KINESIOPHOBIA, WALKING BIOMECHANICS AND FREE-LIVING CADENCE AMONG ADOLESCENTS AND YOUNG ADULTS FOLLOWING PRIMARY ANTERIOR CRUCIATE LIGAMENT RECONSTRUCTION

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PUBLIC ABSTRACT

Individuals with history of primary anterior cruciate ligament reconstruction (ACLR) demonstrate aberrant walking biomechanics such as reduced vertical ground reaction forces (vGRFs) and slow gait speed. These mechanics are related to indicators of poor knee joint health as early as only 6 months post-operative and have also been implicated in the development of knee osteoarthritis (OA). Elevated kinesiophobia is also commonly reported following anterior cruciate ligament (ACL) injury and ACLR, and among individuals with knee OA. As a result, we chose to investigate the association between walking biomechanics, free-living cadence, and kinesiophobia following primary ACLR.

In study 1, 65 participants underwent a walking biomechanics assessment to determine: 1) ACLR limb peak vGRF during the first 50% of stance, 2) Between-limb symmetry index for peak vGRF and 3) gait speed. Seventy-two percent of participants (47/65) were characterized as experiencing elevated injury-related fear 6 months following primary ACLR. Despite this prevalence of elevated injury-related fear, kinesiophobia was not significantly associated with ACLR limb first peak vGRF (P=0.634, F=0.230, ΔR^2=0.0021), first peak vGRF limb symmetry (P=0.589, F=0.295, ΔR^2=0.0048), or gait speed (P=0.856, F=0.0333, ΔR^2=.0005) among our sample. Our findings indicate that kinesiophobia may not have a significant influence on walking biomechanics early following surgery; perhaps other interventions such as real-time gait biofeedback may be more effective in addressing aberrant walking early following primary ACLR.

In study 2, 48 participants completed a laboratory and free-living assessment of walking characteristics. Laboratory-assessed gait speed was associated with peak 1-minute free-living cadence (r=0.444, P=0.002). ACLR peak vGRF was associated with

peak 1-minute free-living cadence ($r=0.331$, $P=0.025$). The findings of this study indicate a disconnect between average laboratory gait and average free-living gait. However, our results also suggest that participants who demonstrated faster walking speeds and greater ACLR limb peak vGRFs during their lab assessment also exhibited faster peak minute-level cadences in free-living conditions.

In study 3, 30 adolescents who were 6-9 months post primary, unilateral ACLR completed 1 week of free-living step count monitoring to determine average steps taken per day and cadence characteristics. Adolescents who reported elevated injury-related fear demonstrated slower mean light cadences ($F=9.518$, $P=0.005$, $\eta_p^2=0.268$) as compared to adolescents who reported acceptable injury-related fear. Management of elevated kinesiophobia 6-9 months following primary ACLR may provide an avenue to intervene on free-living light cadences among adolescents, with the goal of improving long-term knee joint and general health outcomes.

ABSTRACT

Aberrant walking biomechanics such as reduced vertical ground reaction forces (vGRFs) and slow gait speed are related to indicators of poor knee joint health as early as only 6 months following primary anterior cruciate ligament reconstruction (ACLR) and have also been implicated in the development of knee osteoarthritis (OA). Elevated injury-related fear (i.e., kinesiophobia) is commonly reported following anterior cruciate ligament (ACL) injury and ACLR, and among individuals with knee OA. It is postulated that individuals with knee OA may adapt their walking biomechanics and reduce their walking speed, and therefore cadence (i.e., steps taken per minute), in response to similar injury- or pain- related fear. As a result, it is critical to investigate the association between walking biomechanics, free-living cadence, and kinesiophobia following primary ACLR.

In the first study, 65 participants (age: 19.1 ± 5.4 years old, 55% female, 6.3 ± 1.6 months post-ACLR) underwent a walking biomechanics assessment to determine: 1) ACLR limb peak vGRF during the first 50% of stance, 2) Between-limb symmetry index for peak vGRF and 3) gait speed. Seventy-two percent of participants (47/65) were characterized as experiencing elevated injury-related fear 6 months following primary ACLR. Despite this prevalence of elevated injury-related fear, kinesiophobia was not significantly associated with ACLR limb first peak vGRF (P=0.634, F=0.230, ΔR^2=0.0021), first peak vGRF limb symmetry (P=0.589, F=0.295, ΔR^2=0.0048), or gait speed (P=0.856, F=0.0333, ΔR^2=.0005) among our sample. Our findings indicate that kinesiophobia may not have a significant influence on walking biomechanics early following surgery; perhaps other interventions such as real-time gait biofeedback may be more effective in addressing aberrant walking early following primary ACLR.

In study 2, 48 participants (age: 21.3 ± 6.0 years old, sex: 26 F/ 22 M (54% F), height: 174.0 ± 8.0 cm, mass: 77.5 ± 20.0 kg, time since ACLR: 13.9 ± 15.9 months, total monitor wear time: 5910 ± 2372 minutes) completed a laboratory and free-living assessment of walking characteristics. Laboratory-assessed gait speed was associated with peak 1-minute free-living cadence (r=0.444, P=0.002). ACLR peak vGRF was associated with peak 1-minute free-living cadence (r=0.331, P=0.025). The findings of this study indicate a disconnect between average laboratory gait and average free-living gait. However, our results also suggest that participants who demonstrated faster walking speeds and greater ACLR limb peak vGRFs during their lab assessment also exhibited faster peak minute-level cadences in free-living conditions.

In study 3, 30 adolescents who were 6-9 months post primary, unilateral ACLR completed 1 week of free-living step count monitoring to determine average steps taken per day and cadence characteristics. Nineteen adolescents (63.3%) were characterized as experiencing elevated injury-related fear and 11 adolescents (36.7%) were characterized as experiencing acceptable or low injury-related fear as described by a Tampa Scale of Kinesiophobia (TSK-11). Adolescents who reported elevated injury-related fear demonstrated slower mean light cadences (F=9.518, P=0.005, η_p^2=0.268) as compared to adolescents who reported acceptable injury-related fear. Management of elevated kinesiophobia 6-9 months following primary ACLR may provide an avenue to intervene on free-living light cadences among adolescents, with the goal of improving long-term knee joint and general health outcomes.

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CHAPTER 1: INTRODUCTION

STATEMENT OF THE PROBLEM

Osteoarthritis (OA) is a leading cause of disability and more than 27 million adults have been diagnosed with osteoarthritis in the United States.[1–3] Individuals who have sustained a traumatic knee injury, such as an anterior cruciate ligament (ACL) injury, are at a 4-6-fold increased risk of developing knee OA following primary ACL reconstruction (ACLR) as compared to those who have not experienced a knee injury.[4] This is especially concerning because more than half of individuals who experience an ACL injury and opt to undergo ACLR will develop knee OA within only 20 years of surgery. [5] This suggests that 50% of adolescents and young adults who undergo ACLR will have radiographic evidence of knee OA in their 30s or 40s, as compared to an incidence of only 19.2- 27.8% among adults > 45 years old, as reported in the Framingham Study and Johnston County Osteoarthritis Project, respectively. [2,3]

Repetitive, aberrant mechanical loading of the knee is a known contributor to development of idiopathic and posttraumatic knee OA.[6–9] Aberrant walking biomechanics and slow gait speed are related to indicators of poor knee joint health as early as only 6 months following primary ACLR and have also been implicated in the development of knee OA. Elevated injury-related fear (i.e., kinesiophobia or fear of movement/ injury) is commonly reported following ACL injury and ACLR, and among individuals with knee OA. It is postulated that adults with knee OA adapt their walking biomechanics and reduce their walking speeds, and therefore cadences (i.e., number of steps taken each minute), or engagement in physical activity in response to injury- or pain- related fear. As a result, it is critical to investigate the association between walking biomechanics, free-living cadence, and kinesiophobia following ACLR because this is a clinical population that is at increased risk of knee OA development. Therefore, the purpose of this dissertation is three-fold: 1. To determine the associations between kinesiophobia and walking biomechanics 6 months post-ACLR, 2. To assess the associations between laboratory-assessed gait speed, ACLR limb peak vGRF, and peak vGRF symmetry with free-living cadence characteristics among individuals with ACLR, and 3. To compare free-living cadence characteristics and step counts between adolescents who report elevated and acceptable injury-related fear within the first year of ACLR.

Successful completion of manuscript 1 will identify a clinically feasible and patient-reported outcome that may help to identify individuals with ACLR that may benefit from intervention to improve walking biomechanics related to knee OA and reduce elevated kinesiophobia. Successful completion of manuscript 2 will address a critical gap in identifying the relationship between free-living cadence and laboratory-assessed walking biomechanics and gait speed, which may influence future intervention implementation aimed at improving knee joint loading and gait speed in free-living conditions among individuals with ACLR. Lastly, successful completion of manuscript 3 will help to identify whether elevated kinesiophobia, which has been identified as a barrier to return to pre-injury physical activity following ACLR and has been implicated in aberrant and slow walking among individuals with knee OA, influences free-living ambulationamong adolescents with ACLR.

STATEMENT OF THE PURPOSE

Individuals who have undergone ACLR demonstrate aberrant knee joint loading and walking biomechanics that are related to knee OA development.[9,10] In addition, individuals with ACLR and knee OA exhibit elevated kinesiophobia that has been related to reduced self-reported physical activity engagement and may be negatively impacting participation in certain movements or activities as described by the Fear Avoidance Model.[11,12] It is postulated that individuals with knee OA demonstrate activity avoidance and may adapt their walking mechanics or reduce their walking speed, and therefore cadence, in response to injury- or pain- related fear. When considering these associations and the increased risk for knee OA following ACLR, it may be beneficial to investigate the association between walking biomechanics, free-living cadence, and kinesiophobia. Therefore, the purpose of this dissertation is three-fold: 1. To determine the association between kinesiophobia and walking biomechanics among individuals who had undergone ACLR 6 months prior, 2. To evaluate the association between laboratory-assessed ACLR limb biomechanics and walking speed with and free-living cadence characteristics, as cadence is related to gait speed and ambulation patterns across clinical populations, and 3. To compare free-living cadence characteristics and step counts between adolescents who report elevated and acceptable injury-related fear 6-9 months post-ACLR.

