency of a movement, independent of its amplitude and duration." In this context, intermittency refers to the acceleration and deceleration of movements. Movements that consist of more intermittency can lead to unsmooth movement patterns. Smoothness is characteristic of a well-trained and coordinated movement. Studies that investigated the effect of aging, disease, or intervention on sensorimotor performance have often used jerk-based analysis (the time-derivative of acceleration) to quantify movement smoothness and coordination.[91] Minimal jerk trajectories are indicative of smooth movement.

Currently, the most important use of the analysis of movement smoothness is to quantify the ability of subjects to control specific tasks. Neurological and musculoskeletal impairments can lead to unsmooth movement while performing such tasks. For example, patients with neurological conditions such as stroke[92-94], multiple sclerosis[95], and Parkinson's disease[96] demonstrated jerky or unsmooth movement patterns while performing simple tasks such as point-to-point reaching and circle drawing. In stroke patients, movement smoothness of the upper limbs has been used as a marker of motor recovery.[92-94] While the majority of works have been done to assess movement smoothness and coordination of the upper extremity, fewer studies have investigated the overall movement smoothness of the lower extremity, particularly during gait, using jerk analysis. A recent study found that older adults showed a reduced gait smoothness compared to young adults during walking, indicating an age-related decrease in gait smoothness.[75] In that study, jerk analysis showed superior ability in differentiating gait patterns between older adults and young adults, with accuracy ranging from 78% to 89%. In addition, another study found that competitive runners had lower jerk values compared to recreational runners during walking fast and running[97], which may imply that competitive runners have smoother and economical movement patterns.

To our knowledge, it is unknown whether individuals who have undergone ACLR would exhibit altered movement smoothness during gait at different speeds, when compared to uninjured healthy subjects. In addition, whether gait smoothness would be associated with functional and psychological measures in patients with ACLR has not been investigated. The long-term goal of this project will be to provide rehabilitation specialists with a simple gait assessment tool that can identify ACLR patients with gait deficits during rehabilitation. Therefore, there is a need to investigate the following objectives 1) to quantify and compare changes in gait smoothness during rehabilitation in patients with ACLR across time and between ACLR patients and uninjured healthy subjects, and 2) to investigate whether gait smoothness would correlate with ACLR patients' performance on RTSc and self-reported fear of movement/re-injury.

Assessment of shank angular velocity during gait via gyroscopes

In addition to tri-axial accelerometers, tri-axial gyroscopes are included in the common commercial inertial sensors from well-known companies such as Xsens. Gyroscopes are used to provide information about the angular velocity of the body's segments.[98] In gait analysis studies, gyroscopes placed on the shanks have been used to detect gait events (i.e., heel strike and toes off) and gait pattern classifications (i.e., ascending and descending stairs).[98] In addition, gyroscopes were used to quantify between-limb asymmetry in the sagittal plane shank kinematics during walking in patients with ACLR.[99] Typically, the shank rotates anteriorly faster than the thigh during loading response of gait.[99] This movement pattern allows having knee flexion, which is controlled by eccentric quadriceps contraction, to accept body weight and absorb shock.[99] In patients at 3 months after ACLR, the surgical limbs had smaller peak shank angular velocity (SAV) during loading response of walking when compared to the non-surgical limbs.[99, 100] In addition, SAV was found to be moderately to strongly correlated with the knee flexion angle, knee extensor moment, and vertical and posterior ground reaction forces.[99, 100] These findings may establish an important relationship between asymmetry in SAV detected by inertial sensors and asymmetry in other important biomechanical variables measured by motion capture and force plate systems. Considering that gait is a repetitive task, walking or running with altered knee biomechanics may potentially increase the risk for knee degenerative changes, as highlighted early in this chapter. With the limited access to the standard gait analysis systems in clinical settings, research studies are needed to develop a gait assessment tool that can help clinicians to objectively identify gait deficits in patients with ACLR. Building upon the previous findings, there is a need to investigate whether inertial sensors can detect significant and meaningful asymmetry in SAV during loading response at faster gait speeds in patients with ACLR. In addition, the associations between SAV during gait and patients' functional and psychological measures need to be determined.

Specific aims and hypotheses

The specific aims and hypotheses of this dissertation are:

<u>Aim 1: To compare changes in the acceleration patterns of the lower trunk during gait in ACLR patients over time and between ACLR patients and uninjured healthy subjects using accelerometry.</u> Movement smoothness, calculated as normalized jerk (NJ) of trunk accelerations, during walking and walking fast was assessed at 2, 4, and 6 months after ACLR, whereas running smoothness was assessed at 4 and 6 months after ACLR.

- Hypothesis {H1.1}: We hypothesized that patients with ACLR would show lower gait smoothness (higher NJ) at the early stage of rehabilitation when compared to healthy subjects.
- Hypothesis {H1.2}: We hypothesized that patients with ACLR would show improvement in gait smoothness (lower NJ) across time, approaching gait smoothness of healthy subjects at the later stage of rehabilitation.

<u>Aim 2: To investigate whether patients with ACLR would show significant and meaningful between-limb asymmetries in the sagittal plane shank angular velocity (SAV) during gait.</u>

Between-limb asymmetry in the sagittal plane SAV during loading response of walking, walking fast, and running was assessed at 4 and 6 months after ACLR.

- Hypothesis {H2.1}: We hypothesized that patients with ACLR would present with significant and meaningful between-limb asymmetries in SAV during walking, walking fast, and running at 4 months post-surgery and these asymmetries would decrease over time.

<u>Aim 3: To determine whether gait measures (gait smoothness and SAV) are associated with return-to-sport criteria and patient-reported of fear of movement/reinjury in patients at 6 months post-ACLR</u>.

- Hypothesis {H3.1}: We hypothesized that higher gait smoothness (lower NJ) would correlate with better performance on return-to-sport criteria.
- Hypothesis {H3.2}: We hypothesized that higher gait smoothness (lower NJ) would correlate with a lower level of self-reported fear of re-injury, as measured by the Tampa Scale of Kinesiophobia.
- Hypothesis {H3.3}: We hypothesized that higher symmetry in SAV during gait would correlate with better performance on return-to-sport criteria.
- Hypothesis {H3.4}: We hypothesized that higher symmetry in SAV during gait would correlate with a lower level of self-reported fear of re-injury, as measured by the Tampa Scale of Kinesiophobia.

Chapter 2: Monitoring Gait Following Anterior Cruciate Ligament Reconstruction Using Accelerometry: A Prospective Longitudinal Study

Abstract

Background: Persistent gait deficits following anterior cruciate ligament reconstruction (ACLR) are associated with the development of knee osteoarthritis. Clinicians may have limited access to standard gait analysis systems due to high cost, complicated procedure, and large space requirements. Therefore, using an inexpensive, easily administered objective gait assessment tool may help clinicians to better monitor gait abnormality on a regular basis. Measurement of lower trunk accelerations during gait has been shown to provide useful information about gait, which helped to differentiate normal from abnormal gait patterns. In this study, we investigated the use of a single tri-axial accelerometer to measure gait smoothness during various gait speeds in individuals with ACLR.

Objective: To compare changes in gait smoothness at different speeds in ACLR patients over time and between ACLR patients and uninjured healthy subjects using accelerometry

Materials/Methods: This was a prospective longitudinal study. 17 individuals with ACLR and 20 healthy uninjured controls participated in this study. Evaluation of ACLR group took place in clinical settings at 2, 4, and 6 months post-surgery. Participants were instructed to walk and walk fast at 2, 4, and 6 months, and run at 4 and 6 months post-ACLR, at self-selected speeds along a 12-meter straight walkway. The control group was tested once in a laboratory setting. Trunk accelerations were recorded via a wireless tri-axial accelerometer attached to the subject's lumbar spine (L3-L4). Gait smoothness was quantified using jerk (i.e., the time derivative of acceleration) normalized by step distance and step duration. A lower normalized jerk (NJ) value is indicative of greater gait smoothness. For the ACLR group, one-way repeated measures ANOVA analyses were performed to find differences in NJ values across 3-time points (2, 4, and 6 months post-op) during walking and walking fast. Paired t-tests were used to find differences in NJ values across 2-time points (4 and 6 months post-op) during running. Independent t-tests were used to compare differences in NJ values between the ACLR group and the healthy control group at each time point.

Results: During walking and walking fast at 2 months, the ACLR group showed significantly higher NJ values in the vertical and mediolateral directions when compared to 6 months post-ACLR ($p<.05$) and in all directions when compared to the control group ($p<.01$). At 6 months, vertical NJ values of the ACLR group during walking fast was still significantly higher than the control group ($p<.01$). During running at 4 and 6 months, the ACLR group had significantly higher NJ in all directions compared to controls ($p<.05$).

Conclusions: Walking smoothness of the ACLR group improved across time, reaching walking smoothness of healthy controls at 6 months post-ACLR. Movement smoothness at faster gait speeds, mainly running, of the ACLR group did not reach movement smoothness of the control group at 6 months after surgery. Future studies with a longer follow-up period should examine when gait smoothness at faster gait speeds normalize to the level of healthy subjects.

Clinical Relevance: Gait smoothness measured by a single accelerometer attached to the lower back is an inexpensive and practical approach to detect and monitor altered gait patterns in individuals post ACLR in clinical settings during rehabilitation.

Introduction

Anterior cruciate ligament (ACL) rupture is one of the most common knee injuries.[101] Many patients undergo ACL reconstruction (ACLR) to stabilize the knee joint and return to sports.[102] However, cumulative evidence indicates that normal knee biomechanics during walking and running are not fully restored following ACLR. Specifically, two recent reviews found that sagittal plane knee kinematics and kinetics were altered in the surgical limb, when compared to contralateral and control limbs, during the stance phase of walking and running.[23, 43] Moderate to strong evidence indicates that these deficits in sagittal plane knee mechanics persist up to 3-5 years after ACLR during both walking and running. These findings are concerning as altered joint mechanics can lead to degenerative changes, which could potentially increase the risk of developing knee osteoarthritis up to 4 times in ACLR knees when compared to contralateral knees.[103] It seems reasonable to monitor gait over time after ACLR to better understand knee mechanics and assist the treatment decision-making process. However, most gait analysis studies have used expensive and sophisticated laboratory-based motion analysis systems that require extensive training and time. These factors make it difficult to use these gait analysis systems in clinical settings to objectively assess gait deficits in patients after ACLR. Therefore, there is a need to investigate if an objective gait assessment tool that is inexpensive, easily administered, and feasible to clinical settings can be used to monitor gait deviations following ACLR.

In the last decades, many studies have found that the acceleration patterns of the lower trunk during gait are altered in patients with different musculoskeletal conditions at the lower limbs when compared to healthy control subjects.[83-89] The accelerations of the trunk during gait are usually quantified using a single tri-axial accelerometer mounted on the lower back (at the level of lumbar spine), a region approximately close to the body's center of mass.[68, 69] Accelerometers are inexpensive, portable, clinically applicable, and offer a reliable[71] and valid[70] method to quantify trunk accelerations during gait. During normal walking speed in healthy subjects, trunk accelerations in all three movement directions (vertical, mediolateral, and anteroposterior) are characterized by rhythmic and repeatable patterns throughout the gait cycles.[72] In orthopedic populations, patients with different musculoskeletal disorders such as hip osteoarthritis[4] and arthroplasty[83, 84], knee osteoarthritis[85], ankle fracture[86], unilateral lower-limb amputation[87, 88], and ACLR[89] demonstrated altered trunk acceleration patterns during walking when compared to healthy subjects. In the latter study, trunk accelerations of patients with ACLR were found to be altered in the frontal plane (mediolateral accelerations) during walking at 6 months post-operation, when compared to a control group.[89] Together, these studies may provide evidence that disruption of lower limb mechanics, as a result of pathological conditions, reduces the ability to absorb shock during the early stance phase of gait, leading to altered lower trunk accelerations.[104] These findings support the use of trunk accelerometry measurement to identify patients with abnormal gait patterns. However, past studies are limited and examined trunk accelerations in patients after ACLR during walking only. Running is a more challenging task that produces higher impact forces during foot strike, which increases accelerations compared to walking.[104] It is unknown whether trunk accelerations would be altered during faster gait speeds such as running, an activity that is important to be monitored in patients who wish to return to sports following ACLR.[43] In addition, longitudinal monitoring of changes in the lower trunk accelerations during gait at various speeds from early to late stages following ACLR may provide further insight on when patients reach the acceleration patterns of healthy uninjured peers.

The objective of this longitudinal study was to compare changes in gait smoothness at different speeds, calculated as the normalized jerk (NJ) of trunk accelerations, within ACLR patients over a 6-month period and between ACLR patients and a healthy control group using accelerometry measurement. Smoothness of gait during walking, walking fast, and running was assessed at 2, 4, and 6 months after ACLR. A smoother pattern is indicative of a well-coordinated and skilled movement.[90] Walking and running are considered overlearned motor skills that are assumed to be executed with smooth patterns by adulthood.[97] One of the key motor functions during a normal gait cycle is to control lower limb movement to achieve a gentle heel or toe contact with the ground during walking and running.[97] Deviations to movement smoothness can occur as a result of lower limb injury.[97] Jerk-based analysis (i.e., the time-derivative of acceleration) is often used to quantify movement smoothness of upper and lower limbs, where a minimal jerk value is indicative of smoother movement.[90, 91, 97, 105-107] If patients after ACLR present with altered gait patterns, as indicated in previous studies, we hypothesized that those patients would show disrupted gait smoothness (e.g., higher NJ) at the early stage of rehabilitation (2-month), when compared to healthy controls. We also hypothesized that the ACLR group would gradually show improvement in gait smoothness (e.g., decreased NJ) over time to approach normal NJ values of healthy subjects at the later stage of rehabilitation (6-month).

Methods

Participants

A total of 17 patients with ACLR and 20 healthy uninjured subjects participated in the study. The inclusion criteria for ACLR patients were 1) age 18-45 years old, 2) had sustained a primary ACL injury and treated with surgical reconstruction, 3) had no history of ACL injury or reconstruction (except the current injury), and 4) participated in at least recreational activities before the ACL injury (a score of ≥5 on Tegner activity scale[108]), to ensure that physically active individuals would be included in the study. The inclusion criteria for healthy subjects were 1) age 18-45 years old, 2) physically active (a score of ≥5 on Tegner activity scale), and 3) had no history of lower extremity injury. Participants in both groups were excluded if they had cardiovascular or neurological conditions that would influence their performance on gait assessment. All study procedures were approved by a local institutional review board. The study's procedures were explained to all participants. Informed consent was obtained from all eligible participants before participating in this study.

Procedures

Gait assessment using accelerometry

A wireless tri-axial accelerometer (MTu Xsens sensor: 3.5cm-W x 5.8cm-L x 1.5 cm-H; weight = 27g; Xsens North America, Inc. Culver City, CA, USA) was used to record linear accelerations of the lower trunk in three directions: X = vertical (VT), Y = mediolateral (ML), and Z = anterior-posterior (AP). The acceleration signals were recorded by MT manager software (Xsens North America, Inc. Culver City, USA) in a sampling frequency of 75 Hz. All data were wirelessly transmitted and stored via MT manager software in a workstation laptop for further data processing.

Patients with ACLR can typically walk and walk fast at 2 months, whereas they can start running at 4 months post-surgery.[58] Therefore, lower trunk accelerations during walking and walking fast were assessed at 2, 4, and 6 months post-surgery and at 4 and 6 months for running in an outpatient clinic. Medical permission was obtained before performing any of these gait tasks. The control group was tested once in a laboratory setting. Prior to testing, the tri-axial accelerometer was attached to the subject's lower back (over L3 segment of the lumbar spine (Figure 2.1)), using an elastic Velcro strap provided by the manufacturer. The L3 segment was chosen because of its approximation to the location of the body's center of mass during upright standing and walking.[68, 69] All subjects were instructed to walk normally at a self-selected speed, walk fast at a steady pace but do not jog, and run at a steady pace but do not sprint. All subjects performed gait tasks while wearing their own tennis shoes. The distance covered was a straight 12-meter indoor walkway. Participants were instructed to perform one familiarization trial, followed by 2 actual trials for each gait speed.

Data processing

The raw lower trunk accelerations in the VT, ML, and AP directions were extracted using MT manager software and processed using a custom MATLAB program (R2019a, Mathworks, Natick, MA, USA). Acceleration signals were transformed into a true horizontal-vertical coordinate system, to correct for the accelerometer tilting due to the curvature of the lumbar spine of participants and for the gravity component.[69] Raw data was then low pass filtered using 4^{th} order Butterworth filter with a cut-off frequency set at 20Hz, 35Hz, 50Hz for walking, walking fast, and running, respectively. The cutoff frequencies for walking and running were used in other studies that analyzed accelerations at the level of the lower back.[109, 110] The following variable was calculated from the filtered data and used for data analyses:

- Normalized Jerk (NJ): jerk is the time derivative of acceleration and it measures the rate of change in acceleration over time.[91] Rapid changes in the body's acceleration or deceleration during steady movement increases jerk values, resulting in less smooth movement patterns.[90, 91, 107] NJ is a unit-free measure and has been used to quantify movement smoothness and coordination of upper extremity of different neurological populations.[91, 107] Measurement of jerk was found to be confounded by movement duration and amplitude.[91] Therefore, such confounders should be controlled for to obtain a dimensionless jerk measure.[91] In the case of gait analysis, jerk was normalized by step duration and step length.[105, 106] For each subject, jerk of the lower trunk accelerations was computed first, then normalized by step duration and step length using the following equation:

$$NJ_x = \sqrt{\left({}^{1}\!/_{2} \int dt\, j^2\,(x) \times {}^{duration^5}\!/_{length^2}\right)} \qquad (1)$$

Where x is the axis direction (VT, AP, or ML) and j is jerk. Smaller NJ values are indicative of smoother movement patterns.[91, 107] Step duration and step length were calculated using unbiased autocorrelation coefficient sequence from the vertical axis of trunk acceleration time series.[111]

Statistical analysis

Independent t-tests were used to compare group demographics. For the ACLR group, separate one-way repeated measures ANOVA models were performed to find differences in NJ values across time (2, 4, and 6 months post-ACLR) during walking and walking fast. Mauchly's sphericity test was used to test the assumption of sphericity in the ANOVA models. If sphericity was not met, the model was adjusted using the Greenhouse–Geisser correction (if $\epsilon < 0.75$) or the Huynh–Feldt correction (if $\epsilon > 0.75$). Post hoc tests using the Bonferroni correction were used to find where differences in NJ occur across time. For running, paired t-tests were used to find differences in NJ values between time (4 and 6 months post-ACLR).

Independent t-tests were used to compare differences in NJ values between the ACLR group and the healthy control group. Statistical analysis was performed using SPSS (Version 25.0. Armonk, NY: IBM Corp). The significant level was set at .05.

Results

Demographics are presented in Table 2.1. There were no significant differences between groups in age, height, weight, body mass index, and Tegner activity scale.

Within ACLR group comparisons over time

During walking, one-way repeated measures ANOVA showed that mean NJ values differed significantly between time points in the VT ($F_{(1.47, 23.51)} = 8.74$, $p = .003$), ML ($F_{(1.46, 23.36)} = 14.35$, $p < .001$), and AP ($F_{(2, 32)} = 11.29$, $p < .001$) directions for the global test. Post hoc tests revealed that mean NJ values in all directions decreased significantly from 2 to 4 months post-ACLR (Figure 2.2). In addition, NJ values in all directions were significantly decreased from 2 to 6 months post-ACLR. No significant differences in NJ values were observed between 4 and 6 months in all directions.

During walking fast, NJ values differed significantly between time points in the VT ($F_{(2, 32)} = 4.85$, $p = .01$) and ML ($F_{(2, 32)} = 7.72$, $p = .002$), but not in the AP ($F_{(2, 32)} = 1.62$, $p = .21$) directions. Post hoc tests showed that NJ values in the VT and ML directions decreased significantly from 2 to 6 months post-ACLR (Figure 2.3). No significant differences in NJ values were detected between 2 and 4 months, or, between 4 and 6 months.

During running, paired t-tests showed that NJ values in all directions did not significantly decrease from 4 to 6 months following ACLR (Figure 2.4).

Between-group (ACLR vs Control) comparisons over time

During walking and walking fast, independent tests showed that the ACLR group had significantly higher mean NJ values in all directions at 2 months post-surgery when compared to the control group ($p < .01$; Figures 2.2 and 2.3). At 4 months, ACLR groups had significantly higher NJ values in the VT and ML during walking and in all directions during walking fast when compared to the control group ($p < .05$; Figures 2.2 and 2.3). At 6 months, there was no significant difference between the ACLR and control groups during walking in all directions. During walking fast at 6 months, there was no significant difference between the ACLR and control groups in the ML and AP directions; however, the ACLR group still had significantly higher NJ values in the VT direction when compared to the control group ($p = .025$).

When patients started running at 4 months, NJ values for the ACLR group were significantly higher than those of the control group ($p < .01$; Figures 2.4), and the group difference in all directions remained at 6 months ($p < .05$).

Discussion

The purpose of this study was to compare changes in gait smoothness, calculated as NJ of trunk accelerations, at different gait speeds over time between patients with ACLR and uninjured healthy subjects. Our results showed that the ACLR group significantly improved their movement smoothness during normal walking (in all directions) and walking fast (in VT and ML directions) from 2 to 6 months post-surgery. At 6 months post-surgery, movement smoothness during these two gait speeds approached movement smoothness of healthy controls, except in the VT direction during walking fast. On the other hand, running smoothness in all directions did not improve from 4 to 6 months post-ACLR and was significantly less smooth at both testing time points when compared to the healthy control group.

Most biomechanical studies have focused on the effects of ACL injury and subsequent surgery on kinematics and kinetics of knee joint during walking and running.[23, 43] The knee joint motion and quadriceps strength play a major role in absorbing shock when the foot collides with the ground during gait.[15] After ACLR, several studies indicated that some patients with ACLR adopted knee stiffness strategies during gait that are characterized by reduced knee flexion angles, knee extensor moment, and vertical ground reaction force.[22, 51, 112] In addition, quadriceps muscle weakness has been reported to persist for months or even years following ACLR.[113] Therefore, these deficits in knee mechanics and quadriceps strength may reduce the ability of the surgical knee to attenuate shock during the early stance phase of gait, allowing gait-related oscillations to be manifested at the lower trunk. This premise was confirmed in the current study in which the ACLR group had lower movement smoothness (higher NJ) at the lower trunk during walking and walking fast at the early stage of rehabilitation when compared to the later stage of rehabilitation and the healthy control group (Figures 2.2 and 2.3). As the ACLR group progressed through rehabilitation, movement smoothness during walking and walking fast improved significantly over time, likely due to the improvement in the knee joint function.

In gait analysis studies using trunk accelerations, different variables were used to measure different constructs in the acceleration patterns during gait.[104] A previous study used a mathematical algorithm called differential entropy to quantify the periodicity or regularity of the acceleration signals during walking in patients with ACLR.[89] A higher differential value is indicative of greater irregularity in the acceleration signals. These patients showed greater irregularities (higher differential entropy values) in the ML and AP of lower trunk accelerations during walking before surgery, when compared to the same patients at 6 months after surgery. At 6 months post-ACLR, differential entropy values of these patients reached similar values of healthy controls in the AP direction, but not in the ML direction. The result of differential entropy in the VT direction was not reported in that study. In the current longitudinal study, a jerk-based analysis was used to quantify gait smoothness, independent of step duration and length, in the VT, ML, and AP directions. Gait patterns that are characterized by more intermittent movements (i.e., less smooth), due to lower limb injury, tend to produce abrupt changes in accelerations and decelerations within the acceleration signals.[90] Our results showed that NJ was able to detect abnormal gait patterns in patients after ACLR, when compared to healthy subjects. Although the gait variable (i.e., differential entropy) that was used in the previous study has shown to be an important variable in detecting gait deficits in patients post ACL injury and surgery[89], entropy calculations are complex and require larger data sets[114], which may limit its clinical feasibility. On the other hand, computation of NJ is simple and fast, and does not require a larger data set, and thus can be easily used in clinical settings.[105, 106]

Movement smoothness during running did not improve across time nor did it reach a similar movement smoothness of the control group by 6 months post-ACLR (Figures 2.4). The reasons for these findings could be that at faster gait speeds, the demand imposed on the quadriceps muscle as well as on the control of lower limb joints motion is increased[115, 116], which may compromise the trunk smoothness during running for those patients with quadriceps weakness and altered knee biomechanics. However, future studies should investigate such a probability.

The impact of foot strike while running leads to higher shock throughout the musculoskeletal system than walking.[104] Our results suggest that surgical knees of the ACLR group were likely not able to adequately absorb shock of the high impact of the foot contact with the ground during running. This allowed higher running-related accelerations to move up from the foot to the upper body segments, leading to a lower movement smoothness of the lower trunk (higher NJ values in the VT, ML, and AP directions). Therefore, with running being considered an activity that is commonly practiced by this young population with ACLR,[43] movement smoothness of the trunk should not only be assessed during walking, but during running as well. Future studies with a longer follow-up period (> 6 months post-ACLR) should determine when trunk movement smoothness at faster gait speeds, especially running, in patients after ACLR will normalize to the movement smoothness of healthy uninjured subjects. In addition, more comprehensive studies are needed to investigate whether rehabilitation strategies would improve walking fast and running smoothness in patients following ACLR.

Undoubtedly, this study has limitations. We showed that patients with ACLR walked fast and ran with less smoothness at 6 months post-surgery, when compared to healthy subjects. However, follow-up assessment beyond 6 months was not obtained because most patients were discharged to return to recreational or sports activities by their surgeons. Therefore, future studies with longer follow up periods are needed to determine when patients with ACLR would show smoother walking fast and running patterns that are similar to that of healthy subjects. Furthermore, it is possible that disruptions in gait smoothness may be related to commonly reported lower limbs deficits in individuals with ACLR such as quadriceps strength and altered knee biomechanics, as well as other intrinsic factors such as psychological factors.[23, 43, 113, 117] Although the association between gait smoothness and the aforementioned factors are out of the scope of this study, one must bear in mind the need to develop future studies to establish these potential associations and provide the causal factors for the altered gait smoothness in patients with ACLR.

Conclusion

The results of this longitudinal study showed that patients with ACLR had altered movement smoothness of the lower trunk at different gait speeds during early rehabilitation that was improved across time, mainly during walking and walking fast. Walking smoothness of the ACLR group was normalized with that of healthy subjects at 6 months following surgery. However, smoothness of walking fast (in the VT direction) and running (in all directions) of the ACLR group was significantly lower at 6 months post-ACLR, when compared to the control group. Altered lower trunk accelerations at different gait speeds could be attributed to the reduced ability of the surgical knee to attenuate gait-related accelerations at the lower limb, especially at the early stage of rehabilitation. Quantifying lower trunk accelerations, using a wireless tri-axial accelerometer, may offer an inexpensive, less time-consuming, and objective method to assess and monitor gait quantitatively during rehabilitation in individuals with ACLR. Future longitudinal studies should investigate when smoothness of walking fast and running would normalize with that of healthy individuals and potential biomechanical factors contributing to lack of smoothness in trunk accelerations.

Table 2. 1. Participants characteristics (Mean±SD)

	ACLR group (n=17)	Control group (n=20)	*p* Value
Age, y	27.94±6.66	27.20±4.88	.69
Gender, female/male, n	10/7	9/11	…
Height, cm	171.61±10.51	169.95±9.87	.62
Weight, kg	74.28±13.51	67.16±14.35	.13
BMI, kg/m^2	25.06±2.77	23.19±3.69	.09
Autograft type, n			…
Bone-patellar tendon-bone	3		
Hamstring	14		
Tegner activity score (0-10)	7.71±1.76	6.75±1.41	.08

Abbreviations: ACLR, anterior cruciate ligament reconstruction; BMI, body mass index.

Figure 2. 1. The location of a tri-axial accelerometer on the lower back.

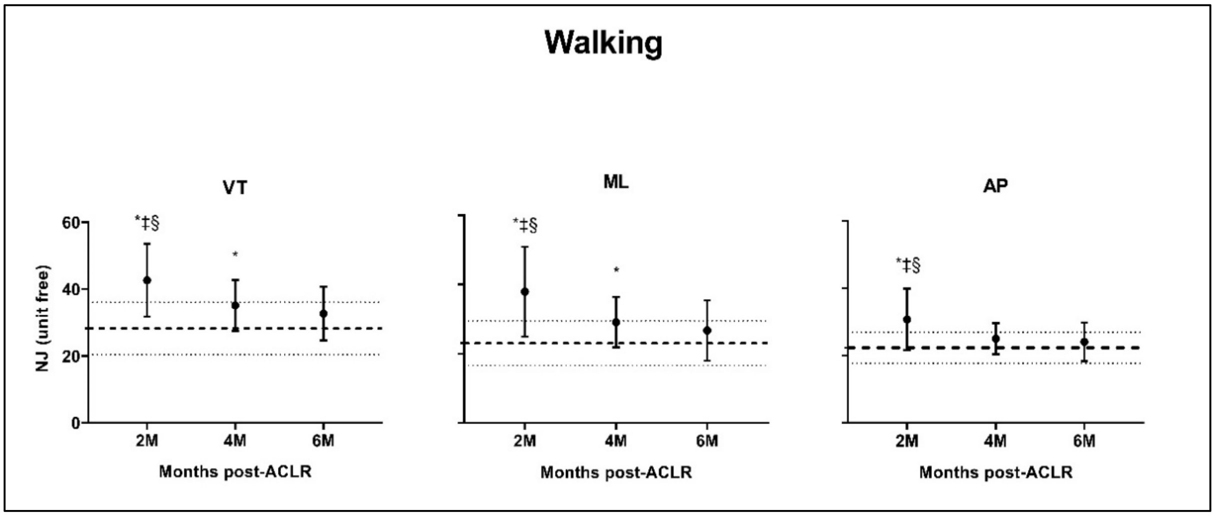

Figure 2. 2. Differences in mean normalized jerk values during walking within the ACLR group over time and between the ACLR group and control group. The dashed horizontal line represents mean normalized jerk for the control group, whereas the upper and lower dotted horizontal lines represent standard deviation. Compared to the control group, NJ values of the ACLR group were significantly higher in all directions at 2 months and in VT and MT directions at 4 months. NJ values improved over time and reaching near the values of the control subjects at 6 months in all directions, whereas the NJ values of the AP direction reached near values of the control subjects at 4 months. NJ, normalized jerk; VT, vertical; ML, mediolateral; AP, anteroposterior; 2M, 2 months; 4M, 4 months; 6M, months; ACLR, anterior cruciate ligament reconstruction.

*$p < 0.05$, compared with control.

‡$p < 0.05$, compared with 4M.

§$p < 0.05$, compared with 6M.

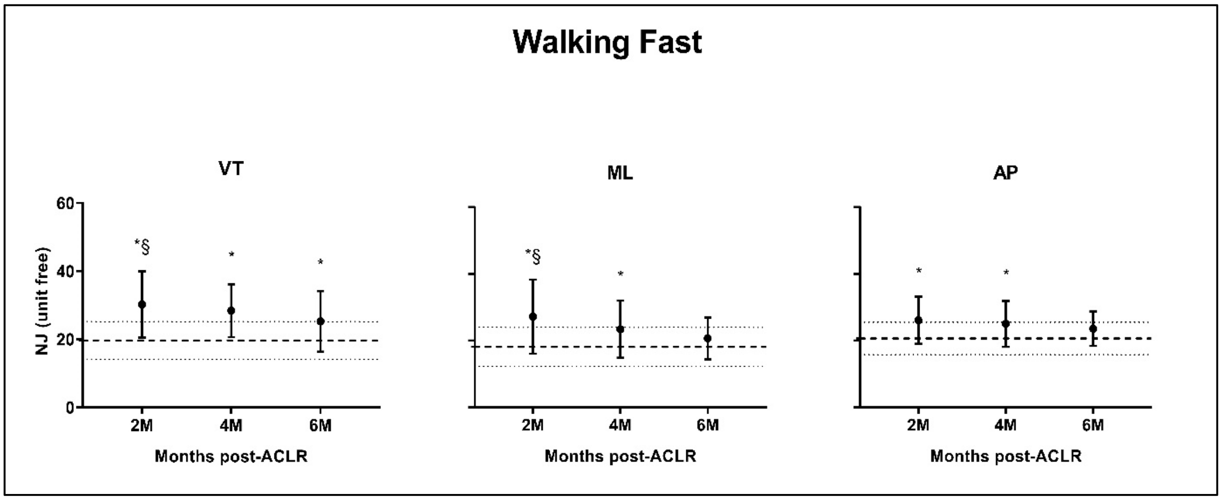

Figure 2. 3. Differences in mean normalized jerk values during walking fast within the ACLR group over time and between the ACLR group and control group. The dashed horizontal line represents mean normalized jerk for the control group, whereas the upper and lower dotted horizontal lines represent standard deviation. Compared to the control group, NJ values of the ACLR group were significantly higher in all directions at 2 and 4 months and reached near NJ values of the control group at 6 months in ML and AP directions. NJ values improved from 2 to 6 months in VT and ML directions in the ACLR group. NJ, normalized jerk; VT, vertical; ML, mediolateral; AP, anteroposterior; 2M, 2 months; 4M, 4 months; 6M, months; ACLR, anterior cruciate ligament reconstruction.

*$p < 0.05$, compared with control.

§$p < 0.05$, compared with 6M.