Kinesiophobia is often referred to as injury-related fear and is reported to be elevated among individuals with ACLR and knee OA.[13–16] In fact, individuals with ACLR who demonstrate elevated injury-related fear are at increased risk of second ACL injury, are less likely to return to pre-injury levels of sport or physical activity participation and may exhibit lower extremity biomechanics different from individuals with acceptable levels of kinesiophobia.[16,17] Individuals with knee pathology such as knee OA who exhibit elevated injury-related fear also engage in less physical activity, walk more slowly, and may reduce participation in physical activity or forgo engaging in certain movements (e.g., walking) due to this fear.[11–13,18] For example, Hart and colleagues identified that individuals with diagnosed lateral knee OA following ACLR exhibit aberrant gait adaptations, such as greater trunk flexion during walking, which were related to elevated kinesiophobia.[12] Consequently, individuals with elevated kinesiophobia may adapt aberrant walking biomechanics in response to this reported elevated injury-related fear. However, the association between walking biomechanics and injury-related fear among individuals 6 months post-ACLR, a clinical timepoint that is associated with elevated injury-related fear and a return to at least modified sports activity,[19] is unclear. Therefore, the purpose of manuscript 1 is to examine the association between patient-reported injury-related fear and laboratory assessed walking biomechanics among individuals 6 months post-ACLR.

Fewer weekly minutes spent in moderate-to-vigorous intensity cadences (≥ 100 steps/ minute), reduced daily step counts and reductions in gait speed have all been identified among individuals with and at-risk for knee OA development. [20,21] It has been suggested that these reductions in physical activity engagement (i.e., step counts) and gait speed, which influence reductions in cadence, may result from aberrant biomechanical adaptations.[11,12] These adaptations may be employed to reduce or avoid pain as briefly described above. As cadence is considered a spatiotemporal parameter of gait speed, it may serve as a clinically feasible avenue to evaluate and intervene on ambulation speeds and patterns under free-living conditions. Consequently, there is a need to identify the relationship between laboratory-assessed walking biomechanics and gait speed, and free-living cadence among this clinical population that is at increased risk of knee OA development. Therefore, the purpose of manuscript 2 is to examine the relationship between laboratory assessed walking biomechanics and gait speed, with free-living cadence characteristics among individuals with history of primary ACLR.

As briefly described above, elevated injury-related fear is commonly reported within the first year of ACLR. Elevated kinesiophobia is related to an increased risk of second ACL injury and has been identified as a primary barrier to return to pre-injury sport and physical activity participation. This is an important consideration for adolescents who are at risk of experiencing the negative consequences of knee OA early in the lifespan. It is postulated that individuals with knee OA may reduce their step counts and walking speed, and therefore cadence, in response to injury- or pain- related fear. As a result, it is critical to investigate the association between free-living cadence and activity (i.e., step counts) with kinesiophobia 6 months following primary ACLR because it is a timepoint that is often associated with elevated kinesiophobia and a return to modified or unrestricted sport and physical activity participation.

Manuscripts 1-3 of this dissertation address current gaps in the literature surrounding: 1) patient-reported indicators of aberrant walking biomechanics related to knee OA development early following ACLR, 2) the relationship between free-living cadence and laboratory-assessed gait speed and walking biomechanics among individuals with ACLR, and 3) the role of patient-reported outcomes and free-living living ambulation related to gait speed following ACLR. Completion of these studies may help to inform future research and clinical interventions aimed at addressing kinesiophobia, walking biomechanics, gait speed or cadence among individuals at risk of experiencing the negative consequences of poor knee joint health and knee OA development.

RESEARCH QUESTIONS AND HYPOTHESES

MANUSCRIPT 1 RESEARCH QUESTIONS AND HYPOTHESES

Primary Purpose: The primary purpose of this study is to assess the association between ACLR limb walking biomechanics (i.e., peak vertical ground reaction forces; peak vertical ground reaction force between-limb symmetry) and gait speed, and patient-reported kinesiophobia among individuals 6 months post-ACLR.

H 1.1: The primary hypothesis is that adults and adolescents who report elevated kinesiophobia (i.e., injury-related fear) will demonstrate lesser ACLR limb vertical ground reaction forces, greater between-limb loading asymmetry during the first half of the stance phase of walking, and slower gait speeds as compared to individuals who report acceptable kinesiophobia as assessed with the Tampa Scale of Kinesiophobia.

MANUSCRIPT 2 RESEARCH QUESTIONS AND HYPOTHESES

Primary Purpose: The primary purpose of this study is to assess the association between laboratory-assessed gait speed, ACLR limb peak vertical ground reaction forces, and ACLR limb peak vertical ground reaction force limb symmetry indices and free-living cadence characteristics (i.e., mean daily cadence, mean light cadence, mean light-to-moderate cadence, and peak cadence) among individuals with history of primary ACLR.

H 2.1: The primary hypothesis is that laboratory-assessed gait speed and walking vertical ground reaction forces will be associated with mean free-living cadence outcomes among individuals with history of primary, unilateral ACLR.

MANUSCRIPT 3 RESEARCH QUESTIONS AND HYPOTHESES

Primary Purpose: The primary purpose of this study is to assess the association between free-living cadence characteristics (i.e., mean daily cadence, mean light cadence, mean light-to-moderate cadence, and peak cadence) and daily step counts, with patient-reported kinesiophobia among adolescents 6 months post-ACLR.

H 3.1: The primary hypothesis is that adolescents who report elevated injury-related fear (i.e., kinesiophobia) as assessed with the Tampa Scale of Kinesiophobia will exhibit reduced daily step counts and slower free-living cadences as compared to adolescents with acceptable injury-related fear.

SIGNIFICANCE OF THE STUDY

Aberrant mechanical loading, including limb under- and over- loading have been related to knee OA severity and development, respectively. Individuals with ACLR demonstrate aberrant laboratory-assessed walking biomechanics related to knee OA[10,22,23], walk at slow gait speeds that have been related to poor knee joint health, and engage in less moderate-to-vigorous intensity physical activity and ambulation as compared to uninjured peers.[24–26] In addition, individuals with ACLR and knee OA exhibit elevated kinesiophobia that has been related to aberrant lower extremity biomechanics, slow gait speeds and reduced self-reported physical activity engagement. This elevated kinesiophobia is postulated to be negatively impacting participation in certain movements or activities among individuals with knee OA and ACLR.[11,12] In fact, individuals with knee OA may adapt their walking biomechanics and reduce their walking speed and cadence in response to this elevated fear. This highlights the critical need to investigate the association between walking biomechanics, free-living cadence, and kinesiophobia among individuals early following ACLR, while they may still be engaged in rehabilitation and receptive to intervention.

Kinesiophobia or greater injury-related fear has been related to aberrant walking mechanics, slow gait speeds, and reduced self-reported physical activity engagement among individuals with or at risk of developing knee OA.[12,18] Despite these identified associations, there are limited investigations examining the influence of injury-related fear on walking biomechanics at a critical clinical timepoint post-ACLR. Therefore, manuscript 1 of this dissertation is significant because it will examine the relationship between injury-related fear and walking mechanics among individuals 6 months following ACLR, contributing to limited investigations of kinesiophobia and walking at this timepoint. Upon successful completion of this study, a low-cost, patient-reported outcome measure may be implemented to help identify individuals who may benefit from psychologically informed and/ or gait-retraining interventions early following surgery. Therefore, when considering aberrant walking biomechanics are related to knee OA development, identifying individuals with ACLR with elevated injury-related fear and aberrant mechanics may help to address these negative adaptations and mitigate the long-term consequences of knee OA development.

Aberrant laboratory-assessed walking biomechanics that have been related to knee OA development have been identified among individuals with ACLR.[9,10] However, these investigations are limited because they are not necessarily representative of free-living gait and ambulation. In addition, while these walking biomechanics may be able to identify the magnitude of limb loading and provide a snapshot of walking mechanics, they fail to capture the frequency of limb loading in free-living conditions. Therefore, manuscript 2 of this dissertation is significant because it will evaluate the association between laboratory-assessed walking biomechanics and gait speed and free-living cadence characteristics. Successful completion of this study will contribute to the limited investigations of free-living cadence among individuals with ACLR. In addition, this study is significant because it will address a critical gap in the literature identifying the association between free-living and laboratory gait characteristics. Successful completion of this study may impact future research interventions or clinical care addressing limb loading, gait speed or cadence in order to promote long-term knee joint health among this at-risk population.

Despite the identified associations between slow gait speeds, aberrant walking mechanics and reduced physical activity with elevated injury-related fear, there are no investigations examining the influence of injury-related fear on free-living cadence and step counts at a critical clinical timepoint post-ACLR.[12,18] Therefore, manuscript 3 of this dissertation is significant because it will examine the relationship between injury-related fear and free-living cadence among adolescents 6 months following ACLR. This is significant because there are no investigations of cadence among adolescents with ACLR and there are no investigations of the relationship between kinesiophobia and free-living cadence post-ACLR to our knowledge. Six months post-ACLR is also a timepoint where kinesiophobia is reported to be elevated and it is often associated with cessation of rehabilitation and a return to modified or even unrestricted sports participation. Upon successful completion of this study, a low-cost, patient-reported outcome measure may be implemented to help identify individuals who may benefit from psychologically informed and/ or wearable-device cadence interventions early following surgery. Therefore, when considering reductions in gait speed and cadence are related to knee OA development, identifying individuals with ACLR with elevated injury-related fear and reduced cadences may help to address these negative adaptations and mitigate the long-term consequences of knee OA development.