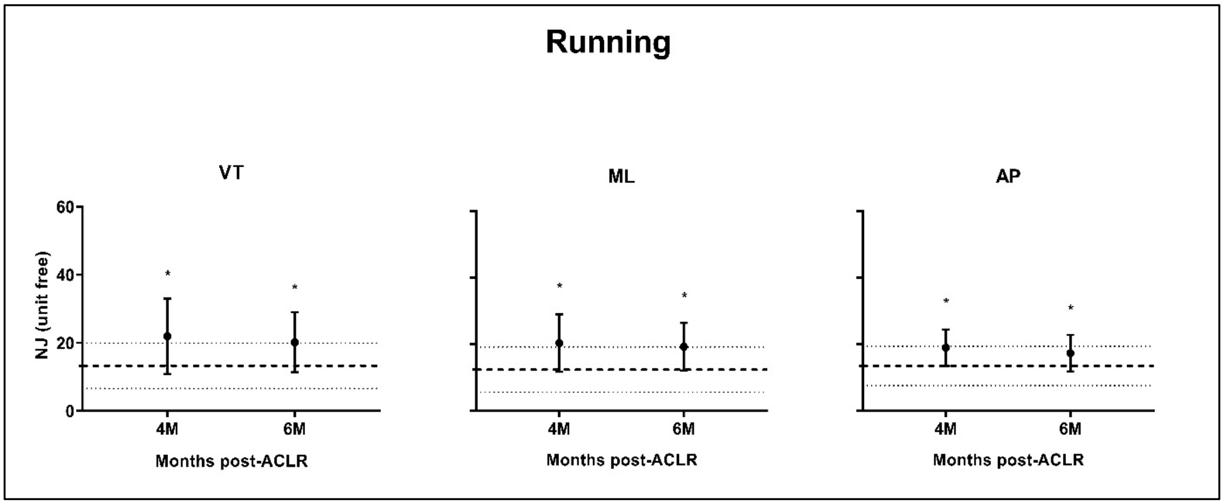

Figure 2. 4. Differences in mean normalized jerk values during running within the ACLR group over time and between the ACLR group and control group. The dashed horizontal line represents mean normalized jerk for the control group, whereas the upper and lower dotted horizontal lines represent standard deviation. The NJ values of the ACLR group were significantly higher than the control group at both 4 and 6 month periods and did not decrease from 4 to 6 months. NJ, normalized jerk; VT, vertical; ML, mediolateral; AP, anteroposterior; 2M, 2 months; 4M, 4 months; 6M, months; ACLR, anterior cruciate ligament reconstruction.

*$p < 0.05$, compared with control.

Chapter 3: Inertial sensors identified asymmetries in shank angular velocity at different gait speeds in individuals with anterior cruciate ligament reconstruction

Abstract

Background: Inertial sensors can detect between-limb asymmetries in shank angular velocity (SAV) during loading response of walking in individuals with ACL reconstruction (ACLR), which may be indicative of abnormal shank kinematics. However, it is unknown whether these SAV asymmetries would exist up to 6 months post-ACLR and at high demanding tasks such as walking fast and running.

Research question: To investigate whether patients with ACLR would show significant and meaningful between-limb SAV asymmetries at different gait speeds at 4 and 6 months post-surgery.

Methods: Fifteen individuals with primary unilateral ACLR participated in this prospective study. Testing took place in clinical settings during routine visits of patients to their surgeons. Participants were instructed to walk, walk fast, and run along a 12-meter walkway while wearing two wireless sensors attached bilaterally on the shanks. The average of sagittal plane SAV peaks during loading response of gait was calculated bilaterally. The smallest meaningful between-limb difference for SAV was calculated from uninjured healthy controls (n=16) to define the limit of meaningful SAV asymmetries in patients with ACLR. Paired t-tests were used to determine between-limb SAV differences at each time point and across time.

Results: At 4 and 6 months post-ACLR, the involved limb had significantly smaller peak SAV during walking ($p<.01$, effect sizes = 0.69-0.85), walking fast ($p<.005$, effect sizes = 1.03-1.07),

and running ($p<.005$, effect sizes = 0.78-1.03) compared to the uninvolved limb. Further, patients with ACLR exhibited meaningful SAV asymmetries at both time points for all gait speeds.

Significance: Individuals with ACLR presented with significant and meaningful SAV asymmetries during walking and running, especially at the time when many patients would return to activities. These asymmetries may be indicative of altered shank kinematics. Inertial sensors are inexpensive and practical tools that may help clinicians to identify patients with gait asymmetries during rehabilitation following ACLR. Future studies are needed to determine the clinical validity of SAV during gait.

Introduction

Approximately 400,000 anterior cruciate ligament (ACL) ruptures and subsequent 100,000 ACL reconstruction (ACLR) are reported annually in the United States[118, 119], with nearly half of ACL injuries are sustained by individuals who are less than 30 years of age.[1] During early rehabilitation after surgery (< 2 months), restoring normal walking patterns is an important milestone during this phase, as it can be used as a marker to progress toward more demanding exercises and activities including running.[58] However, recent systematic reviews and meta-analyses of gait studies indicate that gait deviation can persist for months or even years following ACLR, despite the absence of impaired gait patterns observed visually.[22-24, 42] These findings are particularly concerning in this young population as the development of knee osteoarthritis (OA) could start as soon as 6 months post-ACLR[120], reaching 60-74% within 7-15 years from the surgery.[121-123] Although the underlying mechanism for knee OA is still unknown, abnormal mechanical knee joint loading during gait is thought to be one of many reasons that lead to cartilage degenerative changes.[120, 124-127] Specifically, reductions in peak knee flexion angle, peak knee extensor moment, and vertical ground reaction force in the surgical knee during loading phase of walking have been consistently reported at 3 months to more than 3 years after ACLR.[23, 99, 100, 120, 127] What makes this issue more complex is that clinicians may have limited access to the standard gait analysis systems due to their higher cost, complicated procedures, and large space requirement. Therefore, future studies should develop an alternative objective gait assessment tool is a necessity to help clinicians to identify and address harmful gait patterns during rehabilitation in patients with ACLR.

In recent years, wireless wearable inertial sensors have become a popular gait assessment tool because of their applicability to clinical settings and low cost. These sensors were found to detect subtle gait deviations in several patient populations including individuals with ACLR. In recent studies, the gyroscope of inertial sensors was found to detect altered sagittal plane shank angular velocity (SAV) during walking following ACLR.[99, 128] During loading response of gait, peak SAV measures the rate of anterior shank rotation, which is an important part of heel rocker mechanics.[99, 129] Typically, heel rocker is characterized by rapid anterior shank rotation over the heel immediately after heel strike. This movement pattern advances the shank faster than the thigh, resulting in knee flexion, which is controlled by eccentric quadriceps contraction, and peak knee extensor moment.[99, 129] In patients with ACLR, the involved limb had reduced SAV during loading response when compared to the uninvolved limb at 3 months post-ACLR[99, 100] and healthy controls at 3.5 years after surgery.[128] In addition, SAV during loading response of walking was found to be correlated with peak knee flexion angle, peak knee extensor moment, and peak vertical and posterior ground reaction forces.[99, 100] Therefore, SAV may be an indicator of altered walking patterns.[99, 100] However, the aforementioned studies investigated between-limb SAV asymmetries during walking at a normal pace and at approximately 3 months following surgery. It is still unknown whether inertial sensors can detect SAV asymmetries during high demanding tasks such as walking fast or running in individuals with ACLR. In addition, it is unknown whether these between-limb asymmetries during walking, walking fast, and running would decrease across time, particularly at 6 months post-ACLR when many patients are discharged to return to sport/functional activities.

Therefore, the purposes of this prospective longitudinal study were: 1) to assess between-limb asymmetries in sagittal plane SAV during walking, walking fast, and running at 4 and 6 months after ACLR; and 2) to compare changes in between-limb differences across time for all gait tasks. To determine whether patients with ACLR would show meaningful SAV asymmetry, the smallest meaningful between-limb difference in SAV for each gait speed was estimated from healthy uninjured subjects. We hypothesize that patients with ACLR would present with significant and meaningful between-limb asymmetries during walking, walking fast, and running and these asymmetries would decrease over time.

Methods

Participants

A total of 15 patients with primary unilateral ACLR volunteered to participate in the study. The inclusion criteria were age between 18-45 years, a score of ≥5 for the pre-injury status on the Tegner activity level scale[130], cleared for unrestricted walking and running activities at the time of gait assessment, and had no history of significant lower limb injuries that could have influenced gait other than the current injury. We chose a pre-injury level of at least 5 on the Tegner activity scale to include patients who at least participated in recreational sports before the ACL injury.

Procedures

Gait assessment using gyroscopes

Testing took place during routine clinic visits of patients with their surgeons at 4 and 6 months following ACLR. All study procedures were explained to the participants and written informed consent was obtained prior to participation. All experimental procedures were approved by the University's Institutional Review Board. After consenting the participants, demographic data were collected including age, height, body mass index (BMI), knee medical history, and activity level prior to the injury.

Gait assessment was conducted along a 12-meter straight walkway at the clinic. While patients stood at the starting line, two wireless inertial sensors (MTu sensor, Xsens North America, Inc. Culver City, USA), sampling at 75 Hz, were attached bilaterally on the shanks, about 5 centimeters above the lateral malleoli, using Velcro straps (Figure 3.1). Each sensor contained tri-axial accelerometers, gyroscopes, and magnetometers. The X-axis of the sensors was aligned in the vertical direction while the Y-axis and Z-axis were pointing in the anterior-posterior and mediolateral directions, respectively (Figure 3.1). For the purpose of this study, the velocity of the shank rotation about the Z-axis of gyroscope was used to calculate SAV in the sagittal plane.

Participants were instructed to walk, walk fast, and run at their self-selected speed for each condition. Instructions for each gait task were specified as follows: 1) walk "at your preferred walking speed", 2) walk fast at "steady pace as if you are trying to go somewhere in a hurry but without jogging or running", and 3) run at "steady pace as if you are working out, but do not sprint". Patients were asked to perform some practical trials to become familiar with testing procedures followed by two actual trials for each gait task. During testing, the data was transmitted wirelessly from the sensors to a workstation via MT manager software (Xsens North America, Inc. Culver City, USA) and stored for further data processing.

Data processing

Raw SAV data was extracted from the sensors using MT manager software and processed using a custom MATLAB program (R2018b, The Mathworks, MA, USA). The gyroscope data was filtered using 2^{nd} order Butterworth low-pass filter with cut-off frequencies of 10Hz, 20Hz, and 30Hz for walking, walking fast, and running, respectively. These low cut-off frequencies were used to filter the noise while keeping the filtered signal close to the actual raw signal.[131] Peak SAV during loading response of gait was identified as the first negative peak after heel strike from the filtered data for the involved and the uninvolved limbs.[99] Figure 3.2 shows an example of filtered raw gyroscope signals for the involved and the uninvolved limbs of one patient at 6 months post ACLR. For both limbs, the average of negative peak SAV was calculated from all steps required to complete the 12-meter walkway, except the first and last two steps to remove data corresponding to acceleration and deceleration. The averages of the two trials for each gait task were used for the analysis.

Statistical analysis

An a priori sample-size analysis on the variable of interest (peak SAV) was performed based on an effect size from a previous study.[99] Using a paired t-test, an effect size of 0.8 determined that a total sample size of 15 patients with ACLR was required to detect differences with a power of 90% at an alpha level of 0.05. Power analysis was performed using G*Power 3.1 (Dusseldorf, Germany).

Paired t-tests were used to determine whether there were between-limb differences for peak SAV during loading response at 4 and 6 months post-ACLR. In addition, paired-tests were performed to investigate whether between-limb peak SAV differences (involved – uninvolved limbs) decreased across time for each gait task. Cohen's d effect sizes were calculated to determine the magnitude of the difference between involved and uninvolved limbs for SAV. Effect sizes were interpreted as small ($d = 0.2$), medium ($d = 0.5$), and large ($d = 0.8$). All analyses were performed using SPSS (Version 25.0. Armonk, NY: IBM Corp). The level of significance was set at 0.05.

From 16 uninjured healthy controls (age = 27.69±5.25 y/o; BMI = 23.91±3.42 kg/m^2; Tegner activity scale = 6.94±1.52), the typical between-limb SAV asymmetry was calculated and then used to define limits of meaningful between-limb SAV asymmetry in individuals with ACLR. First, the variability in measurements of the same individual (i.e., the variance within-subjects, which is referred to as error variance) was calculated separately for each gait speed as follows:

$$Standard\ error\ of\ measurement\ (SEM) = SD\ \times\ \sqrt{1-ICC} \tag{1}$$

Where SD is the pooled standard deviation from all observations. The ICC refers to the between-limb intraclass correlation coefficient (two-way mixed, average measure). The following calculation was then used to estimate the smallest meaningful between-limb SAV difference:

$$Estimated\ smallest\ meaningful\ interlimb\ difference = 1.96\ \times\ \sqrt{2} \times SEM \tag{2}$$

Where 1.96 derives from a 95% confidence interval, and √2 was used to account for the two measurements (two limbs) that were involved.[132] In patients with ACLR, a between-limb SAV difference was considered a meaningful asymmetry if the value was greater than the estimated smallest meaningful between-limb difference.

Results

Table 3.1 shows demographic data for patients with ACLR. Compared to the uninvolved limb at 4 months post-surgery, the involved limb had significantly smaller peak SAV during loading response for walking (t_{14} = 4.05; p = .001; d = 0.85), walking fast (t_{14} = 4.30; p = .001; d = 1.07), and running (t_{14} = 4.60; p < .001; d = 0.78) (Figure 3.3). At 6 months after ACLR, peak SAV was significantly smaller on the involved limb compared to the uninvolved limb during walking (t_{14} = 3.26; p = .006; d = 0.69), walking fast (t_{14} = 3.77; p = .002; d = 1.03), and running (t_{14} = 3.98; p = .001; d = 1.03) (Figure 3.4).

Between-limb peak SAV differences decreased across time from 4 to 6 months post-ACLR, but they were not statistically significantly different for the 3 gait tasks (Figure 3.5). In addition, between-limb differences for the peak SAV were meaningful at both 4 and 6 months during walking, walking fast, and running (Figure 3.5).

Discussion

The purpose of this study was to examine between-limb asymmetries in sagittal plane SAV during loading response of walking, walking fast, and running at 4 and 6 months following ACLR. Inertial sensors are inexpensive and practical tools that allowed our gait assessment to be conducted in a clinical setting during patients' regular visits with their surgeons. We confirmed our first hypothesis that our participants had significant and meaningful SAV asymmetries between the involved and uninvolved limbs during walking, walking fast, and running. However, contrary to our second hypothesis, between-limb asymmetries did not significantly decrease from 4 to 6 months post-surgery for all gait speeds.

Consistent with our results, previous studies found that the surgical side had smaller SAV during loading response of walking when compared to the non-surgical side at approximately 3 months post-ACLR.[99, 100] The results of the present study confirm that these asymmetries during walking persisted at months 4 and 6 as well. While the previous studies found 9-12% between-limb asymmetries in SAV during walking at 3 months, the current study found 10% asymmetries at 4 months that were decreased to 8% at 6 months after surgery. When patients were asked to walk fast and run, our results further demonstrated that between-limb asymmetries were evident as well during these faster gait speeds. From 4 to 6 months post-surgery, SAV asymmetries decreased from 12 to 10.7% for walking fast and from 11 to 10.8% for running. These findings may indicate that between-limb symmetries in SAV during gait had an improving trend over time; however, such improvement was not significant. It is likely the short period of time between the two testing sessions was not enough for patients to show significant improvement in SAV. A previous study found that gait asymmetry did not improve from pre-surgery to 6 months post-surgery.[133] In addition, another study showed that asymmetries in the sagittal plane knee loading during gait did not improve from the first to the fourth months after ACLR.[134] In patients with ACLR, findings of the current study along with the results of previous studies may provide evidence that asymmetries in SAV during loading response of gait can persist up to 6 months post-ACLR, the time when some patients likely return to sport/functional activities. Therefore, large sample longitudinal studies are needed to determine whether these gait deficits are diminished over a longer period (>6 months post-ACLR) and, most importantly, whether they represent a risk for the knee reinjury or degenerative changes.

One reason that could explain the decrease in SAV at the affected leg is that some patients adopt knee stiffness strategies, by limiting knee motion, as a protective mechanism to avoid knee joint instability after ACL injuries, and such strategies have been found to persist for months or even years after the surgical reconstruction.[22, 51, 112] These knee stiffness strategies are characterized by decreased knee flexion angle, knee extensor moment, and ground reaction force.[51, 112] Although the current study did not measure those biomechanical variables, previous studies found a relationship between those variables and SAV during normal walking in patients with ACLR.[99, 100] Another possible reason for developing gait asymmetry may be related to psychological factors including fear of movement/reinjury and low confidence. In a recent study, patients with lower psychological readiness to return to sport showed less knee flexion angle in the involved limb compared to the uninvolved limb at approximately 6 months post-ACLR.[67] Decreased muscle strength at the affected leg could also generate SAV asymmetries; however, there is conflicting evidence regarding whether achieving symmetrical quadriceps or hamstring strength would improve gait symmetry[22] and consequently SAV symmetry. Future studies should investigate whether SAV asymmetry during gait is associated with functional and psychological factors and whether improving these factors in early rehabilitation would improve SAV symmetry.

The results of this study showed that between-limb SAV asymmetries were not only statistically significant, but also exceeded the smallest SAV meaningful difference threshold throughout the study period for all gait tasks. In the current study, between-limb SAV asymmetry during walking, walking fast, and running tend to decrease over time from 4 to 6 months post-ACLR (Figure 3.5). At 4 months, the differences between SAV asymmetry and the smallest meaningful difference was 0.12, 0.27, and 0.31 rad/s during walking, walking fast, and running, respectively. These differences decreased across time to 0.07 rad/s during walking, 0.19 rad/s during walking fast, and 0.26 rad/s during running at 6 months after ACLR. Based on these findings, it seems that SAV meaningful asymmetry during walking was closer to be negligible than those of walking fast and running at 6 months. Consistent with the findings of the current study, previous studies found that meaningful between-limb asymmetries in knee kinematics and moments during gait can persist for months or even years following ACLR.[19, 51, 52, 135] At 6 months post-surgery, patients with poor functional performance showed meaningful between-limb asymmetries in knee kinematics during gait than those with higher functional performance.[51] In contrast, other studies using three-D motion analysis found that meaningful gait asymmetries were presented up to 2 years, despite achieving functional and quadriceps strength symmetries.[19, 135]

In the current study, gait assessment started 16 weeks (4 months) following surgery when patients appear to walk, walk fast, and run normally without observable gait deficits. However, our results showed that altered gait mechanics may persist as patients exhibited significant and meaningful SAV asymmetries at different gait speeds throughout the study period. The inability to visually observe impaired gait patterns during rehabilitation could be attributed to the ability of patients to restore symmetry in spatiotemporal gait parameters (e.g., step length or cadence).[99, 136] In addition, between-limb SAV asymmetries during the initial stance phase coincide with small between-limb asymmetries in knee flexion angle (~4º)[100], which makes it difficult to detect differences in knee kinematics subjectively via visual observation in clinical settings. This highlights the importance of developing a clinical objective gait assessment tool that can help clinicians to identify and address gait asymmetry in early rehabilitations while patients are attending training sessions regularly. The current study along with the other recent few studies may provide a first step toward achieving that goal. However, future studies with a large sample size should investigate the diagnostic accuracy of using SAV asymmetry during gait to identify important biomechanical deficits that are commonly reported in patients after ACLR. In addition, the underlying mechanism/s for SAV asymmetry should be investigated.

Undoubtedly, there are limitations to this study. First, although the current study found that patients walked fast and ran with significant and meaningful asymmetry in SAV, the association between this variable during walking fast and running with the common biomechanical deficits reported in this population is still unknown. Second, the smallest meaningful between-limb difference for SAV was presented in our study to provide information about what considered an abnormal asymmetry, which does not mean that these observed asymmetries are necessarily clinically meaningful. Therefore, future studies should investigate whether these SAV asymmetries during gait are clinically meaningful by determining whether they are related to clinical outcomes such as knee degenerative changes or a 2nd ACL injury.

Conclusion

The findings of this study showed that patients with ACLR had significant and meaningful between-limb asymmetries for SAV at 4 and 6 months following surgery. Patients with ACLR demonstrated higher meaningful SAV asymmetries during walking fast and running than walking. These asymmetries in SAV may be indicative of altered sagittal plane shank kinematics during loading response of gait. Clinically, assessing gait deviations via visual observation is subjective and may not identify individuals with altered gait patterns following ACLR. Therefore, inertial sensors may offer an inexpensive and objective gait assessment tool that could help clinicians to monitor gait normalization on a regular basis during rehabilitation in patients with ACLR. Future longitudinal studies should investigate whether SAV asymmetry during gait decreases over a longer follow-up period (more than 6 months post-ACLR). To improve the clinical validity of the current study's findings, future investigations with a large sample size are needed to determine the diagnostic accuracy of SAV in identifying patients with biomechanical deficits such as knee flexion angles and knee extensor moment.

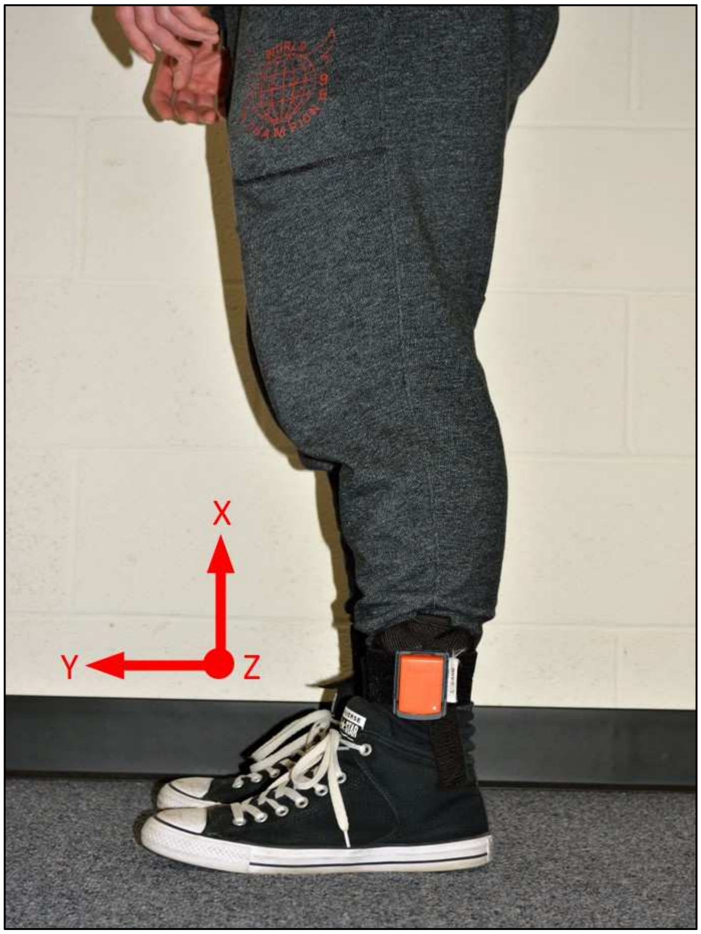

Figure 3. 1. Locations of the inertial sensors. Sensor axes are shown in the red arrows.

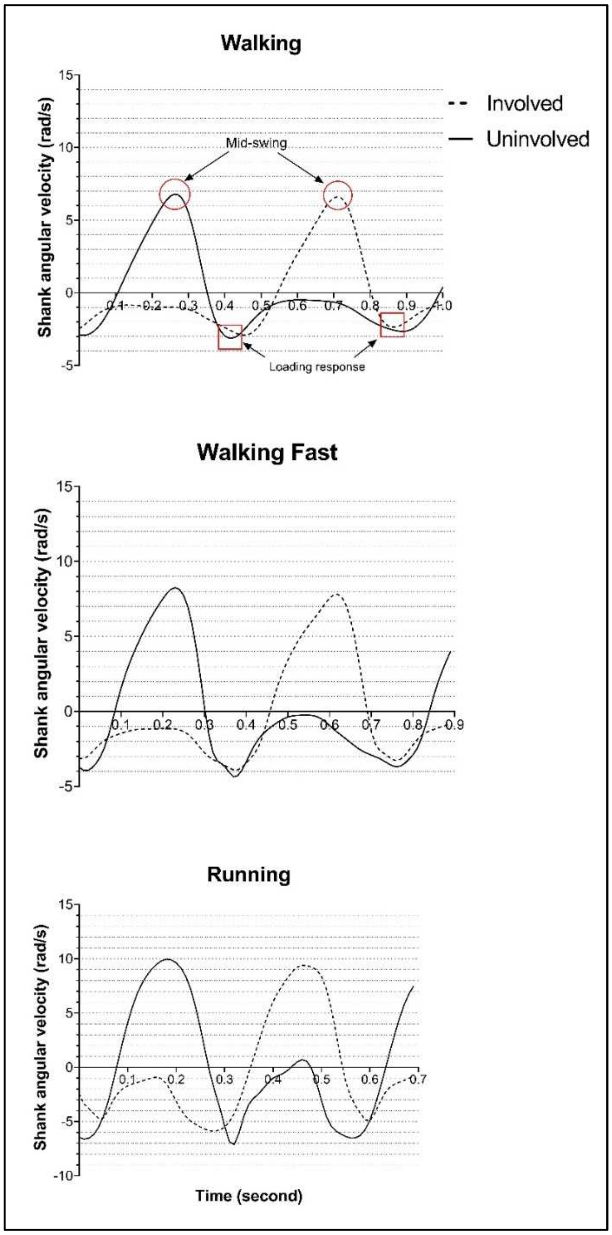

Figure 3. 2. Filtered raw signals for the sagittal plane shank angular velocity for one gait cycle during walking, walking fast, and running of one patient with ACLR at 6 months post-surgery. For each gait speed, positive peaks (circle) represent the mid-swing phase for the involved (dash line) and uninvolved (solid line) limbs, whereas the first negative peaks after mid-swing (square) represent the loading response phase (negative peak shank angular velocity). Rad/s, radian per second.

Table 3. 1. Demographic data (mean ± SD).

	Patients with ACLR (N=15)
Age (Years)	27.87±7.42
Gender, Females/Males, (n)	8/7
Height (cm)	172.60±10.97
Weight (Kg)	76.19±15.61
BMI (Kg/m^2)	25.37±3.37
Autograft type (n)	
Bone-patellar tendon-bone	2
Hamstring	13
Pre-injury Tegner Score (0-10)	7.40±1.50

Abbreviations: ACLR, anterior cruciate ligament reconstruction; BMI, body mass index.

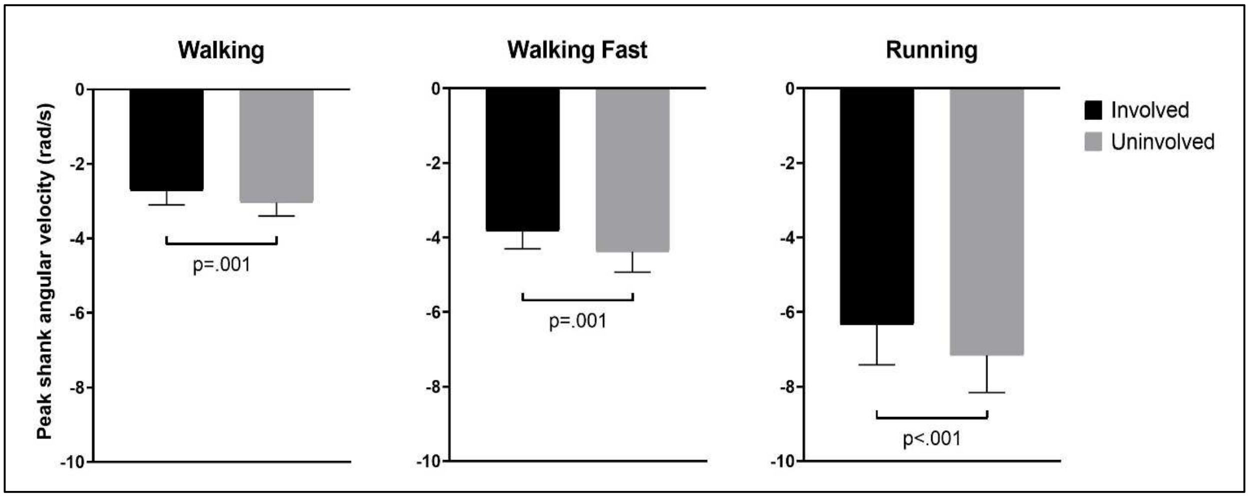

Figure 3. 3. Peak shank angular velocity between involved and uninvolved limbs during walking, walking fast, and running at 4 months following ACLR. Rad/s, radian per second.

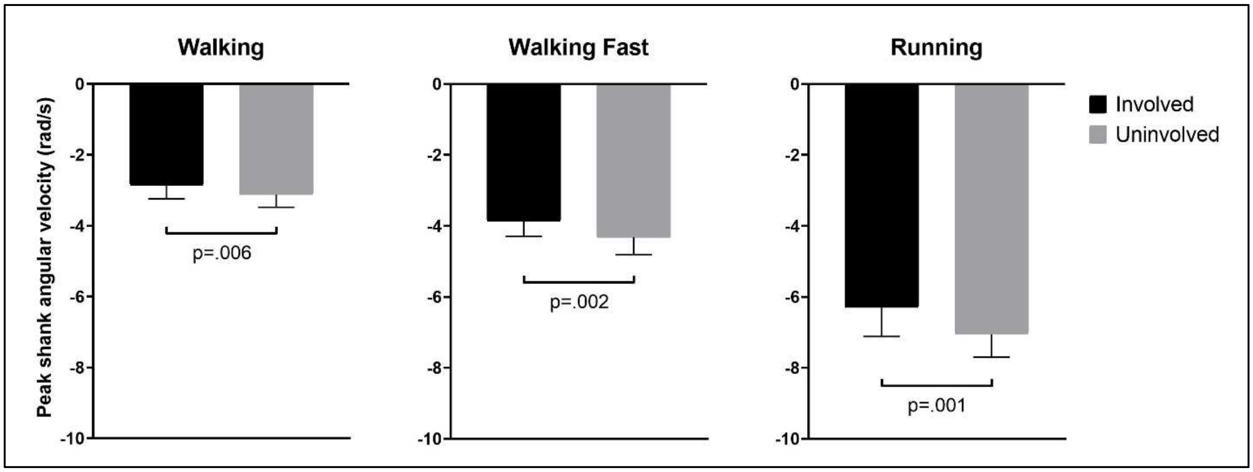

Figure 3. 4. Peak shank angular velocity between involved and uninvolved limbs during walking, walking fast, and running at 6 months following ACLR. Rad/s, radian per second.

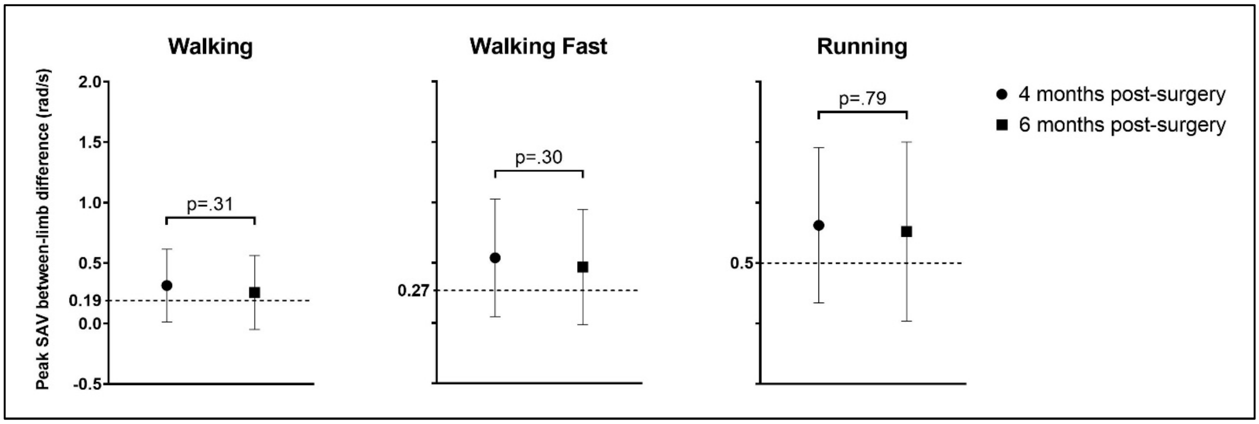

Figure 3. 5. Over time changes in between-limb peak shank angular velocity during walking, walking fast, and running. The horizontal dash lines represent the smallest meaningful between-limb differences for peak shank angular velocity at each gait speed. Rad/s, radian per second; SAV, shank angular velocity.

Chapter 4: Gait smoothness and its association with patients' functional and psychological measures at 6 months following anterior cruciate ligament reconstruction

Abstract

Background: Following anterior cruciate ligament reconstruction (ACLR), gait deficits are commonly reported during walking and running, which could increase the risk of knee degenerative changes. Knee biomechanical impairments post-ACLR may reduce its ability to attenuate gait-related accelerations during the stance phase of walking and running. Using a tri-axial accelerometer attached to the lower back, patients with ACLR showed altered lower trunk accelerations during walking, when compared to uninjured control subjects. However, the associations between gait smoothness, measured by normalized jerk of trunk accelerations, and patients' functional and psychological measures at 6-month post-surgery are still unknown.