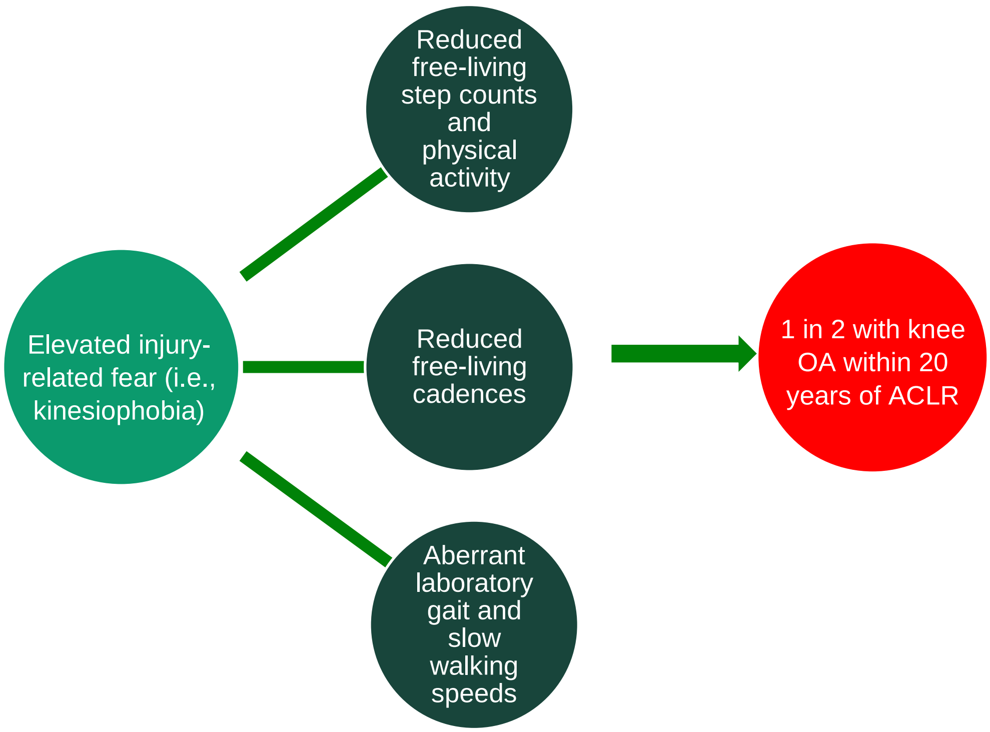
Completion of studies 1-3 presented in this dissertation may provide greater understanding of how kinesiophobia is related to knee joint loading and cadence post-ACLR and how these laboratory-assessed mechanics are related to free-living activity and cadence. In summary, study 1 may influence and help to inform future research or clinical interventions aimed at identifying individuals early following ACLR who may benefit from psychosocial and/ or gait retraining interventions. Study 2 may help to inform future interventions aimed at improving walking biomechanics, gait speed or cadence, and even intensity of ambulation or activity, in free-living conditions outside of the laboratory environment. Finally, study 3 may also help to inform future interventions or research aimed at helping to identify adolescents who may benefit from psychosocial and/ or wearable-device cadence interventions to improve ambulation post-ACLR.

CHAPTER 2: REVIEW OF THE LITERATURE

INTRODUCTION

This literature review will address knee joint anatomy, factors related to primary ACL injury, basic ACLR procedure and factors related to second ACL injury. Next, this review will address considerations for return to sport, age and maturation, and biological sex among individuals with ACLR. Additionally, this review will summarize current ACLR rehabilitation practice in the United States and common clinical outcomes assessed following ACL injury and ACLR. Finally, this review will summarize walking biomechanics, kinesiophobia, and free-living cadence among individuals with history of knee pathology including ACLR and knee OA as described in Figure 1.

Figure 1. Kinesiophobia and Mechanical Contributors to Knee OA Following Primary ACLR



It is postulated that individuals with knee OA respond to injury-related fear through biomechanical adaptations that have resulted in aberrant walking biomechanics, slow gait speeds, and thus reduced cadences, as well as inadequate physical activity participation and reduced step counts. This is concerning because elevated injury-related fear, aberrant walking, slow gait speeds and reduced steps and cadences have all been observed among individuals with ACLR who are at increased risk of knee OA development.

ACLR=anterior cruciate ligament reconstruction, OA=osteoarthritis

EPIDEMIOLOGY OF ANTERIOR CRUCIATE LIGAMENT INJURY AND ACLR

Knee Joint Anatomy

Four bones form the bony anatomy of the knee joint, including the femur, tibia, fibula, and patella. The first articulation of the knee joint is between the femur and tibia and the second articulation is between the patella and the patellar surface of the femur. However, the anatomy of the skeletally immature knee is different from the mature, adult knee. The distal femur and proximal tibia each have active physis for continued growth. The tibial tubercle is also associated with an apophysis, for active growth. The immature ACL attaches at the distal femoral chrondral epiphysis and the perichondral cuff of the tibial epiphysis.[27] Functional anatomy of the immature knee is different when compared to the mature knee, indicated by an open epiphyseal plate, which may influence management of this injury.

The musculature of the knee joint can be divided into knee flexors and extensors. The knee flexors are primarily the hamstrings muscle group (i.e., biceps femoris, semimembranosus, and semitendinosus) sartorius, and popliteus muscles. The knee extensors are the quadriceps muscle group, including the rectus femoris, vastus lateralis, vastus medialis, and vastus intermedius. There are seven total ligaments that aid in stabilization of the knee joint. The four main ligaments of the knee joint are the anterior cruciate ligament (ACL), the posterior cruciate ligament (PCL), the medial (tibial) collateral ligament (MCL) and lateral (fibular) collateral ligament (LCL). The anterior cruciate ligament (ACL) is primarily located in the knee joint capsule and attaches from the intercondylar region of the tibia to the condyles of the distal femur.[28]

There are mainly two bundles of the ACL, the anteromedial (AMB) and the posterolateral (PLB) bundles. The AMB is taut in flexion, and lax in extension, whereas the PLB is taut in extension and lax in flexion. Both bundles of the ACL experience load sharing and contribute to knee joint stability. The AMB and PLB work to limit anterior translation relative to the tibia.[29–33] The primary purpose of the ACL is to resist anterior tibial translation and internal tibial rotation at the knee joint. The ACL is innervated by the tibial nerve and is robust with mechanoreceptors. Mechanoreceptors are receptor cells related to changes in mechanical forces, encapsulating afferent fibers. With a stimulus, these afferent fibers generate action potentials, sending information to the central nervous system regarding joint mechanics and the integration of somatosensory, vestibular, and visual information. Mechanoreceptors account for approximately 2.5% of the ACL and are mostly located in the femoral and tibial ends of the ligament. The ACL contains three types of mechanoreceptors in addition to free nerve endings. The three types of mechanoreceptors in the ACL include Ruffini-like receptors, Golgi-tendon organs and Pacini-like corpuscles. Ruffini afferents are slowly adapting, low threshold fibers that are particularly sensitive to cutaneous stretching and track the movement and position of the joint. Golgi-tendon organs are high-threshold, slowly adapting receptors in the ACL that send information to the central nervous system regarding changes in tension at the joint. Pacinian corpuscles are low-threshold, rapidly adapting fibers that detect vibration and signal joint acceleration. Loss of mechanoreceptors following ACL injury has been related to negative consequences such as arthrogenic muscle inhibition due to a lack of motor unit recruitment.[34–36]

Primary ACL Injury

Annually in the United States there are an estimated 150,000 to 250,000 anterior cruciate ligament (ACL) injuries, with approximately 60-80% accounting for sport or physical activity related injuries.[37] Patients with ACL injury experience knee instability, culminating in poor knee function that may limit activities of daily living and reduce physical activity participation. Average incidence of ACL injury across age groups and sexes is estimated to be more than 68.6 per 100,000 (person-years).[38] ACL injury is commonly experienced during sport participation and may be due to contact or non-contact mechanisms, with contact injuries being most highly reported among male, high-school aged (i.e., 14-18 years old) athletes.[39] Incidence of ACL injury continues to increase due to the greater participation of young individuals (i.e., pediatric, adolescent) and females across sport types.[39–41] While adolescents and young adults experience the largest number of ACL injuries in the United States,[37] sex, sport participation type, and a variety of other modifiable and unmodifiable risk factors can influence risk of experiencing an ACL injury.[42] While physically mature males experience the greatest incidence of ACL injuries, women have a higher rate of non-contact ACL injuries in sex-comparable sports. In fact, incidence of ACL injury is highest among female soccer and basketball players with relative risks between 2.53-5.85 and among male football players regardless of age (273 per 100,000). [41] Between sexes, men have the highest incidence of ACL injury between the ages of 19 and 25 years old (i.e., collegiate) and women have the highest incidence of ACL injury between the ages of 14 and 18 years old (i.e., high school ages).[40,41] Age of the patient at the time of ACL injury and patient biological sex may play a significant role in risk for primary ACL injury.

Primary ACLR and Influence of Graft Source

In the United States, ACL injury is often followed by surgical reconstruction (ACLR) in order to restore knee joint stability and enhance long-term function. ACLR is performed arthroscopically using transphyseal tunneling and a graft reconstruction technique, typically an autograft of one of the hamstring tendons or a patellar tendon graft. Two reconstruction techniques are referred to as either single bundle or double bundle repair.[30,31] Single bundle repair of the ACL reconstructs only the anteromedial bundle. Double bundle repair, however, reconstructs both the anteromedial and posteromedial bundles. At the time of ACLR, concomitant procedures may also occur if other structures within the knee have sustained injury (e.g., meniscal repair or meniscectomy, other ligament repair). It should be noted that other surgical considerations (i.e., meniscal involvement, other ligament injury, etc.) can significantly influence patient post-operative outcomes including rehabilitation timelines and patient-reported knee function. For the purposes of this review, we will review two common reconstruction graft source materials and their relationship with patient-reported and functional outcomes following ACLR.