Objective: To investigate whether gait smoothness at different speeds is correlated with patients' functional and psychological measures at 6-month post-ACLR.

Materials/Methods: 19 individuals with ACLR and 20 healthy uninjured controls participated in this study. Participants were instructed to walk, walk fast, and run along a 12-meter straight walkway. A tri-axial accelerometer was attached to the subject's lower back to record trunk accelerations in the vertical, mediolateral, and anteroposterior directions. From the recorded data of trunk accelerations, gait smoothness was quantified using jerk (i.e., the time derivative of acceleration) normalized by step duration and step length. A lower normalized jerk (NJ) value is indicative of greater gait smoothness. Patients' functional and psychological measures were assessed using return-to-sport criteria and the Tampa Scale for Kinesiophobia-11 (TSK-11), respectively. Independent t-tests were used to compare differences in NJ values between the ACLR and control groups. One-tailed Pearson's correlations were used to determine whether gait smoothness is associated with functional and psychological measures.

Results: Compared to controls, patients had significantly higher NJ values in the vertical direction during walking fast ($p < .05$) and in all directions during running ($p < .05$ for all) at 6 months post-ACLR. Walking smoothness in the vertical direction was correlated with between-limb ratios of single hop, triple hop, and triple-crossover hop for distance tests ($r = -0.402$-0.561, $p < .05$). Walking smoothness in the anteroposterior direction was correlated with between-limb ratios of quadriceps strength ($r = -0.434$, $p < .05$) and single hop for distance test ($r = -0.413$, $p < .05$). Running smoothness in the vertical ($r = -0.415$, $p < .05$) and in the anteroposterior ($r = -0.447$, $p < .05$) directions was correlated with the TSK-11.

Conclusions: Patients who walked with smoother patterns, similar to those of controls, showed better performance on quadriceps strength and hop for distance tests. However, patients who ran with less smooth patterns, compared to controls, reported a low level of fear of re-injury. Achieving good patient-reported knee functions (on The Knee Outcome Survey-Activities of Daily Living Score and The Global Rating Scale of Perceived Function) might have mediated the inverse association between running smoothness and fear of re-injury. Assessment of lower trunk accelerations during gait using accelerometry is an inexpensive, fast, simple and objective method that may provide clinical information regarding patients' functional status at 6 months post-ACLR.

Introduction

After anterior cruciate ligament reconstruction (ACLR), altered knee biomechanics during walking and running have been reported from 3 months to at least 5 years following surgery.[23, 42, 43] Specifically, recent reviews indicate that patients with ACLR are commonly presented with reduced knee flexion angles and knee extensor moment during early stance phase of walking and running.[23, 42, 43] These findings are a serious concern since knee biomechanical deficits in surgical knees, compared to contralateral knees, are linked to the development of knee degenerative changes.[120, 124-127] Detecting those knee biomechanical deficits require expensive gait analysis systems, such as motion capture and force plates. As a result, many clinicians may rely on visual observation to assess gait deviations, which could hinder their ability to identify and address remaining joint biomechanical deficits during rehabilitation following ACLR. However, commercially available accelerometers may have a potential to objectively test and identify patients with abnormal gait patterns.[137]

It has been found that the impact of anterior cruciate ligament injury and subsequent ACLR are not limited to the knee mechanics only, but also to the lower trunk kinematics (i.e., accelerations) during walking.[89] Normally, the knee joint plays a major role in attenuating gait-related accelerations resulted from foot strike onto the ground before accelerations reach the upper body segments (e.g., trunk). Disruption to the knee joint due to injury and the following surgery could potentially reduce its ability to absorb shock in the early stance phase of gait. Assessment of trunk accelerations can be easily performed by using a wearable, wireless tri-accelerometer attached to the subject's lower back, a place closer to the body's center of mass.[68, 69] Most importantly, recent advancements in accelerometers allow clinicians to objectively monitoring gait in a shorter duration and at low cost. In patients with ACL injury, lower trunk accelerations during walking were found to be altered in the frontal and sagittal planes pre-operatively, when compared to 6 months post-operatively.[89] While these patients showed significant improvement in the sagittal plane trunk accelerations at 6 months post-ACLR, the frontal plane trunk accelerations remained altered when compared to healthy controls.[89]

Previous studies showed that patients with deficits in knee kinematics and kinetics during gait had poor functional and psychological performance after ACLR.[15, 51, 52, 67] However, it is unknown whether altered lower trunk acceleration at different gait speeds following ACLR are associated with patients' functional and psychological measures. Therefore, the purpose of this study was to determine whether gait smoothness, calculated as normalized jerk (NJ) of trunk accelerations, would be associated with functional and psychological measures at 6-month post-surgery in patients with ACLR. We hypothesize that gait smoothness during gait would be correlated with functional and self-reported fear of reinjury measures. The results of this study may provide clinicians with an alternative and simple way to obtain clinical information regarding patients' functional status via trunk accelerometry in clinical sites.

Methods

Participants

A total of 19 patients with ACLR and 20 healthy uninjured control subjects participated in the study. The inclusion criteria for the ACLR group were: 1) age between 18-45 years old, 2) had a primary unilateral ACLR, 3) participated in at least recreational activities before injury (scored ≥5 for the preinjury status on the Tegner activity level scale), 4) cleared to return to unrestricted activities by their surgeons at the time of assessment, and 5) had no history of significant lower limb injuries (other than the current ACLR) or neurological conditions that would influence gait and functional assessment. The inclusion criteria for the control group were: 1) age between 18-45 years old, 2) a score of ≥5 on the Tegner activity level scale, and 3) no history of a significant lower limb injury or surgery (e.g., a ligament rupture or bone fracture). All study procedures were approved by a local institutional review board at a university. The procedures of the study were explained to all participants. Written informed consent was obtained from eligible patients before participation. Demographic data were collected from all participants including age, weight, height, body mass index (BMI), and activity level prior to the ACL injury.

Procedures

Gait assessment using accelerometry

Accelerations of the lower trunk during walking, walking fast, and running were assessed along a 12-meter straight walkway. Prior to testing, a tri-axial accelerometer (Xsens North America, Inc. Culver City, USA) was attached to the subject's lower back (over L3 segment of the lumbar spine), using an elastic strap provided by the manufacturer. Instructions provided to all subjects were as follows: walk at a normal pace, walk fast at a steady pace but do not jog, and run at a steady pace but do not sprint. Participants performed one familiarization trial and 2 actual trials for each gait speed that were used for data analysis.

The wireless tri-axial accelerometer was used to record linear accelerations of the lower trunk in the X, Y, and Z directions, which corresponded to the vertical (VT), mediolateral (ML), and anteroposterior (AP) directions, respectively. The sampling frequency was 75 Hz. The acceleration signals were wirelessly transmitted to a workstation laptop and stored via MT manager software (Xsens North America, Inc. Culver City, USA) for further data processing.

The raw data of lower trunk accelerations in the VT, ML, and AP directions were extracted using MT manager software and processed using a custom MATLAB program (R2019a, The Mathworks, MA, USA). Acceleration signals were transformed into a true horizontal-vertical coordinate system.[69] Raw data was then low pass filtered using 4th order Butterworth filter with a cut-off frequency set at 20Hz, 35Hz, 50Hz for walking, walking fast, and running, respectively. The cutoff frequencies for walking and running were used in previous studies that analyzed accelerations at the level of the lower back.[109, 110] Normalized Jerk (NJ) of trunk accelerations was calculated in the VT, ML, and AP directions. Jerk is the time derivative of acceleration and it measures the rate of change in acceleration over time.[91] Rapid changes in the body's acceleration or deceleration during steady movement increases jerk values, resulting in less smooth movement patterns.[90, 91, 107] Jerk analysis can be confounded by movement duration and amplitude.[91] Therefore, Jerk of the lower trunk accelerations was computed first, then normalized by step duration and step length using the following equation[91]:

$$NJ_x = \sqrt{({}^{1}/_{2} \int dt\, j^2\,(x) \times {}^{duration^5}/_{length^2})} \qquad (1)$$

Where x is the axis direction (VT, AP, or ML) and j is jerk. NJ is a unit-free measure.[91] Smaller NJ values are indicative of smoother movement patterns.[91, 107] Step duration and step length were calculated using unbiased autocorrelation coefficient sequence from the vertical axis of trunk acceleration time series.[111]

Functional and psychological measures

After gait assessment, functional evaluation of the ACLR group at 6 months post-ACLR was assessed using return-to-sport criteria (RTSc).[26, 28, 51, 52] RTSc are commonly used at the later stage of rehabilitation to release patients to return to sports participation. Athletes who wish to return to cutting/jumping sports must score 90% or greater in all of these tests as objective criteria to pass RTSc.[28] RTSc consist of 7 tests, which include two self-reported functional questionnaires, quadriceps isometric strength, and 4 single-leg hop tests.

The self-reported questionnaires included were The Knee Outcome Survey-Activities of Daily Living Score (KOS-ADLS) and The Global Rating Scale of Perceived Function (GRS). Scores on both questionnaires range from 0-100, where 100 indicates no knee-related symptoms or the level of knee function is similar to pre-injury status, respectively.[138]

The maximum voluntary isometric contractions (MVICs) of the quadriceps muscle were assessed bilaterally using a hand-held dynamometer (microFET2, Hoggan Scientific, LLC; West Jordan, UT). This method has shown to be reliable and valid when testing quadriceps isometric strength at 90 degrees of knee flexion.[139] Briefly, the quadriceps strength was tested with the participants in a sitting position at the edge of a medical treatment table with both knees and hips joints flexed at 90 degrees. Before testing, the subjects were instructed to adjust their sitting position to make the shank of the testing leg in a position that is parallel to the leg of the treatment table. Then, a safety belt folded in half and crossing horizontally was used to stabilize the hand-held dynamometer against the back of the table's leg in one end and the anterior side of the shank (about 5 centimeters above the lateral malleolus) at the other end. Participants' skin at the shank's contact level was protected by a soft pad embedded in the belt. Patients were asked to perform one practice trial, followed by three separate MVICs (5 seconds for each trial with 1-minute rest between trials) for each leg. All trials were accompanied by verbal encouragement to ensure that patients would achieve their maximal effort. The values of the maximal peak force during quadriceps strength testing were recorded and transformed to peak torques. The average of peak torque values was calculated for each leg and then normalized to body weight (kg). In the athletic population, a score of 90% or greater in comparison to the uninvolved side is required to pass the quadriceps strength test. However, a score of 80% or above is indicative of adequate quadriceps strength in non-athletic normal population.[15, 140]

Following the quadriceps strength assessment, participants performed 4 single-leg hop tests.[141] The hop tests consisted of single hop for distance (cm), triple hop for distance (cm), triple-crossover hop for distance (cm), and 6-meter timed hop (seconds). After a practice trial for each hop test, patients were asked to complete two trials for each limb. The limb symmetry indices (LSI) for quadriceps (Q-LSI) and the first three tests of hop for distance were calculated using the following formula: LSI = (involved limb / uninvolved limb) x 100%. For the 6-meter timed hop, the LSI was calculated as (uninvolved limb / involved limb) x 100%, because patients are expected to hop faster and complete the 6-meter timed hop in a short time when using the uninvolved side, as compared to the involved side.

The fear of movement or re-injury was assessed using the self-reported Tampa Scale for Kinesiophobia (TSK-11) questionnaire. Previous studies used this questionnaire to assess pain-related fear of movement/re-injury in patients with ACLR.[65, 66] The TSK-11 scores range from 11 to 44 points. A higher score on the TSK-11 indicates a higher level of fear of movement/re-injury.

Statistical Analysis

Statistical analysis was performed using SPSS (Version 25.0. Armonk, NY: IBM Corp). To determine whether patients with ACLR would show altered gait smoothness at different gait speeds, independent t-tests were used to compare differences in NJ values between the ACLR group and the healthy control group. One-tailed Pearson’s correlation coefficient was used to assess whether NJ values in the 3 directions at each gait speed would be associated with RTSc and patient-reported fear of movement/reinjury. Correlation coefficients were interpreted as weak (<0.4), moderate (0.4 - 0.6), or strong (0.7-1.0). Two patients with ACLR could not complete the triple-crossover hop for distance and six-meter timed hop tests, due to fatigue. This resulted in four missing data points. To overcome this issue, expectation-maximization imputations were used to estimate these missing values. The significant level was set at .05.

Results

Participants' demographics, RTSs, and patient-reported fear of re-injury are presented in Table 4.1. No significant differences were found between the ACLR and control groups, except for weight and BMI. Only three out of 19 patients passed all RTSs tests.

Table 4.2 shows differences in mean NJ values between the ACLR group and the control group. No group difference was noted during normal walking speed. During walking fast, the ACLR group presented with higher NJ values in the VT direction, when compared to the control group ($p = .04$). During running, the ACLR group showed higher NJ values in the VT, ML, and AP directions, when compared to the control group ($p < .05$).

The results of correlations are summarized in Table 4.3 and also shown in Figures 4.1, 4.2, and 4.3. During walking, significant moderate correlations were found between mean NJ values in the VT direction and single-leg hop for distance (r = - 0.561, $p = .006$, Figure 4.1A), triple hop for distance (r = - 0.423, $p = .036$, Figure 4.1B), and triple-crossover hop for distance (r = - 0.402, $p = .044$, Figure 4.1C). In addition, NJ values in the AP direction during walking were significantly and moderately correlated with quadriceps strength (r = - 0.434, $p = .032$, Figure 4.2A) and single-leg hop for distance (r = - 0.413, $p = 0.04$, Figure 4.2B). During walking fast, no significant correlations were noted. During running, significant moderate correlations were found between NJ values in the VT (r = - 0.415, *p* = .039, Figure 4.3A) and in the AP (r = - 0.447, *p* = .027, Figure 4.3B) directions with the TSK-11.

Discussion

The goal of this study was to investigate the association between gait smoothness, as measured by normalized jerk of trunk accelerations, at different speeds and patients' functional and psychological measures at 6 months following ACLR. At 6 months post-ACLR, patients walked with smoother patterns as healthy subjects, but ran with significantly less smoothness. The overall correlations results showed that walking smoothness was associated with quadriceps strength and hop for distance tests (single-leg hop, triple hop, and triple-crossover hop). In addition, running smoothness was correlated with self-reported fear of movement/re-injury. Based on these findings, it appears that patients with smoother walking patterns showed better performance in quadriceps strength and functional measures. On the other hand, patients with lower running smoothness had a lower level of fear of movement/re-injury.

At 6 months post-ACLR, the patient group showed altered gait smoothness at higher speeds, mainly during running, when compared to the control group. Although there was an association between walking smoothness and some of the patients' functional measures, the lack of association of walking fast and running smoothness with functional measures indicates that other impairments may have contributed to these alterations in movement smoothness. Specifically, deficits in knee biomechanics, such as decreased knee flexion angles, in the sagittal plane during running have been reported up to 5 years after ACLR.[43] A previous study found decreased knee flexion angles during the early stance phase of running were associated with increased trunk accelerations in healthy subjects.[142] Because running produces higher impact forces during the foot contact with the ground, decreased knee flexion angle during this phase increases leg stiffness, resulting in less shock absorption and increased body's accelerations.[142] This could potentially lead to running-related injuries.[142] However, the contribution of knee biomechanical impairments on altered movement smoothness during walking fast and running should be investigated in future studies in patients with ACLR.

The significant moderate correlation of walking smoothness in the horizontal (or VT) and sagittal (or AP) planes with hop tests indicate that patients with smoother walking patterns had a good performance on the single-leg hop, triple hop, and triple-crossover hop for distance tests. During walking in a straight line, the motion of the body's center of mass occurs mainly in the VT and AP directions.[143] Similarly, the body motion during the hop tests occurs mainly in the VT and AP directions. Therefore, the same group of lower limb muscles that work during walking is likely used, with more substantial muscle force productions, while performing hop tests. A previous study found that gluteus maximus, quadriceps, hamstrings, gastrocnemius, and soleus provide vertical support and forward progression accelerations of the body's center of mass during walking.[144] Of these groups of muscles, deficits in quadriceps strength were linked to altered knee biomechanics during gait and worse performance on the hop tests in patients with ACLR.[13, 15, 140, 145] In addition, patients with hamstrings weakness showed altered gait patterns and low functional performance.[146, 147] In the current study, better quadriceps strength was weakly to moderately associated with better walking smoothness in the VT (r = - 0.369, p = .06) and AP (r = - 0.434, p = .03) directions. Additionally, and consistent with the previous studies[13, 140], good quadriceps strength was moderately to strongly associated with good performance on hop tests (r = 0.599-0.770, p <.005). Therefore, it is likely that quadriceps strength was a mediator factor for the association between walking smoothness and hop tests. Further, these findings may explain the lack of association of frontal plane (or ML direction) walking smoothness with quadriceps strength and hop tests. Future studies should investigate whether other groups of muscles, including hamstrings strength, are mediator factors for the association between walking smoothness and hop tests.