There is evidence that hamstring graft failure rate is higher than patellar tendon graft failure during the first several years post-ACLR.[43,44] However, this evidence is conflicting, with the exception that allograft sources have higher failure rates than autograft sources.[45] Moreover, individuals with patellar tendon grafts also tend to have greater rehabilitative delays related to healing and surgical damage when compared to those with hamstring graft sources that may persist long-term.[46] This is supported by clinical imaging based evidence that hamstring autografts mature better within the first year following reconstruction when compared to patellar tendon autografts.[47]

When considering patient-reported function post-ACLR, graft source can influence outcomes such as patient perceptions of symptoms, knee function, pain and psychological response to injury. Individuals with hamstring graft sources report better knee function using validated patient-reported questionnaires such as the International Knee Documentation Committee (IKDC) and Knee injury and Osteoarthritis Outcomes Score (KOOS) especially when compared to those with a patellar tendon graft source.[46,48] There is also evidence that those individuals that undergo ACLR with a hamstring graft type report better long term outcomes such as less pain (KOOS-pain), symptoms (KOOS-symptoms) and better quality of life (KOOS-QOL) when compared to those with a patellar tendon graft type.[46] When considering graft source, there is evidence that patellar tendon versus hamstrings autografts can influence patient function at 1 and 2 years post-ACLR. There is evidence that due to a more extensive healing process for patellar-tendon autografts, there are delays in rehabilitative outcomes such as patient knee extensor strength and symmetry. Outcomes that may be limited or impacted by graft source include quadriceps strength and symmetry, with individuals with patellar tendon grafts displaying worse isometric knee extension strength and reporting worse reported knee pain.[46,49] While deficits in hamstrings strength are reported in those individuals who undergo reconstruction with hamstring graft source, those who undergo reconstruction with patellar tendon graft sources tend to report worse and persistent quadriceps strength deficits.[50,51] Moreover, individuals that undergo ACLR with hamstring or patellar tendon graft sources also display other functional differences with evidence that those individuals who undergo ACLR with a patellar tendon graft source display greater landing asymmetries and poorer balance and hopping outcomes.[52–54] Though, these graft type functional differences have conflicting evidence with some findings statistically similar between hamstring and patellar tendon sources. [55] Though, there is evidence that deficits (i.e., quadriceps strength) may be remedied in individuals > 1-year post-operative. [56] Collectively, there is a wide range of literature describing the influence of graft type at the time of ACLR on post-operative knee function. This provides greater evidence for the need of patient-centered care dependent upon demographic and surgical characteristics such as graft type.

Second ACL Injury

While the primary objective of ACLR is to restore knee joint stability, there is evidence that more than 20% of individuals that opt to undergo ACLR under the age of 25 years old will experience a second ACL injury within only 24 months of primary reconstruction.[57] This is further supported with evidence that among adolescents and young adults with ACLR, nearly 30% will experience an ipsilateral or contralateral ACL injury within the first 2 years of surgery.[58–60] When compared to peers that have not previously sustained an ACL injury, individuals with ACLR have a nearly 6 times greater risk of sustaining a second ACL injury.[58] Women aged 15-25 years old with primary ACLR are at greatest risk of second ACL injury compared to any other age or sex stratified groups.[42] There are a variety of risk factors related to second ACL injury risk including graft type, younger age and male sex for ipsilateral injuries and young age and female sex are related to contralateral ACL injury.[59] In addition to these non-modifiable, demographic factors, time since ACLR is a known contributor to second ACL injury risk. Individuals who returned to sport within 9 months post-ACLR were 50% more likely to sustain a second ACL injury as compared to those who delayed return to play by more than 9 months post-operative.[61]

This indicates a need for targeted investigation of clinical outcomes related to second ACL injury risk as well as patient-centered interventions that can help to mitigate these worse outcomes.

Considerations for Return to Sport Following ACLR

Rates of return to sport (or pre-injury activity level) among young patients with ACLR is relatively high, with upwards of almost 80% of individuals returning to some level of activity, but only roughly 50-65% of individuals who undergo ACLR returning to pre-injury activity levels.[62–64] It is also important to note that while individuals may report return to sport, only about half of these individuals return to competitive levels of sport participation.[65] While return to sport is a common goal for individuals undergoing ACLR, it is also important to consider that many of these individuals do not meet physical activity recommendations regardless of return to sport status. [66,67] Importantly, a large consideration for return to sport criteria includes pre-injury activity level and post-operative timepoint of assessment. However, the meaningfulness of these criteria as they relate to long-term knee joint health remains unclear.

Often, return to sport criteria include metrics such as single leg hopping distance and between limb symmetry (> 90%), isokinetic quadriceps and/ or hamstrings strength and symmetry (> 90%), isometric quadriceps strength and symmetry (>90%), patient-reported outcome questionnaires for knee function and fear of re-injury, and satisfactory landing mechanics. Webster et al. reported a battery of common clinical outcomes for return to sport including: single leg hop and triple crossover hop for distance between limb symmetries, isokinetic quadriceps strength symmetry, patient-reported knee function using the International Knee Documentation Committee 2000 (IKDC), and patient psychological readiness to return to sport using the Anterior Cruciate Ligament Return to Sport after Injury (ACL-RSI) scale. [68] Commonly, a 90% between limb symmetry cut-off criterion is applied for successful task completion for return to sport (i.e., between limb hopping and strength outcomes). Though it is important to note that while these commonly applied clinical criteria provide insight for patient function following ACLR, these criterion are not infallible. In fact, there is evidence that between limb symmetry indices (LSI %s) may overestimate patient function and pre-injury levels of function (i.e., pre-injury uninjured limb quadriceps strength) may be an important future consideration. [69] Finally, inclusion of an assessment of jump-landing mechanics (i.e., biomechanical or clinically-based) is an important consideration for return to sport testing as it is valid, reliable, and landing mechanics are related to primary and secondary ACL injury and may be an important component of sport-related activities.[16,70–72] For patient-reported outcomes such as the IKDC for patient reported knee function, a score > 85 is indicative of acceptable patient symptom state and for psychological readiness to return to sport, a score > 65 for the ACL-RSI at 6-months post-operative is considered acceptable as it is related to successful return to sport at 12-months post ACLR.[68,73] Importantly, these patient-reported metrics are an important component of the return to sport battery of tests because better patient reported knee function and better psychological readiness to return to sport are related to successful return to sport 2 years following ACLR and may even predict second ACL injury. [71,74] A combination of these types of performance-based and patient-reported clinical outcome measures may be important to incorporate in return to sport assessments.

ACL Injury and ACLR Considerations for Age and Maturation

Incidence of ACL injury in skeletally immature individuals is increasing due to increased participation in competitive sports at younger ages. [75] Previous reports assessing the influence of skeletal and sexual maturation on ACL injury risk have mixed findings. Some research groups report that ACL injuries are more common in skeletally immature boys and, conversely, more common in skeletally mature girls. Overall, however, complete ACL tears are still more often reported in skeletally mature males with rates steadily increasing among adolescent and young adult women. [76]

ACL injury and surgical management in skeletally immature individuals is challenging. Evaluation of skeletal maturity of young patients with ACL injury is often a consideration when evaluating timing of ACLR and technique. Often, skeletal maturity is assessed utilizing radiographic or MR imaging techniques. Importantly, clinicians must often consider skeletal maturity, sexual maturity, radiographic evaluation, and family growth history when determining appropriate steps for ACL injury rehabilitation. Some skeletally immature patients will opt for nonsurgical management of ACL injury, modifying activity level and participation, knee-bracing, and rehabilitation. At the time of maturity, these patients often undergo traditional transphyseal ACL reconstruction, minimizing the risk for damage and growth disturbances. However, surgical delay is often associated with knee instability, increased cartilage and meniscal damage, and poorer patient quality of life. In fact, increased risk of secondary meniscal and chondral injuries has been reported for those who delayed surgery when compared to those who did not delay surgery. Therefore, delay of surgical intervention is often discouraged, if possible. [77]

Surgical techniques are sometimes considered risky for skeletally immature individuals. However, there is evidence that this risk is minimized in those individuals with limited growth remaining. In skeletally mature adults, ACL reconstruction is completed via transphyseal tunneling, however, this poses a risk in those who have not reached skeletal maturity. The potential for growth disturbance and deformity are risks that are often considered due to physeal disruption. There is also evidence that utilizing bone-patellar-tendon-bone grafts should be discouraged because these grafts may not be successful in skeletally immature patients. This recommendation is due to the increased risk of physeal disturbance, and therefore potentially increased risk of growth disturbance with this graft choice. [77]

There are a variety of physeal-sparing techniques that can minimize damage or help avoid the physeal plate. However, these techniques do not report the same levels of knee stability following surgery. Modified traditional transphyseal reconstruction in skeletally immature, prepubescent individuals has been completed with more success, with roughly only 3% of these individuals requiring surgical revision. This surgical modification encourages the use of hamstring tendon grafts and metaphyseal fixation in skeletally immature patients in order to minimize growth disturbance risk. Limited studies, however, report that the patellar-tendon graft provides greater knee stability and decreased risk of meniscal damage. [27,77]

ACL Injury and ACLR Considerations for Biological Sex

Adolescent and young adult women are at 4-12 times greater risk of primary and secondary ACL injury risk as compared to age-matched male peers.[42] Female sex and post-pubertal maturation status are associated with highest risk of ACL injury, though skeletally mature males still represent the largest number of ACL injuries, annually.[37,42] When considering the pubescent age group alone, female athletes have a 3-5 times increased ACL injury risk when compared to their male peers. In other words, adolescent and young adult women are at greatest risk of primary ACL injury, and they are also at greatest risk of secondary ACL injury following primary ACLR. Sex-based disparities in post-ACLR outcomes are especially evident when evaluating lower extremity biomechanics. These poorer movement strategies that are related to injury risk are often associated with achieving physical maturation in females.[78] In fact, physical maturation is often the mark of this increased ACL injury risk among females. There is speculation that increased hormones, accelerated increases in body mass and height, and body composition changes play a deleterious role in adolescent female ACL injury risk. One research group suggests that sex differences in biomechanical outcomes emerge at the time of puberty and may be connected to increased injury risk in females. [79–81] Most literature identifying differences, however, is limited as age cut-offs are commonly implemented which may fail to characterize the influence of maturation (e.g., skeletal, somatic, sexual maturation). While the influence of maturation status on ACL injury risk is not well understood, female biological sex is consistently associated with poorer lower extremity biomechanics, worse post-operative clinical outcomes, and increased risk for primary and secondary ACL injury.

Identification of Current Gaps in the Literature

Based upon the present review, there are evident gaps in the literature surrounding ACL injury risk, management, and knee function following ACLR. Importantly, while there is substantial evidence for an influence of sex and age on risk for ACL injury, and strong evidence for the influence of sex on post-ACLR function, there is conflicting evidence for the influence of age on post-operative outcomes. While the exact influence of age post-ACLR on clinical outcomes is not well understand, when considering the prevalence of ACL injury and subsequent reconstruction in young athletes and recreationally active individuals, especially when considering the incidence of ACL injury among young women, more research is required in order to better understand the influence of age and sex post-ACLR.

REHABILITATION FOLLOWING ACL INJURY AND ACLR

In the United States, ACL injury is followed by surgical reconstruction (ACLR) among more than 90% of cases. Following ACLR, an extensive 4-6 months of formal outpatient rehabilitation is recommended. However, in a recent review, patients who opt to undergo ACLR and complete formal rehabilitation complete nearly 90% of their formal sessions with a healthcare professional within only 4 months of surgery and only attend 16 sessions. More recently, individualized, tailored rehabilitation interventions have been proposed, but these are often costly and may place burden on the healthcare system or patient resources. In this portion of the review, we will comment on current rehabilitation practices, gaps and recommendations.

Current Practices

Following ACL injury, “pre-surgical” rehabilitation interventions have been more recently introduced in the United States and have been widely implemented as a primary part of post ACL injury care and treatment in other countries. These interventions commonly aim to strengthen knee extensors and flexors or improve gait biomechanics, offer engagement in formal activity and may even offer psychosocial benefits such as social support at a critical time point when knee function and self-efficacy are reported to be lowest.

In the United States, ACLR is commonly followed by 2-3 months of neuromuscular outpatient rehabilitation. The rehabilitation is typically characterized by 4 phases: 1) early (weeks 1-3 post ACLR), 2) middle (weeks 4-6), 3) late-middle (weeks 7-12), 4) late; return to (modified) sports activities (weeks 16+*). Early rehabilitation is characterized by a restoration of gait without the use of an assistive device, closed kinetic chain exercises, restoration of full knee extension and flexion ROM through 90 degrees. In mid-stages of rehabilitation, gait re-training as well as quadriceps and hamstring strengthening, and single leg dynamic movements are introduced. Finally, during the late mid-stages of rehabilitation, the patient’s knee should have full ROM restored, and more dynamic exercises (i.e., single leg landing) are also introduced. Typically, during months 4-6, regular running is introduced and a return to (modified) sports activity is often reported. However, at 4-6 months post-operative, most adolescent and young adult patients fail to meet common return to sport criteria and many report a failure to reach pre-injury levels of sport activities.

Among patients with ACLR who complete rehabilitation approximately 4-6 months post-operatively, 50-80% fail to meet common return to sport criteria such as sufficient isometric knee extensor strength and symmetry, single leg hopping for distance, and poor landing biomechanics. In addition to these functional and performance-based limitations, patients 4-6 months post-ACLR commonly report inadequate psychological readiness to return to sport as measured by the ACL-RSI, poor knee function as described by the patient acceptable symptom state for the International Knee Documentation Committee

(IKDC) short form questionnaire, and even report levels of symptom burden that have been related to the need to seek medical care among individuals with other knee pathology.

A recent clinical review has suggested that current practices should include pre-operative rehabilitation, early post-operative quadriceps strengthening and regularly scheduled testing, and a delay of full return to sport until at least 9-12 months post-operative after successful completion of return to sport clinical criteria. In addition, this review also suggests the importance of psychosocial monitoring and the importance of secondary ACL injury prevention training and return to pre-injury fitness levels prior to full return to sport. It is important to recognize that these needs are likely not met in only 16 formal rehabilitation sessions and there is a clear critical need to address this gap in post-operative care. Perhaps, delayed return to sport in combination with individualized, tailored rehabilitation protocols may help to mitigate worse post-ACLR outcomes.

Gaps in the Literature

While patients may engage in return to sport or secondary ACL injury prevention programs to help address these gaps in post-operative care, these interventions are often costly and require the patient to accrue further out-of-pocket expenses, on the already rising costs of ACLR, especially among patients in the United States. Therefore, there is a need to identify clinically feasible and cost-accessible interventions to help address this gap in post-operative care and these disparate clinical outcomes.

CLINICAL OUTCOMES FOLLOWING ACLR

Individuals with an ACL injury report worse knee function and instability, demonstrate aberrant walking and jump-landing biomechanics, and exhibit poor knee extensor strength when compared to uninjured age-matched peers. While the premise of ACLR is to restore knee joint stability and a common goal of adolescent and young adult patients is to return to pre-injury levels of sport or physical activity participation, many individuals fail to return to sport at any level following surgery. In addition, individuals with ACLR also demonstrate knee extensor and flexor strength deficits and aberrant movement biomechanics as compared to their uninjured control limbs and healthy uninjured peers. When considering these post-ACLR deficits and the negative consequences associated with poor post-operative function (i.e., secondary ACL injury risk, long-term poor knee joint health), it may be important to better understand how to address these negative post-ACLR outcomes.

Knee Extensor Strength following ACLR

Males and females demonstrate strength deficits following ACLR, but females often exhibit poorer strength of the knee flexors and extensors when compared to their male counterparts. In addition to lesser lower extremity strength magnitude, strength asymmetry is a known contributor to primary and secondary ACL injury risk and is also insufficient 4-6 months post-ACLR. Limb symmetry is reported as a primary return to sport outcome, comparing the strength differences between the reconstructed and uninvolved limbs. Commonly a limb symmetry index (LSI) is reported as: ACLR limb/ Uninvolved limb * 100 and is reported as a percentage of function. In a recent study completed by Walaszek et al., which comprised a demographically diverse sample of 173 individuals 5-7 months post-ACLR, 85% of individuals did not meet clinical strength or strength symmetry cut-offs, and 40% of participants had clinically significant knee symptoms that may be indicative or poor knee function and quality of life. In addition, there is evidence that age may also influence knee extensor strength post-ACLR. There is evidence from a study from Ithburn and colleagues that pediatric and adolescent groups both perform better than adults, indicating younger age at the time of ACLR may be related to better knee function and greater knee extensor strength. Unfortunately, while these groups are based upon chronological age (groups two and three), and surgical considerations, there is a lack of true maturation assessment. Moreover, distribution of these groups was significantly unbalanced, and this study may have more comprehensively described the influence of surgical technique in combination with age on these outcomes. Therefore, the implications of these findings are limited. More recently, though, open physes status among young men with ACLR has been related to greater body weight normalized isometric quadriceps strength and better knee function. This suggests that age may have an influence on knee-extensor strength following ACL injury and ACLR. Among male and female adults and adolescents, inadequate quadriceps strength has been related to a variety of poor outcomes including incidence of second ACL injury, failure to return to sport, poor perceived knee function and aberrant biomechanics during dynamic movements such as landing or pivoting and activities of daily living such as overground walking. Therefore, it may be especially important to address these strength and symmetry deficits early following surgery in order to mitigate risk of poor long-term outcomes.

Evaluating Knee Extensor Strength

Inadequate ACLR limb peak isometric knee extension torque and quadriceps strength asymmetry following ACLR are related to poor knee function and risk of second ACL injury among individuals with ACLR. Peak isometric knee extension torque or quadriceps strength is commonly measured using a handheld or multi-modal dynamometer. Knee extension maximal voluntary isometric contraction (MVIC) torque is commonly assessed using a MicroFET 2 handheld dynamometer or Biodex multi-modal dynamometer. The handheld dynamometer is a valid and clinically feasible method for assessing knee extension torque (Nm). The distance (cm) from the lateral knee joint line to a point 5 cm proximal to the distal lateral malleolus is measured and this value is then multiplied by the peak force (N) to obtain knee extension MVIC torque. This value is then normalized to body mass (Nm/kg). A similar method is utilized when implementing the gold-standard assessment approach to isometric knee extension strength using a multi-modal dynamometer such as a Biodex System 4 Multi-Modal Dynamometer (Shirley, NY). Individuals are positioned and secured in the dynamometer at 85° of hip flexion and 90° of knee flexion. For isometric testing, the arm is secured at 90° of knee flexion, and the participant is asked to kick outward as if extending their knee as hard and as fast as possible. Verbal encouragement and visual feedback representative of torque output is commonly provided and results in greater performance as compared to no feedback during testing. MVIC torque is also typically normalized to body mass using this method (Nm/kg).

Knee-related Quality of Life following ACLR

Adolescents and adults with ACLR report poor knee-related quality of life as early as a few months up to 10 years post primary reconstruction. Evidence for age or sex-specific outcomes disparities, however, is conflicting. No significant sex differences in patient-reported knee function and quality of life have been reported by Kuenze et al., but other research groups have reported worse knee-related quality of life among women with

ACLR that may persist up to 5 years post-operatively, as compared to males with ACLR. Management of knee-related quality of life may be an especially important clinical outcome for consideration for a variety of reasons. First, the Knee injury and Osteoarthritis Outcome (KOOS) questionnaire is a short, clinically feasible approach to evaluating and monitoring patient knee-related quality of life following ACL injury for several years following ACLR. Knee-related quality of life as assessed by the KOOS quality of life subscale has been identified as an indicator of knee function and has been related to a host of other clinical outcomes including walking biomechanics, physical activity participation, quadriceps strength and likelihood of return to sport. Importantly, clinical thresholds for the KOOS-QOL have been widely implemented. For example, the Patient Acceptable Symptom State (PASS) threshold of 62.5/ 100 has been established among patients who underwent ACLR 1-5 years previously. This indicates that meeting or exceeding this clinical threshold is considered acceptable knee-related quality of life following ACLR. In addition, knee-related quality of life is a commonly assessed outcome measure across knee pathology populations and has been shown to improve following psychological, social (e.g., group exercise) and neuromuscular rehabilitation protocols. When considering the robust insight of knee-related quality of life on other common clinical measures, and knee-related quality of life deficits among women with ACLR, quality of life may serve as an important metric to monitor and evaluate post-ACLR.

Evaluating Knee-related Quality of Life

Knee-related quality of life is commonly assessed utilizing the KOOS-QOL subscale. The KOOS-QOL is a valid and reliable outcome that has been used previously implemented by several research groups to capture knee-related quality of life across knee pathologies, including ACLR. The KOOS-QOL is the most responsive KOOS subscale to intervention and has been related to a host of clinical outcomes among individuals with knee pathology including those rehabilitating from ACLR. The KOOS-QOL is reported on a 0-100 scale with 100 indicative of ideal knee-related quality of life. The KOOS-QOL is comprised of 4 items that are scored from 0 (no problems, never) to 4 (severe problems, constantly). These 4 items and response choices are outlined below in Table 1.