The results of this study found that walking smoothness in the sagittal plane was moderately correlated with isometric quadriceps strength. Specifically, patients who walked with smoother patterns in the AP direction had better quadriceps strength (Figure 4.2A). Quadriceps strength deficits are commonly reported following ACLR.[113] Previous studies indicated that quadriceps activities play a major role during the early stance phase of gait in modulating the forward progression of body's center of mass and shock attenuation.[142, 144] In the current study, 12 out of 19 patients had less than 20% side-to-side differences in the quadriceps limb symmetry index, a score that indicates achieving adequate quadriceps strength in the non-athletic normal population.[15] In addition, the ACLR group showed walking smoothness that was similar to that of the healthy uninjured group at 6 months post-ACLR. Therefore, these findings suggest that having adequate quadriceps strength may have contributed to smoother walking patterns in the AP direction for patients with ACLR. However, the correlation between these two variables was moderate and thus future studies should investigate other factors (e.g., knee biomechanics or hamstring strength) that could contribute to walking smoothness in patients with ACLR.

The results of this study found associations between running smoothness (in the VT and AP directions) and the patient-reported fear of re-injury. Unexpectedly, these findings suggest that patients with lower running smoothness (higher NJ values) reported a lower level of fear of re-injury (Figure 4.3). It is likely that reporting good knee functions post-ACLR had mediated this correlation between running smoothness and the level of fear of re-injury. For instance, previous studies found a lower level of fear on the TSK-11 was linked to better patient-reported knee functions in patients with ACLR.[66, 148] This association is supported in the current study in which a lower fear of re-injury was related to better patient-reported knee functions on the KOS-ADLS (r = - 0.491, p = .016) and the GRS (r = - 0.571, p <.01). Therefore, it is possible that having good knee function might have led patients to report a lower level of fear. This in turns might have led these patients to not worry about their involved knee and ran without optimizing their movement smoothness. Even with reporting a low level of fear, the findings of the current study showed that the ACLR group had significantly lower running smoothness, when compared to the control group. Within this context, these patients might have coped with potential biomechanical and strength deficits that decreased their running smoothness. A potential concern of these findings could be that running with less smooth patterns might increase joints loading, which may lead to running-related injuries in the long term.[97, 142] However, future studies should investigate whether having less running smoothness can lead to knee or running-related injuries in individuals with ACLR.

There are limitations to this study. First, this was a cross-sectional study and therefore it does not establish cause and effect relationships between the studied variables. In addition, the results of this study should be interpreted with caution as the strength of the associations between the studied variables were moderate. Furthermore, the average weight and BMI of the ACLR group were significantly higher (weight = 78.16 kg, BMI = 25.96 kg/m2) than the control group (weight = 67.16, BMI = 23.19 kg/m2). This significant difference was determined by one subject in the ACLR group whose BMI of 35.6 kg/m2 was found to be an outlier. However, a Mann-Whitney test showed no significant difference between the two groups in the BMI (U = 118, p = .11). Even though we considered this participant's data in the analysis to increase the statistical power of the study, the results of between-group differences in NJ values did not change for all gait tasks with or without this participant's data.

Conclusion

The purpose of this study was to investigate whether gait smoothness, as measured by normalized jerk of trunk accelerations, at different speeds would be associated with patients' functional and psychological measures at 6 months following ACLR. When compared to healthy subjects, patients with ACLR showed similar walking smoothness, but ran with less smoothness. The correlation results showed that walking with smoother patterns was moderately associated with good performance on quadriceps strength and hop for distance tests. There were no correlations between any functional measures and movement smoothness during walking fast and running. In addition, running with less smoothness was moderately associated with a lower level of fear of re-injury. These findings suggest that walking smoothness, assessed by trunk accelerometry, may provide information regarding the functional status of patients with ACLR. Future studies are needed to determine whether altered lower trunk accelerations during gait are associated with knee biomechanics, knee injuries, or knee degenerative changes.

Table 4. 1. Demographic characteristics, RTSc, and patient-reported fear of re-injury.

	ACLR group (n=19)	Control group (n=20)	*p* Value
Age, y	27.68±6.79	27.20±4.88	.79
Gender, female/male, n	10/9	9/11	…
Height, cm	172.65±10.45	169.95±9.87	.41
Weight, kg	78.16±17.65	67.16±14.35	.039
BMI, kg/m^2	25.96±3.81	23.19±3.69	.027
Autograft type, n			
Bone-patellar tendon-bone	3	…	…
Hamstring	16		
Tegner activity score (0-10)	7.53±1.78	6.75±1.41	.14
KOS-ADLS, %	93.01±3.78	…	…
GRS, %	82.74±12.8	…	…
Q-LSI, %	87.02±18.61	…	…
Single hop, %	85.64±15.74	…	…
Triple hop, %	87.03±11.08	…	…
Triple-crossover hop, %	87.16±13.41	…	…
6-m timed hop, %	94.37±11.05	…	…
TSK-11	18.79±4.91	…	…

Abbreviations: ACLR, anterior cruciate ligament reconstruction; BMI, body mass index; GRS, global rating scale of perceived function; KOS-ADLS, Knee Outcome Survey–Activities of daily living subscale; Q-LSI, quadriceps limb symmetry index; TSK-11, Tampa Scale of Kinesiophobia.

Table 4. 2. Differences in mean normalized jerk values between the ACLR group and the control group in the VT, ML, and AP directions during walking, walking fast, and running at 6 months post-ACLR.

Gait Tasks	Directions	ACLR Group (N=19)	Control Group (N=20)	*p* Value
Walking	VT	32.33±7.99	28.23±7.83	.11
	ML	27.33±8.46	23.05±6.47	.08
	AP	23.83±5.76	22.34±4.61	.38
Walking Fast	VT	24.57±8.79	19.61±5.52	**.04**
	ML	20.40±6.06	18.05±5.87	.23
	AP	22.99±5.23	20.56±4.89	.14
Running	VT	19.99±8.37	13.25±6.69	**.008**
	ML	18.96±6.86	12.39±6.79	**.005**
	AP	17.12±5.24	13.47±5.88	**.048**

Abbreviations: VT, vertical; ML, mediolateral; AP, anteroposterior; ACLR, anterior cruciate ligament reconstruction. Significant differences ($p < .05$) are presented in bold.

Table 4. 3. Pearson's correlations between normalized jerk values at different gait speeds and patients' functional and psychological measures at 6 months post-ACLR.

Gait Tasks	Directions	KOS-ADLS	GRS	Q-LSI	Single hop	Triple hop	Triple-crossover hop	6-meter timed hop	TSK-11
Walking	VT	-0.026	0.069	-0.369	**-.561****	**-.423***	**-.402***	-0.355	0.177
	ML	-0.017	0.012	-0.175	-0.357	-0.078	0.034	-0.175	0.005
	AP	-0.062	-0.036	**-.434***	**-.413***	-0.319	-0.267	-0.320	-0.070
Walking Fast	VT	0.278	-0.080	0.015	-0.011	0.010	-0.040	0.274	-0.090
	ML	0.259	-0.184	-0.163	-0.157	0.080	0.060	0.045	-0.027
	AP	0.322	0.225	0.088	-0.007	-0.056	-0.067	0.034	-0.296
Running	VT	0.142	0.344	-0.043	0.012	-0.087	0.054	0.005	**-.415***
	ML	0.386	0.315	-0.030	-0.344	-0.332	-0.053	-0.176	-0.361
	AP	0.300	0.278	0.001	-0.120	-0.269	-0.064	-0.063	**-.447***

Abbreviations: VT, vertical; ML, mediolateral; AP, anteroposterior; KOS-ADL, The Knee Outcome Survey-Activities of Daily Living Score; GRS, the Global Rating Scale of Perceived Function; Q-LSI, quadriceps limb symmetry index; TSK-11, the Tampa Scale of Kinesiophobia 11-item.

**. Correlation is significant at the 0.005 level (1-tailed).

*. Correlation is significant at the 0.05 level (1-tailed).

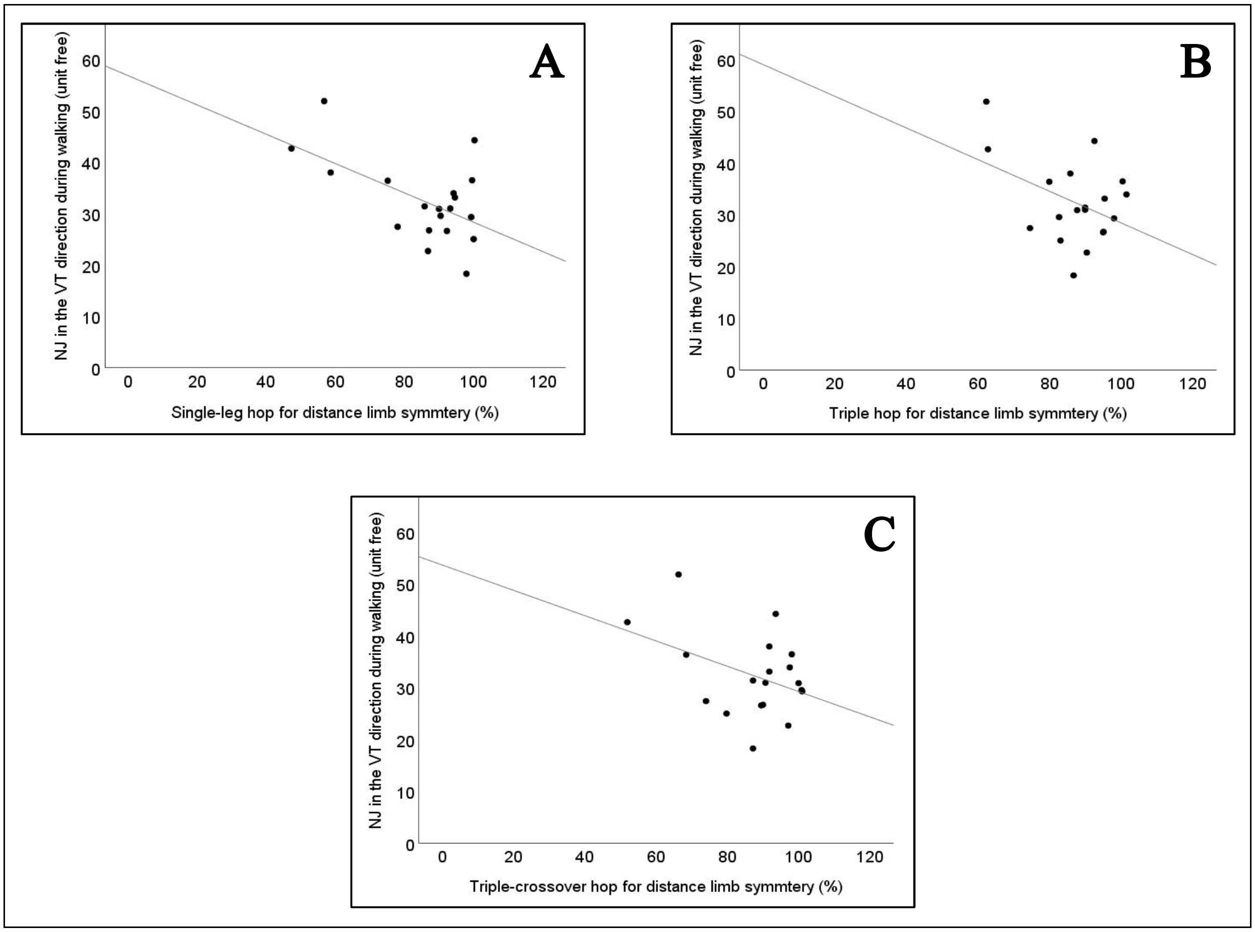

Figure 4. 1. The correlation between walking smoothness in the vertical direction and single-leg hop (graph A), triple hop (graph B), and triple-crossover hop (graph C). NJ, normalized jerk; VT, vertical.

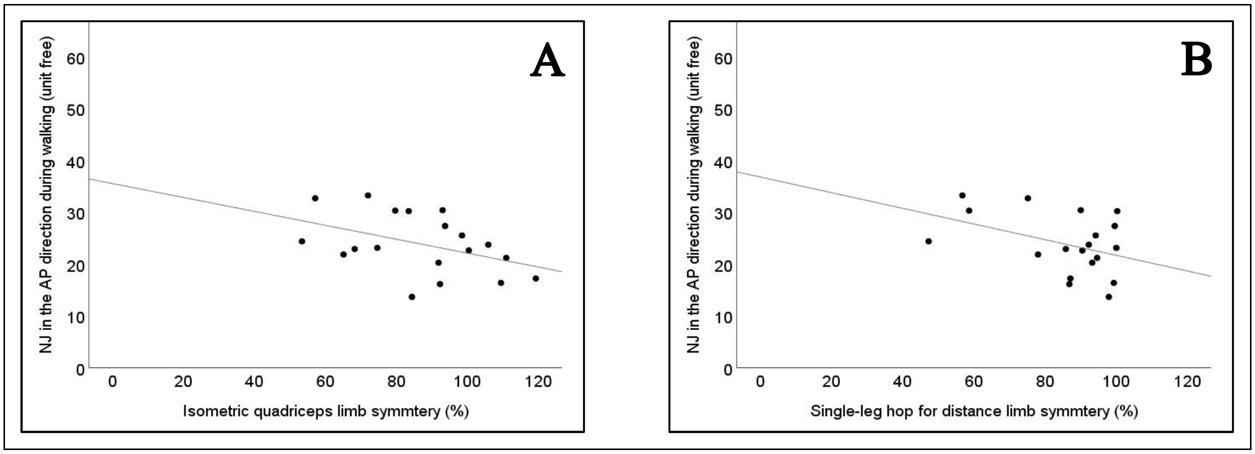

Figure 4. 2. The correlation between walking smoothness in the anteroposterior direction and isometric quadriceps strength (graph A) and single-leg hop (graph B). NJ, normalized jerk; AP, anteroposterior.

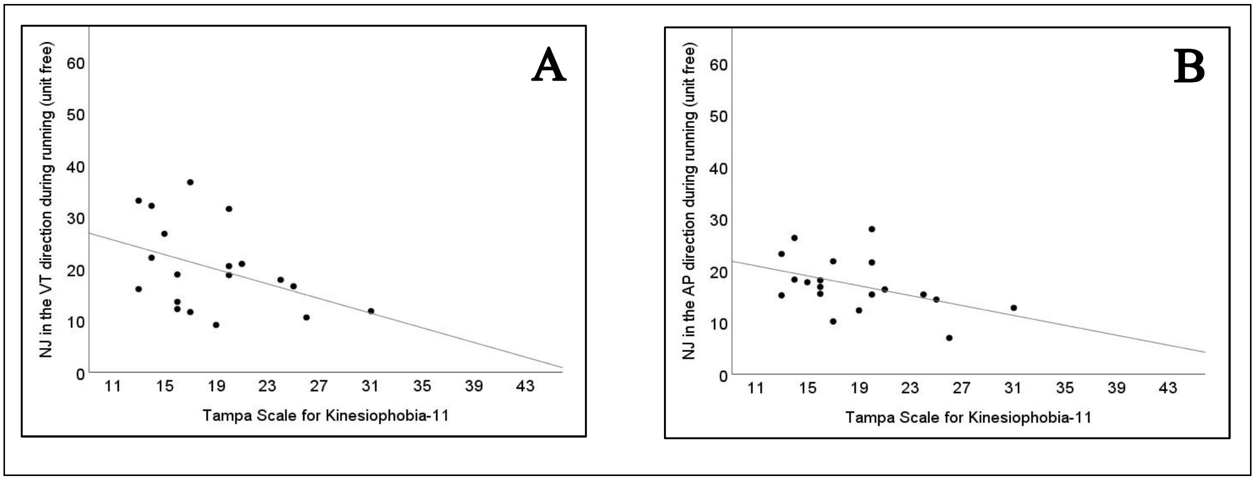

Figure 4. 3. The correlations between running smoothness in the vertical (graph A) and anteroposterior (graph B) directions with the Tampa Scale for Kinesiophobia-11. NJ, normalized jerk; VT, vertical; AP, anteroposterior

Chapter 5: Asymmetry in shank angular velocity during different gait speeds is related to asymmetry in quadriceps strength and functional measures following anterior cruciate ligament reconstruction

Abstract

Study Design: Cross-sectional study.

Background: Inertial sensors identified interlimb asymmetry in sagittal plane shank angular velocity (SAV) during loading response of walking following anterior cruciate ligament reconstruction (ACLR). It is unknown whether SAV asymmetry during gait is related to functional and psychological measures.

Objectives: To investigate whether sagittal plane SAV during loading response of gait at different speeds correlates with quadriceps strength, functional measures, and patient-reported fear of re-injury at 6 months post-ACLR.

Methods: Seventeen individuals with primary, unilateral ACLR were instructed to walk, walk fast, and run along a straight walkway while wearing one wireless inertial sensor on each shank. The average of SAV peaks was determined bilaterally during loading response for each gait speed. In addition, participants completed return-to-sport criteria evaluation, including isometric quadriceps strength and 4 single-leg hop tests. Patient-reported fear of re-injury was assessed using the Tampa Scale of Kinesiophobia (TSK-11). Pearson's correlations were used to determine whether interlimb peak SAV asymmetry is associated with strength, functional, and psychological measures.

Results: Peak SAV at each gait speed was significantly correlated with quadriceps strength and all hop tests ($r = -0.470$-0.859; $p<.05$ for all). Further, peak SAV during running was significantly correlated with the TSK-11 ($r = 0.439$; $p=.039$).

Conclusion: Patients with greater SAV asymmetry at different gait speeds showed greater asymmetry in quadriceps strength and hop tests. SAV asymmetry during gait, measured by inertial sensors, may offer an inexpensive, fast, and objective clinical assessment to identify individuals with asymmetry in quadriceps strength and hop tests.

Key Words: anterior cruciate ligament reconstruction, wearable sensors, gait, return-to-sport criteria, shank kinematics

Introduction

After anterior cruciate ligament (ACL) rupture, many patients choose to undergo ACL reconstruction (ACLR) to restore knee stability and function.[149] Clinically, it is expected that patients should walk normally without visible gait deviations during the first few weeks (6-8 weeks) of rehabilitation before progressing to higher demanding exercises such as running.[58] However, recent biomechanical studies indicate that gait asymmetries can persist for months after ACLR.[23, 42, 43] Having biomechanical deficits at the knee joint during gait is a risk factor for the development of knee osteoarthritis.[120, 124-127] Assessment of knee biomechanical deficits during gait has traditionally been undertaken in costly laboratories that require extensive training and time. For this reason, research studies have been conducted in recent years to develop an inexpensive and objective gait assessment tool to can help clinicians in identifying patients with gait asymmetries during rehabilitation following ACLR.[99, 128]

Wireless wearable inertial sensors have gained popularity in gait analysis research because of their low cost, convenience, and is easy to use.[150] Recent advancement of these sensors allows for collecting gait data in clinical settings.[150] One application of these sensors is to measure shank angular velocity (SAV) in the sagittal plane during gait.[99, 100] Peak SAV can provide information about the angular velocity of anterior shank rotation during loading response of gait.[99] Normally, a faster forward shank rotation than the thigh during this phase can result in knee flexion, which is controlled eccentrically by quadriceps contraction, to accept body's weight and absorb shock.[99] In patients with ACLR, inertial sensors were found to be able to detect asymmetry in sagittal plane SAV during walking at 3 months following surgery.[99, 100] Specifically, the surgical limbs showed reduced peak SAV during loading response of walking when compared to the non-surgical limbs. In addition, SAV during normal walking was found to be correlated with knee flexion angle, knee extensor moment, and vertical and posterior ground reaction forces.[99, 100]

Several studies suggest that biomechanical knee impairments are linked to quadriceps strength deficit[15, 145], which is also a persistent problem following ACLR.[113, 151] In addition, patients who demonstrated gait asymmetries were more likely to fail return-to-sport criteria (RTSc), which include 2 self-report functional questionnaires, quadriceps strength testing, and 4 single-legged hop tests, at the time of returning to sport/activities following ACLR.[51, 52] However, the association between SAV asymmetry during gait at different speeds and quadriceps strength and self-reported knee function has not been investigated. In addition, it is unknown whether SAV asymmetry during less challenging tasks such as walking and running would be linked to asymmetrical performance in high challenging tasks such as hop tests. Establishing such associations may provide clinicians with an inexpensive (compared to an isokinetic dynamometer used to measure quadriceps strength), less-time consuming, and simple tool to identify patients with quadriceps strength deficits and side-to-side movement asymmetry at the time of discharge to unrestricted activities.

In addition to strengthening and functional evaluations, psychological factors, such as fear of reinjury, have gained attention in recent years because of their contributions in decreasing the ability of patients to return to sport[65] and increasing the risk of ACL re-injury.[66] Specifically, patients with a high level of self-reported fear of reinjury (assessed by Tampa Scale for Kinesophobia-11) at 6 months post-ACLR were not able to return to pre-injury level of sport participations[65] and were 13 times more likely to sustain an ipsilateral second ACL injury within 24 months after return to sport.[66] In terms of the relationship between psychological factors and gait asymmetry following ACLR, patients who showed lower psychological readiness to return to sport had greater between-limb asymmetry in knee flexion angles (measured by 3-D motion analysis) during walking at 6 month following surgery.[67] To our knowledge, it is still unknown whether patients with a high level of self-reported fear of reinjury would show greater between-limb asymmetry in SAV at different gait speeds post-ACLR.

Therefore, the purpose of this cross-sectional study was to determine whether sagittal plane SAV during loading response of gait at different speeds would correlate with RTSc and patient-reported fear of re-injury at 6 months post-ACLR. We hypothesized that patients who showed greater between-limb asymmetries in SAV would demonstrate poor performance on RTSc and a high level of self-reported fear of reinjury.

Methods

Participants

A total of 17 participants with ACLR were recruited from a local orthopedic and sports performance center clinic. Participants were included in the study if they were between 18-45 years old, had a primary unilateral ACLR, participated in at least recreational activities before injury (scored of ≥5 for the preinjury status on the Tegner activity level scale[108]), cleared to return to unrestricted activities by their surgeons at the time of assessment, and had no history of significant lower limb injuries (other than the current ACLR) or neurological conditions that would influence gait and functional assessment. All study procedures were approved by the Institutional Review Board at the University of Kansas Medical Center. The study's procedures were explained to all participants and written informed consent was obtained from each individual before participation. Demographic data were collected from all participants including age, body mass index, knee medical history, and activity level prior to ACL injury.

Procedures

<u>Gait assessment using gyroscopes</u>

Shank kinematics were collected during walking, walking fast, and running in a straight walkway in the clinic during patients' regular visits with their surgeons-at 6 months post-ACLR. One wireless inertial sensor (MTu sensor, Xsens North America, Inc. Culver City, USA) was attached to each shank, about 5-centimeter above the lateral malleolus. Collected data were sampled at 75Hz. The angular velocity of the shank rotation about the Z-axis of gyroscope was used to calculate SAV in the sagittal plane.

At the starting line of a 12-meter straight walkway, participants were instructed to walk, walk fast, and run. The instructions provided for each gait speed were: 1) walk at your preferred speed, 2) walk fast at steady pace as if you are trying to go somewhere in a hurry but do not jog or run, and 3) run at a steady pace as if you are working out, but do not sprint. After familiarization trials, data from two actual trials were collected for each gait speed. Data from the sensors were wirelessly transmitted to a workstation laptop and stored via MT manager software (Xsens North America, Inc. Culver City, USA) for further data processing.

The raw data from gyroscope sensors was extracted using MT manager software and processed using a custom MATLAB program (R2018b, The Mathworks, MA, USA). The raw gyroscope signal was filtered using 2^{nd} order Butterworth low-pass filter with cut-off frequencies of 10Hz, 20Hz, and 30Hz for walking, walking fast, and running, respectively. The variable of interest was peak SAV during loading response of gait, which was identified as the first negative peak after mid-swing from the filtered data for the surgical and non-surgical limbs.[99] The average of SAV peaks was calculated for each limb and used for the analysis.

Return-to-sport criteria (RTSc)

After the gait analysis, the performance of patients on RTSc was tested. RTSc consist of seven tests including two self-reported functional questionnaires, quadriceps isometric strength, and 4 single-leg hop tests. RTSc are commonly used to determine the patient's readiness to return to sport/activity.[26, 28, 51, 52] Cutoff scores of 90% or greater in all of these tests have been suggested as objective criteria to pass RTSc.[28]

The Knee Outcome Survey-Activities of Daily Living Score (KOS-ADLS) is a 14-item self-reported questionnaire that was used to assess knee symptoms and functional limitations.[138] The KOS-ADLS score ranges from 0-100, where 100 indicates no knee-related symptoms or functional limitations. The Global Rating Scale of Perceived Function (GRS) is a single item that asked patients to rate their current knee function during their usual daily activities on a scale from 0 to 100, with 100 being the level of knee function prior to the injury and 0 being the inability to perform any daily activities.[138]

The maximum voluntary isometric contractions (MVICs) of the quadriceps muscle were quantified using a modified belt-stabilized hand-held dynamometer (microFET2, Hoggan Scientific, LLC; West Jordan, UT). This method has shown to be reliable and valid when testing quadriceps isometric strength at 90 degrees of knee flexion.[139] Patients were seated in an upright position with their legs hanging from the edge of a treatment table, and with the hip and knee flexed to 90 degrees (Figure 5.1). A gait belt with a foam pad was used to stabilize the dynamometer on the back of the table leg, with the foam pad positioned across the anterior aspect of the tibia. Patients were asked to perform one practice trial, followed by three separate MVICs (5 seconds for each trial with 1-minute rest between trials) for each leg. The surgical side was tested first, followed by the non-surgical side. All trials were accompanied by verbal encouragement to ensure that patients would achieve their maximal effort. The values of the maximal peak force during quadriceps strength testing were recorded and transformed to peak torques. The average of peak torque values was calculated for each leg and then normalized to body weight (kg). The quadriceps limb symmetry index (Q-LSI) was calculated using the following formula: Q-LSI = (involved quadriceps MVIC/uninvolved quadriceps MVIC) x 100%.

Following the quadriceps strength assessment, participants performed 4 single-leg hop tests.[141] These hop tests are commonly used clinically and have good measurement reliability in patients following ACLR.[152, 153] The hop tests were performed in the following order: single hop for distance (cm), triple hop for distance (cm), triple-crossover hop for distance (cm), and 6-meter timed hop (seconds). After a practice trial for each hop test, patients were asked to complete two trials for each limb. For each of the first 3 hop distance tests, a limb symmetry index (LSI) was calculated from the average of two trials for the surgical and non-surgical limbs using the following formula: LSI = (involved limb hop distance/uninvolved limb hop distance) x 100%. The LSI for the 6-meter timed hop was calculated as (uninvolved limb hop time/involved limb hop time) x 100%.

Patient-reported fear of movement/re-injury

Each participant completed the short version of the Tampa Scale for Kinesiophobia (TSK-11). Previous studies used this questionnaire to assess pain-related fear of movement/re-injury in patients with ACLR.[65, 66] The TSK-11 includes questions that are related to somatic sensations (such as "Pain always means I have injured my body") and activity avoidance (such as "I'm afraid that I might injure myself if I exercise"). The TSK-11 scores range from 11 to 44 points. A higher score on the TSK-11 indicates a higher level of fear of movement/re-injury.

Patients with a score of 19 or higher were 13 times at risk of sustaining a second ipsilateral ACL injury.[66]

Statistical Analysis

Statistical analysis was performed using SPSS (Version 25.0. Armonk, NY: IBM Corp). Paired t-tests were used to assess peak SAV asymmetries between the surgical and non-surgical limbs during walking, walking fast, and running. Effect sizes were calculated to determine the magnitude of side-to-side SAV asymmetries. Effect sizes were interpreted as small (d = 0.2), medium (d = 0.5), and large (d = 0.8). One-tailed Pearson's correlation coefficients were used to assess whether peak SAV asymmetry for each gait speed would be associated with RTSc and patient-reported fear of movement/reinjury. Correlation coefficients were interpreted as weak (<0.4), moderate (0.4 - 0.6), or strong (0.7-1.0). The significant level was set at .05.

Results

Participants' demographics, RTSs, and patient-reported fear of re-injury are shown in Table 5.1. Graft types used in ACL reconstruction for the cohort included 2 patellar tendon autografts and 15 hamstring tendon autografts. The average of the pre-injury level of activity on the Tegner activity level scale was 7.40±1.50 (mean±SD). Only three out of 17 patients passed all RTSs tests.

On average, the surgical limb had significantly smaller peaks SAV during walking (p=.002), walking fast (p=0.001), and running (p=0.0003), compared to the non-surgical limb (Table 5.2). The results of correlations are summarized in Table 5.3. During walking, the interlimb difference for peak SAV was significantly correlated with 5 RTSc variables: Q-LSI (r = − 0.764, p<.001) and all hop tests (r = − 0.470-0.654, p<.05 for all). During walking fast, interlimb peak SAV difference was significantly correlated with 6 RTSc variables: Q-LSI (r = − 0.781, *p*<.001), all hop tests (r = − 0.700-0.859, *p*<.005 for all), and the GRS self-reported questionnaire (r = − 0.424, *p*=.045). During running, interlimb peak SAV difference was significantly correlated with 5 RTSc variables and patient-reported fear of movement/re-injury: Q-LSI (r = − 0.658, *p*<.005), all hop tests (r = − 0.433-0.696, *p*<.05 for all), and the TSK-11 (r = 0.439, *p*=.039).

Discussion

The primary goal of this study was to investigate whether sagittal plane shank kinematics during loading response of gait at different speeds would be associated with RTSc and patient-reported fear of movement/re-injury in individuals at 6 months following ACLR. The results of this study supported the tested hypothesis in that interlimb SAV asymmetries during walking, walking fast, and running were moderately to strongly correlated with interlimb asymmetries in isometric quadriceps strength and hop tests. In addition, interlimb SAV asymmetries during walking fast and running were moderately correlated with patient-reported perceived function and patient-reported fear of movement/re-injury, respectively. Thus, the level of association between shank kinematics asymmetry, measured by inertial sensors, and quadriceps strength and functional measures may offer clinicians with inexpensive (compared to dynamometry used to assessed quadriceps strength), less time consuming, and objective evaluation to identify patients with asymmetry in quadriceps strength and hop tests at the time for return to sport/activity.

The results of the study indicate that patients with greater side-to-side SAV asymmetry at different gait speeds had greater asymmetries in isometric quadriceps strength. It is likely patients with smaller peak SAV during loading response of gait on the surgical limb had weaker quadriceps strength. Consistent with the findings of the current study, Lewek et al[15] found that patients with asymmetrical knee angles and moments during walking and jogging had weak quadriceps strength (more than 10% differences between surgical and non-surgical side), when compared to patients with strong quadriceps strength. In addition, knee flexion angle at the early stance phase of gait was significantly correlated with quadriceps strength in patients with ACLR.[145] In the current study, we found that a combination of SAV asymmetries at all gait speeds explained 57% of the variance in the isometric quadriceps strength (adjusted $R^2 = 0.57$, p=.003). Therefore, these findings suggest that asymmetrical SAV during gait at different speeds is linked to asymmetry in quadriceps strength in patients with ACLR. Future studies should determine whether improving quadriceps strength would improve SAV symmetry during gait.

Similarly, the results of this study showed that patients with greater SAV asymmetry at different gait speeds showed greater asymmetries in all hop tests at 6 months post-ACLR. These results indicate that patients with smaller SAV during loading response of gait on the surgical limb had shorter hop distance on the single-leg hop for distance tests and longer hop time on the 6-m timed hop test. This poor performance on the hop tests might be attributed to deficits in quadriceps strength, as shown in past studies.[13, 140] This is also supported in our study in which we found that poor Q-LSI was significantly correlated with worse performance on all hop tests (r = 0.640-0.796, $P < .005$ for all). In the current study, a combination of SAV asymmetries at all gait speeds accounted for 43% to 79% of the variance in the hop tests (adjusted R^2 = 0.43-0.79, $p<.05$). These findings suggest that patients who exhibited asymmetry during a less challenging task such as gait would likely show asymmetrical performance while performing a more challenging task such single-leg hop tests. However, future research with larger sample sizes is required to support these findings.

A significant correlation with moderate strength was found between SAV during running and the TSK-11. Similar findings were reported in a recent study that found a weak, but significant relationship between knee kinematics asymmetry during walking and psychological readiness to return to sport at 6 months following ACLR.[67] The aforementioned study found patients who walked with less knee flexion angle at initial contact on the surgical limb, compared to the nonsurgical side, had lower psychological readiness to return to sport (as measured by Anterior Cruciate ligament-Return to Sport after Injury Scale). In our study, patients who ran with smaller peak SAV during loading response in the surgical limb, compared to the nonsurgical side, reported a high level of fear on the TSK-11. Altogether, these findings suggest that patients with a high level of fear of reinjury are likely to show gait asymmetry after ACLR. Future studies should investigate whether reducing the level of fear of reinjury during rehabilitation would improve SAV symmetry during running, or whether addressing running SAV asymmetry would reduce the level of fear of movement or reinjury.