Table 1. Knee injury & Osteoarthritis Outcomes Score Quality of Life (KOOS-QOL)

The KOOS survey asks for your view about your knee. This information will help us keep track of how you feel about your knee and how well you are able to perform your usual activities. Answer every question by selecting the appropriate choice, only one choice for each question. If you are unsure about how to answer a question, please give the best answer you can.
1. How often are you aware of your knee problem? Never Monthly Weekly Daily Constantly
2. Have you modified your lifestyle to avoid potentially damaging activities to your knee? Not at all Mildly Moderately Severely Totally
3. How much are you troubled with lack of confidence in your knee? Not at all Mildly Moderately Severely Extremely
4. In general, how much difficulty do you have with your knee? None Mild Moderate Severe Extreme

Adapted from: Roos, E. M. and L. S. Lohmander (2003). "Knee injury and Osteoarthritis Outcome Score (KOOS): from joint injury to osteoarthritis." Health Qual Life Outcomes 1: 64.
Roos, E. M., H. P. Roos, et al. (1998). "Knee Injury and Osteoarthritis Outcome Score (KOOS)--development of a self-administered outcome measure." J Orthop Sports Phys Ther 28(2): 88-96.

Considerations and Gaps in the Current Literature

Individuals that have experienced an ACL injury and undergone ACLR exhibit deficits related to ACL injury risk such as poor knee extensor strength and symmetry as well as insufficient knee-related quality of life. When considering these post-ACLR deficits, it may be especially important to identify patients early following surgery who may benefit from interventions that aim to address these gaps in clinical care.

WALKING BIOMECHANICS FOLLOWING ACLR

Aberrant lower extremity walking biomechanics are contributors to the pathomechanics of knee OA development following ACLR and are well established among adults within 6-12 months following surgery up to several years post-ACLR.[10,18] Lesser involved limb peak vertical ground reaction forces (vGRFs) have been associated with worse knee-related symptoms and indicators of poor knee joint cartilage health within only the first year following ACLR.[82–85] Within the first 2 years following ACLR, adults also exhibit sagittal plane deficits during walking, including reduced involved limb peak knee flexion angles when compared to the uninjured limb.[10] In addition, adults within the first year of ACLR also exhibit alterations of medial knee joint loading as described by lesser external knee adduction moments which have been related to poor load absorption in the medial compartment of the knee and osteoarthritis development following ACLR.[86] When considering these collective deficits in knee joint range of motion and alterations in loading patterns, it is hypothesized that articular cartilage may respond positively or negatively to this altered loading, and contribute to the pathomechanics of posttraumatic knee OA development.[7,9,87]

The following portion of this review will briefly summarize the aberrant kinetics and kinematics that have been identified at the knee at the frontal and sagittal planes, with limited evidence for aberrant mechanics at the transverse plan. In addition, we will summarize aberrant hip and ankle kinetics and kinematics, though evidence is more limited. Finally, individuals with ACLR also exhibit aberrant total limb loading of the involved limb as measured by peak vGRFs as compared to both their contralateral limb and healthy matched control limbs which will be briefly reviewed.

Sagittal Plane Kinetics and Kinematics at the Knee

According to a recent systematic review and meta-analysis, individuals with an ACL injury who have not undergone ACLR exhibit reduced peak knee flexion angles and peak knee flexion moments as compared with healthy, uninjured control limbs and the contralateral limb at almost any time point post ACLR as early as only 3 months following surgery and more than five years following surgery.[10,18] Interestingly, at 24 months post-ACLR, there is evidence of restoration of sagittal plane knee kinematics with the reconstructed limb exhibiting larger peak knee flexion angles as compared to uninjured control and contralateral limbs.[10,88] Goetschius et al. provide further evidence of early aberrant mechanics that appear to remedy 2-3 years post-operative, with a return of aberrant mechanics at later timepoints.[89] Smaller peak external knee flexion moments and peak external knee extension moments are typically reported in the reconstructed limb within the first year and at more than 2 years post-operative.[10,18] Early following ACLR (< 6 months post-ACLR), peak knee flexion angles of the reconstructed limb are reported to be 12.7-24˚ with minimal evidence for reduced sagittal plane motion as compared to healthy uninjured control limbs (13.7-22.2˚) and the contralateral limb (9.1˚). Consistently, however, from 6-18 months post-ACLR, reduced peak knee flexion angles of the reconstructed limb are reported.[10] However, inconsistencies in cohort demographics and surgical characteristics may limit the generalizability of these findings and therefore comparisons across cohorts. Importantly, > 2 years post-ACLR, reductions in sagittal plane range of motion at the knee is consistently reported among individuals with ACLR and individuals with ACL injury only. The consistent evidence of reductions in sagittal plane range of motion at the knee joint is postulated to result from weakness of the knee extensors (i.e., quadriceps muscle group) following ACL injury and ACLR.[87] Andriacchi first identified this "quadriceps avoidance gait" pattern during overground walking among 16 individuals with unilateral ACL injury.[9,87] These gait adaptations (i.e., reduced peak knee flexion angles and peak external flexion moments) have been correlated with reduced knee extensor strength as assessed with an isokinetic dynamometer ($R=0.562$, $p<0.001$), and this relationship is still moderately significant among uninjured, healthy individuals as well ($R=0.442$, $p=0.003$) and even among women with knee osteoarthritis.[90–92] Several research groups have identified similar gait patterns among individuals with ACLR and have identified quadriceps strength as a contributor to peak knee flexion among individuals with ACL injury and ACLR ($R^2=0.260$, $p=0.036$).[90] Therefore, quadriceps weakness may be a contributor to these aberrant sagittal plane gait adaptations observed at the knee following ACLR and among individuals with knee OA.

These aberrant changes in sagittal plane mechanics at the knee are significant because reduced peak knee flexion angles have been related to indicators of poor cartilage health as early as 3 months post-ACLR and contribute to the pathomechanics of knee OA development several years following primary ACLR. Peak knee flexion moment between-limb symmetry measured during overground walking has been related to T_2 relaxation time, which is an indicator of cartilage health, as early as only 3 months following ACLR. Among individuals who had undergone ACLR five years prior to biomechanical assessment and did or did not have medial compartment knee OA, those with diagnosed OA exhibited significantly lower peak knee flexion angles (19.1 (2.9) ˚) as compared to individuals without OA (24.3(4.6˚) (p=0.01).[93] In addition, the same study reported lower knee flexion moments among individuals with OA (4.4(1.2) % body weight) as compared to those without knee OA (5.3(1.2) % body weight) (p=0.05).[93] Interestingly, however, Hart et al. reported that peak knee flexion angles were greater in the reconstructed limb among individuals with lateral knee OA as compared to healthy, matched controls (3.5˚, 0.9-6.1).[12] While sagittal plane gait mechanics have been related to indicators of cartilage health and knee OA development, they have also been related to indicators of patient function as early as 6 months following surgery and have been predictive of function up to 8 years post-surgery.[83,94] In fact, peak knee flexion moment during the first half of stance of overground walking 2 years post-ACLR has been related to pain and quality of life as assessed by the KOOS 8 years post-operative.[94] This indicates that sagittal plane knee mechanics that have been widely observed following ACLR may contribute to patient perceptions of knee function, cartilage health, and even knee OA development among this clinical population.

Frontal Plane Kinetics and Kinematics at the Knee

There have been inconsistencies in reports of knee adduction angles and moments among individuals with ACLR as compared to the contralateral and uninjured control limbs.[10,94–98] As early as 11 months post ACLR, there is evidence of greater adduction angles, but smaller adduction angles are reported 2 years and more than 5 years post-surgery.[10] In the same meta-analysis, individuals with an ACL injury who have not undergone ACLR exhibited reduced peak external knee adduction moments as compared with healthy, uninjured control limbs.[10] Among individuals who underwent ACLR five years prior to a lower extremity biomechanics assessment, those with knee OA exhibited modestly greater peak knee adduction moments as compared to those without knee OA.[93] Though, among this sample, peak medial knee joint compartment load was not different among individuals with and without medial knee joint OA following ACLR.[98] Smaller peak knee adduction angles have been reported in the reconstructed limb as compared to uninjured healthy control limbs between 6 and 12 months post-ACLR. Though, this difference seems to remedy by 2 years post-ACLR, while larger knee adduction angles and moments have been identified in the ACLR limb > 3 years post-operative.[10] However, in a recent systematic review and meta-analysis that included 2 high quality and 4 moderate quality studies, among individuals who were 6-12 months post ACLR, there was moderate evidence of no differences in peak knee adduction angles between individuals with and without ACLR (-0.43, -0.91 to 0.05; I^2=51%, p=0.10).[18] In the same meta-analysis, one high quality study provided evidence for lower peak knee adduction angles of the reconstructed limb as compared to healthy, uninjured control limbs. A similar trend of no differences in peak knee adduction angles more than

3 years post-ACLR was supported, though evidence was limited. As compared to the contralateral limb, the same meta-analysis reported no significant differences between peak knee adduction angles at any post-ACLR timepoint.[18] However, greater, high-quality evidence investigating knee adduction angle longitudinally following ACLR may be warranted as present evidence for differences between injured and uninjured limbs is limited. Similarly, no differences in peak knee adduction moments between ACLR and healthy uninjured control and contralateral limbs were reported consistently across post-operative time points from 6-12 months to more than 3 years post-ACLR.[10,12] Knee adduction moments, however, may be an important consideration for females who have experienced an ACL injury.[95] Webster et al. reported that the external knee adduction moment was 23% greater among females who were nearly two years post-ACLR as compared to males of a similar age post-ACLR.[95] Despite this difference between sexes, the authors reported no differences between the ACLR and contralateral limbs for knee adduction moment among this sample.

Despite somewhat limited evidence of differences in frontal plane kinetics and kinematics at the knee joint following ACLR, knee adduction angles and moments have been related to a wide range of indicators of patient function, knee joint health, and knee OA development among this population. Greater external knee adduction moments have been consistently reported among individuals with radiographic and symptomatic knee OA during walking as compared to individuals without knee OA. Greater knee adduction moments during walking have even been related to greater disease severity and progression among this population. Part of the pathomechanics of knee OA development is postulated to occur from aberrant loading of the articular cartilage due to changes in gait patterns.[86] Knee adduction moments are often utilized as a proxy for medial knee joint compartment loading and greater knee adduction moments suggest that the medial compartment is being loaded to a greater magnitude than the lateral compartment. It is postulated that this aberrant loading of the cartilage of the medial knee joint compartment may result in poor tissue adaptations resulting in cartilage degradation and thus knee OA development.[9,87] Interestingly, however, Wellsandt et al. reported that individuals who had undergone ACLR five years prior to biomechanical assessment and had radiographic evidence of knee OA walked with lower knee adduction moments and impulses as compared to those without knee OA following ACLR.[98] Greater investigation of changes in knee adduction moment following ACLR and how this influences knee OA development is warranted.