The results of the current study showed that the surgical side had reduced SAV during loading response of walking, when compared to the non-surgical side at 6 months post-ACLR. Consistent with these findings, interlimb asymmetry in SAV during walking was reported at 3 months following surgery.[99, 100] Together, these findings may suggest that SAV asymmetry during walking are indicative of altered shank kinematics that can persist for up to 6 months following ACLR.[99, 100] It is likely that reduced SAV during walking on the involved limb may be linked to knee stiffness strategies that are adopted by some patients after ACLR.[99, 100] These knee strategies are characterized by lower knee flexion angle and knee extensor moment.[99, 100] Further, the results of the current study added to previous studies[99, 100] that SAV asymmetry was more evident during walking fast and running with larger effect sizes than that of normal walking

(Table 5.2). However, it should be noted that the associations between SAV during walking fast and running with commonly reported knee biomechanical deficits in patients with ACLR are still unknown. Therefore, these results warrant further investigations to determine the accuracy SAV asymmetry in identify patients with altered knee biomechanics that are linked to knee degenerative changes.

This study has some limitations. First, we did not include patients who had bilateral ACLR or ACL revisions. Therefore, the results of this study cannot be generalized to all patients who undergo ACLR. In addition, this was a cross-sectional study and therefore it does not establish potential cause-and-effect relationships between the studied variables. However, these results may provide valuable information for future research. Lastly, whether asymmetry in SAV during gait is clinically meaningful warrant future investigations to find the link between this variable and the risk of developing knee OA or a second ACL injury.

Conclusion

At 6 months post-ACLR, the results of this study showed that asymmetry in shank kinematics, measured by inertial sensors, at different gait speeds were related to quadriceps strength and functional measures. Patients with greater side-to-side asymmetries during loading response of walking, walking fast, and running demonstrated greater interlimb asymmetries in isometric quadriceps strength and the 4 single-leg hop tests. In addition, patients with greater SAV asymmetry during running had a higher level of self-reported fear of re-injury. Therefore, the level of association between gait asymmetry, measured by inertial sensors, and quadriceps strengthening and hop tests may offer clinicians with inexpensive, fast, and objective evaluation to identify patients with side-to-side strength and movement asymmetry at the time for the return to sport/activity following ACLR. Future studies need to investigate whether increasing quadriceps strength would reduce SAV during loading response of gait. Furthermore, future research should determine whether decreasing the level of fear of re-injury would reduce SAV running symmetry, or vise visa.

Table 5. 1. Demographic characteristics, RTSc, and patient-reported fear of re-injury.

	Patients with ACLR (N=17) Mean±SD
Age, y	27.87±7.42
Gender, female/male, n	9/8
Height, cm	173.06±10.77
Weight, kg	78.44±18.62
BMI, kg/m^2	25.37±3.37
Autograft type, n	
Bone-patellar tendon-bone	2
Hamstring	15
Preinjury Tegner activity score (0-10)	7.40±1.50
KOS-ADLS, %	93.69±3.19
GRS, %	83.65±12.16
Q-LSI, %	88.28±19.12
Single hop, %	84.91±16.39
Triple hop, %	86.88±11.72
Triple-crossover hop, %	87.19±14.22
6-m timed hop, %	94.55±11.69
TSK-11	18.47±4.85

Abbreviations: ACLR, anterior cruciate ligament reconstruction; BMI, body mass index; GRS, global rating scale of perceived function; KOS-ADLS, Knee Outcome Survey–Activities of daily living subscale; Q-LSI, quadriceps limb symmetry index; TSK-11, Tampa Scale of Kinesiophobia.

Table 5. 2. Interlimb differences in shank angular velocity at different gait speeds (mean±SD).

Mean interlimb SAV differences	Surgical limb	Non-surgical limb	Mean difference	p Value	Effect size
Walking (rad/s)	-2.88±0.35	-3.15±0.34	0.27	.002	0.78
Walking fast (rad/s)	-3.86±0.42	-4.31±0.45	0.46	.001	1.03
Running (rad/s)	-6.35±0.79	-7.11±0.62	0.76	<.001	1.07

Abbreviations: SAV, shank angular velocity; Rad/s, radian per second.

Table 5. 3. One-tailed Pearson's correlations of interlimb differences in shank angular velocity at different gait speeds with return-to-sport criteria and patient-reported fear of movement/re-injury.

Mean interlimb SAV differences	KOS-ADL	GRS	Q-LSI	Single hop	Triple hop	Triple-crossover hop	6-meter timed hop	TSK-11
Walking	-.103	-.402	-.764**	-.470*	-.622**	-.654**	-.508*	.371
Walking fast	-.158	-.424*	-.781**	-.799**	-.859**	-.796**	-.700**	.358
Running	-.102	-.259	-.658**	-.696**	-.621**	-.433*	-.604*	.439*

Abbreviations: SAV, shank angular velocity; KOS-ADL, The Knee Outcome Survey-Activities of Daily Living Score; GRS, the Global Rating Scale of Perceived Function; Q-LSI, quadriceps limb symmetry index; TSK-11, the Tampa Scale of Kinesiophobia 11-item.

**. Correlation is significant at the 0.005 level (1-tailed).

*. Correlation is significant at the 0.05 level (1-tailed).

Figure 5. 1. Isometric quadriceps strength test. The set-up configuration for a modified belt-stabilized hand-held dynamometer.

Chapter 6: Conclusion

Following anterior cruciate ligament reconstruction (ACLR), recent reviews indicate that walking and running deficits may persist for months or even years following surgery, which could potentially contribute to the development of knee degenerative changes.[23, 42, 43] In gait analysis studies, biomechanics of lower limbs, particularly the knee joint, are commonly assessed using motion capture systems and force plate technology. Although those measurement systems are considered the gold standard for gait analysis, their implementation in clinical settings is difficult, due to the high cost, complicated procedures, and large space requirements. Therefore, many clinicians may rely on visual observations to detect gait deviations in individuals with ACLR. However, assessing gait by visual observation is subjective and cannot objectively determine the amount of differences in kinematics or kinetics of the involved limb, when compared to the contralateral limb or the limb of healthy uninjured subjects.

In recent years, many studies suggested that inertial sensors (i.e., accelerometers and gyroscopes) can be used as an alternative gait assessment tool, due to their low cost and clinical applicability.[150] In patients with ACLR, lower trunk and shank kinematics were found to be altered during walking within few months following surgery.[89, 99, 100] To build upon the findings of previous studies, this dissertation work covers three main components. First, a triaxial accelerometer was used to compare differences in lower trunk accelerations at different gait speeds overtime during rehabilitation in patients with ACLR as well as between ACLR patients and healthy controls. Second, between-limb asymmetry in sagittal plane shank angular velocity at different gait speeds was assessed over time in patients with ACLR. Third, the association of trunk accelerations and shank angular velocity with patients' functional and psychological factors were investigated. All testing procedures were conducted in a local orthopedic out-patient setting during patients' regular visits with their surgeons. A conclusion for each aim is covered in the following sections.

Conclusion for Chapter 2

In this longitudinal study, we compared changes in gait smoothness, calculated as normalized jerk (NJ) of trunk accelerations, at different speeds measured over time in patients with ACLR and between the ACLR and healthy control groups using accelerometry. Movement smoothness during walking and walking fast was assessed at 2, 4, and 6 months after ACLR, while running smoothness was assessed at 4 and 6 months. We hypothesized that these patients would show lower gait smoothness (higher NJ) at the early stage of rehabilitation (2-month), when compared to the later stage of rehabilitation and healthy controls. We also hypothesized that the ACLR group would gradually show higher gait smoothness (lower NJ) across time, approaching a similar movement smoothness as healthy subjects at the later stage of rehabilitation (6-month).

In agreement with our first hypothesis, the results of this study showed that the ACLR group had higher NJ values (less smoothness) in the vertical, mediolateral, and anteroposterior directions during walking and in the vertical and mediolateral directions during walking fast at the early stage of rehabilitation, when compared to the later stage of rehabilitation and control group. Our second hypothesis was partially fulfilled where we found that walking smoothness (in all directions) and walking fast smoothness (in the mediolateral and anteroposterior directions) of the ACLR group were comparable to those of the control group at 6 months post-surgery. On the other hand, running smoothness (in all directions) of the ACLR group neither improved across time nor approach running smoothness of the control group.

Overall, patients with ACLR showed lower movement smoothness during walking and walking fast at the early stage of rehabilitation that was improved over time, when compared to the later stage of rehabilitation and healthy subjects. At 6 months post-ACLR, patients walked and walked fast (except in the vertical direction) with similar smoother patterns as healthy subjects. Improvements in knee function throughout rehabilitation might have contributed to the increased in movement smoothness seen during walking and walking fast in patients with ACLR. However, when patients performed a higher demanding activity that involves more knee range of motions and muscle activities such as running, they showed less movement smoothness that did not improve with time and did not reach running smoothness of control subjects at 6 months after surgery.

As gait speed increases, the impact of foot strike to the ground increases, leading to higher running-related accelerations. Therefore, running with less smoothness could be attributed to the inability of the involved knee to absorb high impact, when compared to normal walking. Future studies with a longer follow up period (> 6 months) should investigate when patients with ACLR may run with smoother patterns as healthy uninjured individuals. In addition, the associations between gait smoothness and patients knee biomechanics should be investigated too.

Conclusion for chapter 3

In this study, we investigated whether patients with ACLR would show significant and meaningful between-limb SAV asymmetries at different gait speeds at 4 and 6 months post-surgery. Between-limb asymmetry in sagittal plane SAV was measured during loading response of gait at 4 and 6 months post-surgery. The hypothesize was that patients with ACLR would present with significant and meaningful between-limb asymmetries during walking, walking fast, and running and these asymmetries would decrease over time. To examine whether these SAV asymmetries were considered as "abnormal asymmetries", data from healthy uninjured control subjects were used to estimate the smallest meaningful between-limb differences for SAV for each gait speed.

The results of this study confirmed our first hypothesis in which the surgical limbs had significantly smaller SAV during loading response of walking, walking fast, and running at 4 and 6 months post-ACLR, when compared to the non-surgical limbs. However, between-limb differences in SAV at all gait speeds tended to decrease from 4 to 6 months, but they did not reach statistical significance. In addition, our results showed that patients had meaningful SAV asymmetries for all gait tasks at both testing times. Overall, patients with ACLR had significant and meaningful SAV asymmetries between the involved and uninvolved limbs during walking, walking fast, and running at 4 and 6 months following surgery.

Consistent with our findings, previous studies found that patients walked with smaller SAV during loading response in the surgical limbs, compared to the non-surgical limbs, at an average of 3 months after ACLR.[99, 100] These studies found that SAV during walking was correlated with knee flexion angles, knee extensor moment, and vertical and posterior ground reaction forces. Therefore, walking with asymmetrical SAV in the current study may be related to the biomechanical deficits reported in the previous studies. In addition, the results of the present study expanded the knowledge on SAV-based ACLR research showing that patients walked fast and ran with larger between-limb differences in SAV, when compared to normal walking. However, it is unknown whether increased asymmetries in SAV at faster gait speeds would be associated with increased asymmetries in other important biomechanical measures that are commonly observed in the sagittal plane in this population, such as knee flexion angles and knee extensor moment. Furthermore, whether SAV asymmetry during gait is related to the development of knee osteoarthritis is still unknown. Therefore, future studies should investigate those potential associations.

Conclusion for chapter 4

In this study, we investigated whether gait smoothness, calculated as normalized jerk (NJ) of trunk accelerations, would be associated with patients' functional and psychological measures at 6-month post-ACLR. We hypothesized that gait smoothness during gait would be correlated with functional and self-reported fear of reinjury measures.

Our hypothesis was partially supported in that walking with higher NJ values (less smoothness) in the VT was moderately correlated with asymmetrical performance on three single-leg hop tests: single-leg hop for distance, triple hop for distance, and triple-crossover hop for distance. In addition, higher NJ values in the AP direction during walking were moderately correlated with asymmetries in quadriceps strength and single-leg hop for distance test. No associations were found between any functional measures and movement smoothness during walking fast and running. On the other hand, running with higher NJ values in the VT and AP directions were moderately correlated with a lower level of patient-reported fear of movement/re-injury.

To our knowledge, this was the first study to investigate the associations between gait smoothness at different speeds and patients' functional and psychological measures at 6 months after ACLR. Typically, knee range of motions and quadriceps contraction play a major role in absorbing shock and attenuating gait-related accelerations that resulted from the foot contact with the ground. Previous studies showed that knee kinematics in the sagittal plane during the stance phase of walking was associated with quadriceps strength. In the current study, the results showed that walking smoothness in the sagittal plane was moderately associated with quadriceps strength. In addition, higher walking smoothness in the horizontal and sagittal planes was moderately associated with the single-leg hop for distance test. The lack of associations between movement smoothness during walking fast and running with the studied functional variables suggests that other deficits such as those related to lower limb biomechanical factors might have contributed to altered lower trunk accelerations during these gait tasks. For instance, a previous study found that running with less knee flexion angles during the stance phase increased trunk accelerations in healthy subjects, which could potentially lead to running-related injuries. Smaller knee flexion angles are also commonly reported during running in patients with ACLR and therefore future studies are needed to investigate the association between knee biomechanics and running smoothness.

In the current study, lower running smoothness was moderately correlated with a lower level of patient-reported fear. A possible explanation for this finding could be that having good patient-reported knee function might have led some patients to report a lower level of fear of movement/reinjury. This, in turn, might have led some of these patients to not worry about their involved knee and ran without optimizing their movement smoothness. Even with reporting a lower level of fear, running with less smoothness may lead to running-related injuries in the long term. However, future studies are needed to investigate this premise in patients with ACLR.

Conclusion for chapter 5

In this chapter, we investigated whether sagittal plane SAV during loading response of gait at different speeds correlates with quadriceps strength, functional measures, and patient-reported fear of re-injury at 6 months post-ACLR. The hypothesis was that patients who showed greater interlimb asymmetries in SAV would demonstrate poor performance on RTSc and a high level of self-reported fear of reinjury.

Our hypothesis was confirmed in that greater asymmetries in peak SAV during walking, walking fast, and running were moderately to strongly correlated with greater asymmetries in isometric quadriceps strength and 4 single-leg hop tests (single-leg hop, triple hop, triple-crossover hop, and 6-meter timed hop). In addition, asymmetry in peak SAV during running was moderately correlated with the Tampa Scale for Kinesophobia-11.

The results of this study indicate that asymmetries in SAV at different gait speeds were related to asymmetries in quadriceps strength and hop tests, with moderate to strong strength. A faster rotation of the shank in the sagittal plane during loading response of gait allows the tibia to advance faster than the thigh, resulting in knee flexion and eccentric quadriceps contraction. Therefore, the findings of the current study are consistent with findings of previous studies that found a relationship between knee flexion angles and quadriceps strength during walking in patients with ACLR. In addition, our results suggest that patients who showed asymmetries in SAV during less challenging tasks such as walking and running may show asymmetrical performance while performing higher challenging tasks such as hop tests. Furthermore, running with asymmetrical SAV was associated with a higher level of patient-reported fear of re-injury.

This chapter provided some clinical relevance for altered shank kinematics in individuals with ACLR. In previous studies, SAV during normal walking was found to be correlated with knee flexion angles, knee extensor moment, and vertical and posterior ground reaction forces in patients with ACLR. In the current study, we found that SAV asymmetry during walking was moderately to strongly correlated with quadriceps strength and hop tests. Altogether, these findings suggest that having SAV asymmetry during walking may be related to deficits in knee biomechanics, quadriceps weakness, and poor performance on hop tests. Future studies are needed to investigate associations between SAV during walking fast and running with other important knee biomechanical deficits such as knee flexion angles, knee extensor moment, and ground reaction forces.

Clinical relevance

Inertial sensors are an inexpensive and practical gait assessment technology that allowed this research project to be conducted in clinical settings during patients' regular visits to their surgeons. Using these sensors, the results of this project indicate that patients with ACLR had altered movement smoothness during running as well as asymmetry in shank kinematics at different gait speeds that persisted for up to 6 months post-surgery. In addition, the findings of this project indicate that a higher walking smoothness was related to higher symmetries in quadriceps strength and three single-leg hop for distance tests. Furthermore, we found that higher between-limb symmetries in shank kinematics during walking, walking fast, and running were related to higher symmetries in quadriceps strength and four single-leg hop tests. We also found that higher asymmetry in shank kinematics during running was related to a high level of fear of movement/reinjury. Put together, these findings, along with findings of past studies[89, 99, 128], support the use of inertial sensors as an objective gait assessment tool that can be used to identify altered gait patterns in patients with ACLR in clinical settings. Future studies with larger sample sizes should investigate the diagnostic accuracy of inertial sensor measurements in identifying ACLR patients with weak quadriceps strength and knee biomechanical deficits (e.g., knee flexion angle and knee extensor moment). Most importantly, and as the prevalence of knee re-injury and OA is alarmingly high in this population, future studies should determine the diagnostic accuracy of inertial sensor measurements in detecting patients with ACLR who are at risk of reinjury and OA.

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