As early as 6 months post-ACLR, lesser knee adduction moments of the ACLR limb and symmetry between limbs have been related to indicators of poor knee joint health including greater plasma matrix metalloproteinase-3 concentrations and interleukin-6 which are indicators of plasma degenerative enzymes and pro-inflammatory cytokines, respectively.[85] In addition to these negative biochemical indicators of cartilage health, greater knee adduction angles and external knee adduction moments were related to thinner cartilage thickness at the medial condyles (R^2=0.2, p=0.03), and knee adduction moment was considered a predictor of cartilage thickness at the medial condyles.[88] Though, the generalizability of these relationships is limited as this investigation was among women with ACLR who were 60.6 ± 24.8 months post-operative. A recent investigation by Evans-Pickett et al. describes that lesser proteoglycan density of the cartilage as indicated by greater T1 ρ relaxation times were related to lesser knee adduction moments early following ACLR.[99] However, there is evidence that knee adduction moments may become more similar between individuals with and without ACLR > 12 months post-operative.[10] Greater evidence for changes in knee adduction angles and moments, as well as its relationship with knee OA development is warranted among this clinical population.

Transverse Plane Kinetics and Kinematics at the Knee

Reduced peak internal rotation angles have been reported post-ACLR, especially > 12 months post-operative as compared to both the contralateral and healthy, matched control limbs[10,18]. Peak external knee-external rotation moments are also reported to be smaller in the ACLR limb several years following surgery as compared to the contralateral and uninjured control limbs. Webster et al. reported that at 9 months post-ACLR, the reconstructed limb demonstrated a significantly reduced peak internal rotation angle (7-8˚) as compared to healthy, uninjured control limbs (13.5˚) and the contralateral limb (13.1˚).[10,95] When considering these reported differences, it is important to consider that transverse plane kinematics and kinetics have not been widely reported or homogeneously calculated across this literature. In addition, the transverse plane is also related to largest degree of measurement error when considering three-dimensional motion capture with the margin of error (up to 3˚), sometimes surpassing typical range of motion during walking. Lack of evidence surrounding knee joint transverse plane kinematics and kinetics limits conclusions regarding how these changes in gait might contribute to joint degeneration and therefore knee OA development.

Kinetics and Kinematics at the Hip and Ankle

In addition to changes in walking biomechanics at the knee joint, there is evidence of aberrant adaptations at the hip and ankle joints following ACL injury and ACLR.[10] For example, individuals with ACL deficiency exhibit reduced hip adduction angles as compared to uninjured control limbs. Following ACLR, there is also evidence of reduced sagittal plane range of motion at the hip and is greatest at the reconstructed limb consistently between 9 and 11 months post primary ACLR. In addition, in a meta-analysis of knee and hip kinetics and kinematics following ACLR, Slater et al. reported reduced peak hip flexion angles providing additional support muscle dysfunction and persistent weakness contributing to poor walking biomechanics among this population. [10]

Studies detailing ankle kinetics and kinematics during overground walking among individuals with ACLR are limited, with evidence of smaller sagittal plane moments of the reconstructed limb as compared to the contralateral and healthy, uninjured control limbs > 12 months post-operative. However, individuals with lateral knee OA and history of ACLR exhibited greater peak ankle dorsiflexion moments (0.1 Nm/kg, 0.0-0.2) as compared to individuals without knee OA.[12] Overall, high-quality evidence of ankle kinetics and kinematics prior to and following ACLR is limited with support for mechanics that are different from both the contralateral and healthy control limbs.

Vertical Ground Reaction Forces During Walking

Vertical ground reaction forces (vGRFs) have been utilized as a surrogate measure of total loading at the limb across a variety of clinical populations, including individuals with ACLR. Peak average vGRFs during the first 50% of stance of walking are reported to be between 1.03 and 1.17 times body weight on the reconstructed limb among adults 6 months to several years post-ACLR.[82,84,100,101] Aberrant ACLR limb loading as compared to the uninjured limb and as compared to healthy, uninjured controls have been widely observed during walking, running, jumping and a variety of dynamic tasks. However, the ideal magnitude and frequency of knee joint loading to promote optimal cartilage health following ACLR and even among uninjured individuals is unknown. ACLR limb underloading during walking at 6 months post-operative is associated with increased circulating concentration of biomarkers of collagen turnover and has been associated with radiographic evidence of posttraumatic knee OA development only 5 years following surgery.[85,97,100] Conversely, limb overloading has been associated with idiopathic and posttraumatic knee OA development among adults and greater relative loading of the ACLR limb during repetitive, cyclical kinematics (i.e., walking gait) is postulated to contribute to cartilage degradation of the tibiofemoral joint and the pathomechanics of knee OA development.[87] There is limited evidence linking these postulated cartilage changes post-ACLR that lead to knee OA. However, among women who were several years post-ACLR, greater ACLR limb peak vGRFs (1.13(0.09) x BW) were related to greater cartilage thickness at the medial condyle (R^2=0.21, p=0.03).[102] However, the exact mechanistic link between cartilage thickness and limb loading during walking is unclear among this clinical population. In addition to these mechanical considerations, peak vGRFs during walking only two years post-ACLR have been predictive of patient-reported function 10 years post-ACLR. Erhart-Hledik et al. recently reported that individuals that demonstrated ACLR limb overloading compared to their contralateral limb two years post-ACLR during walking demonstrated worse patient reported function as measured with the International Knee Documentation Committee (IKDC), and KOOS pain, symptoms, and quality of life 10 years post-ACLR (IKDC: $R = -0.391$, $p = 0.040$; KOOS pain: $\rho = -0.396$, $p = 0.037$, KOOS symptoms: $\rho = -0.572$, $p = 0.001$, and KOOS quality of life: $R = -0.458$, $p = 0.014$).[94] Total limb loading as measured by vGRFs during walking may provide insight into mechanical function, symmetry and even future patient function. In addition to these considerations, assessment of vGRFs during walking is significantly less costly, requires less technical expertise and can be implemented in the laboratory, clinic and in free-living conditions.

Considerations for Walking Symmetry Following ACLR

Increasingly, symmetry indices have been reported to describe walking biomechanics characteristics and to provide a comparison between the reconstructed and uninjured limbs post-ACLR.[52,82,103] For example, peak vGRF asymmetry (i.e., ACLR limb underloading or overloading compared to the uninjured limb) has been related to various indicators of poor knee joint cartilage health and inflammation within the first year of ACLR as described above. While symmetry may provide insight into function of the contralateral limb, there is evidence that both limbs are negatively impacted by unilateral ACLR.[23] Davis-Wilson et al. report that early following ACLR (6-12 months post-operative), individuals demonstrate lesser peak vGRFs of the ACLR and contralateral limbs in early stance and greater peak vGRFs bilaterally during midstance as compared to healthy controls without history of knee injury. This indicates that individuals with ACLR are demonstrating aberrant limb loading bilaterally at 6 and 12 months post-ACLR as compared to individuals without injury.[23] While walking symmetry indices related to limb loading and joint specific kinetics and kinematics may provide insight into contralateral limb function, these indices may not serve as an adequate comparator.

Lower Extremity Biomechanics Following ACLR: Consideration for Age and Sex

Individuals with ACLR demonstrate aberrant lower extremity biomechanics prior to surgery, and even up to 2 years following reconstruction. While both sexes demonstrate unfavorable biomechanical adaptations post-ACLR, these have been more commonly reported among young women across a variety of tasks including walking, single leg hopping and jump-landing.

Sex-specific adaptations have been reported following ACLR during walking, jumping, hopping and landing tasks. For example, females demonstrate greater knee joint frontal plane motion (i.e., abduction) at initial contact and upon take-off during a double limb landing as compared to their male peers. In addition, females who had undergone ACLR at least two years prior to biomechanical assessment also demonstrate greater reconstructed limb loading (i.e., vGRFs) and loading rates as compared to their uninjured limbs and healthy control limbs, but males do not exhibit this biomechanical adaptation. Females also often exhibit greater knee abduction angles, increased internal adduction moments, increased vGRFs, and decreased knee flexion angles when compared to their male counterparts regardless of injury status.[78] Pubertal females also commonly exhibit poorer lower extremity biomechanics characterized by greater knee abduction angles and greater limb loading when compared to pre-pubertal females, and as compared to males regardless of maturation status, though this is most commonly observed during landing and hopping tasks. Importantly, these movement patterns, especially increased vGRFs in combination with reduced knee flexion angles or greater knee abduction angles have been previously related to the risk of primary and secondary ACL injury and knee OA development. Another research group has reported that during walking males demonstrate smaller hip excursions and knee moments on the reconstructed limb as compared to the uninvolved limb regardless of time since surgery, when comparing pre-surgical and 6-months post-surgical time points.[104] Other research groups, however, have reported no significant sex differences in lower extremity biomechanics nearly 2 years following ACLR. Sigward et al. examined the sex and maturation influences on side-step cutting biomechanics in a group of young (ages 9 to 23 years) male and female soccer athletes. Importantly, the authors did not report any sex and maturation interactions for any joint kinetic or kinematic outcomes. Overall, however, there is evidence for differences in mechanics following ACLR between men and women, though future longitudinal investigation is warranted.

Measurement of Walking Biomechanics

Lower extremity biomechanics have been studied widely among individuals with and without ACL injury and ACLR, including walking, running, hopping and jumping tasks. Largely, these studies have focused on young adult populations who have experienced an ACLR within the previous several years. Among this population, walking biomechanics are kinetically and kinematically evaluated in a traditional laboratory setting using force platforms embedded in the ground or treadmill, but have also more recently been evaluated using clinical alternatives such as insole devices which provide measures of total limb loading (i.e., vGRFs) or markerless motion capture systems that provide an indication of kinematics.

Three-dimensional motion capture camera systems integrated with force platforms are the most common method of assessing post ACL injury and ACLR lower extremity biomechanics. Three-dimensional motion capture is considered the gold standard assessment of kinematics with an average margin of error < 3 degrees at the sagittal, frontal and transverse axes.[105] Force platforms that independently capture limb ground reaction forces are also considered the gold standard assessment of vGRFs with an average margin of error < 5 N.[106] The effectiveness of these systems, though, is influenced by a variety of factors including camera placement and aiming, system calibration, anatomical references (e.g., marker placement), across a host of environmental factors such as non-relevant reflections that can contribute to inaccurate data capture. These systems are also costly depending upon size (e.g., number of cameras, force platforms) and require training for proper data collection. In addition, there is evidence that having multiple assessors (e.g., multiple individuals placing markers or creating models) may limit reliability of these collected data.

To evaluate walking biomechanics, typically at least 2 force platforms are utilized to capture a full stride without normal gait being disrupted. For example, stutter stepping or purposeful stepping onto the force platforms should be avoided. According to recommendations from the International Society of Biomechanics, a minimum of 5 movement trials should be captured and the average across should be reported in order to account for within-participant variability and data should be normalized to participant size.[107] In order to capture kinematics, clusters and/ or individual retro-reflective markers can be placed on the lower extremities and spine. For example, a modified Helen-Hayes model has been widely applied which consists of markers and/ or clusters applied bilaterally to the lateral aspects of the thighs and shanks, the dorsal surface of the feet, and the sacral spine. Next, identified anatomical landmarks can be used to estimate joint centers using a centroid method.[31] Landmarks for the modified Helen-Hayes include: C7-

T1 spinal segment, L5-S1 spinal segment, medial and lateral tibiofemoral joint lines, medial and lateral malleoli, and the tip of the second toes. The bilateral anterior and posterior superior iliac spines are also identified to calculate hip joint centers using a variety of methods such as the Bell method. Marker trajectory data are typically sampled between 100 and 150 Hz and force data are sampled at 800 to 2500 Hz.

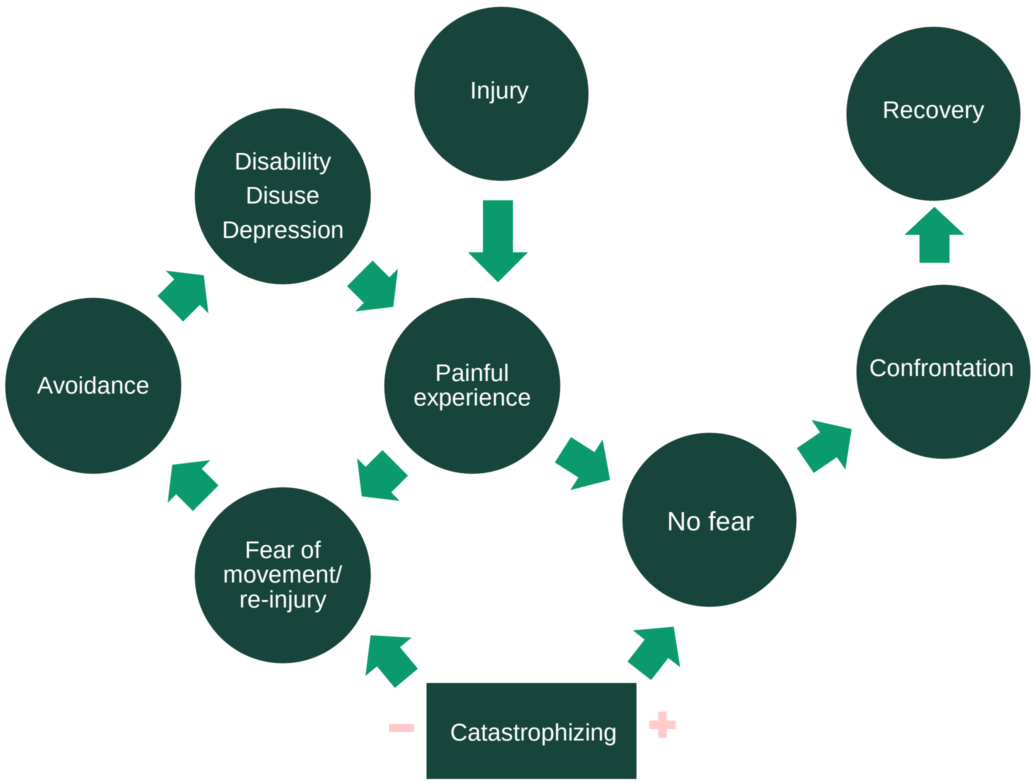
To quantify knee, hip and ankle kinematics, right-hand Euler angle sequences can be utilized. Marker trajectory and ground reaction force data are typically processed with a standard inverse dynamics approach to quantify knee, hip and ankle joint kinetics. It is recommended that data are filtered with a fourth order, low-pass Butterworth filter with a cutoff frequency of 6-32 Hz and 60-240 Hz for kinematic and kinetic data, depending upon sampling and task.[34] The International Society of Biomechanics recommends that joint moments are normalized to body mass and height ($Nm*(kg*m)^{-1}$), and vGRFs are normalized consistently such as body weight ($N*(BW)^{-1}$).

More recently, wearable devices such as loadsol® force-sensing insole devices have been more widely implemented to capture vGRFs during walking and landing among individuals with and without ACLR. These insole devices offer a portable and convenient method of evaluating vGRFs as a proxy for limb loading outside of the traditional laboratory environment and offer capabilities to capture a larger volume of data (e.g., greater number of landing trials or steps) as compared to traditional laboratory assessments. Loadsol® force sensing insoles are valid and reliable for the measurement of vGRF during walking and jump-landing tasks among individuals with and without knee injury. Loadsol® insoles can be inserted into participants' shoes and calibrated (e.g., body mass) using a standardized loading protocol described by the manufacturer. However, these devices are largely limited as they do not provide joint specific kinematic or kinetic data. In addition to insole devices, markerless motion capture systems are also becoming more readily used to evaluate kinematics of movement, but these systems are still largely underutilized for capturing lower extremity biomechanics. In addition, these devices provide different limitations including greater error in calculation of joint specific kinematics, depending upon movement speed and camera capture rate and capabilities. While these devices have greater ecological validity because they can be used in free-living conditions, they are still limited when compared to the comprehensive data that can be gathered from a traditional laboratory assessment.

KINESIOPHOBIA FOLLOWING ACLR

Kinesiophobia is defined as an irrational and debilitating fear to carry out physical movement(s) or activity due to feeling(s) of vulnerability from (painful) injury.[108] Kinesiophobia has been widely studied among individuals with musculoskeletal pain and chronic pain, and from pediatric and adolescent patients through individuals ages 65 years or older.[108] Kinesiophobia has been operationally defined as fear of movement, injury-related fear or fear of re-injury when applying the fear avoidance model to individuals who have experienced an ACL injury as described in Figure 2.[109,110] It is postulated that injury-related or pain-related fear may contribute to activity avoidance or changes in ambulation among individuals with knee OA and ACLR (Figure 2). Among individuals who have undergone ACLR, elevated kinesiophobia has been identified through qualitative interview studies as well as through patient-reported measures such as the Tampa Scale of Kinesiophobia (TSK-17, TSK-11) as early as pre-operative through several years post-ACLR. It is postulated that pain and perhaps unmanaged or poor psychological response following ACLR may contribute to fear avoidance of certain movements and/ or activities among this patient population which may lead to failure to return to pre-injury activity or even disability (Figure 2).[109]

Figure 2. The Fear Avoidance Model Adapted from Vlaeyen et al. 1995



Arden et al. consistently identified that psychological response to injury such as psychological readiness measured with the ACL-Return to Sport after Injury Index (ACL-RSI), was the largest barrier to return to pre-injury activity or sport engagement.[17] In fact, among this same cohort, nearly 24% of patients identified fear of a new injury as a barrier to return to pre-injury physical activity engagement.[111] This finding was supported by a systematic review and meta-analysis from the same author group that identified injury-related fear as a limiting factor to return to pre-injury activity participation.[112] Kvist et al. reported that among 62 individuals who had undergone ACLR at least 3 years prior, only 53% returned to pre-injury activity engagement. Among those individuals who had failed to return to sport, TSK-11 scores were elevated as compared to those who had returned to pre-injury participation.[15] Consistently, greater injury-related fear or movement related fear has been related to poorer physical activity participation and lack of re-engagement in pre-injury activity or sport levels post-ACLR.

Kvist et al. also first identified that women with ACLR may experience elevated levels of injury-related fear as compared to males (TSK-11 scores: 18 ± 5 and 15 ± 7; women and men, respectively).[15] However, it should be noted that gender or sex-based differences of fear of re-injury as measured with the TSK-11 are conflicting. Among men and women who were approximately 6 months post-ACLR, Kuenze et al. reported similar TSK-11 scores and ACL-RSI scores and only identified gender-based differences in patient perceptions of knee function and pain as measured with the IKDC and KOOS pain subscale, respectively.[113] Further investigation of injury-related fear, with particular consideration for longitudinal assessments is needed in order to determine how kinesiophobia may change over time, especially between groups.

In addition to the relationship between levels of kinesiophobia and return to sport, injury-related fear has been related to a host of performance-based, clinical and patient-reported outcomes among individuals with and without knee injury. Knee-related quality of life as measured with the KOOS quality of life subscale has been moderately related to injury-related fear assessed with the TSK-11 among individuals with ACLR ($r=-0.50$, $p<0.05$).[14] The relationship between kinesiophobia and quality of life has been consistently identified among individuals with ACLR, regardless of time since surgery. This suggests that lesser injury-related fear is related to better perceptions of quality of life among this patient population regardless of post-operative timepoint. In addition to these psychological considerations post-ACLR, elevated injury-related fear has been related to a host of other poor post-operative outcomes. Paterno et al. identified that individuals with higher injury-related fear (TSK-11 score ≥ 19) were 13 times more likely to sustain an ipsilateral ACL injury within only 2 years of primary ACLR (19.8 ±4.0, 16.4 ±3.6, $P=0.03$). Of the same cohort, individuals with elevated injury-related fear as characterized by a score ≥ 17 at the time of return to sport were also 4 times more likely to report low physical activity engagement and were 6-7 times more likely to demonstrate worse performance-based outcomes such as single leg hop for distance and quadriceps strength as compared to individuals that reported acceptable levels of injury-related fear.[16] In addition, sport-related deficits such as poorer (i.e., slower) lower extremity visuomotor reaction times and single leg hop performance post-ACLR have been related to greater injury-related fear from as early as a few months up to 10 years post primary ACLR.[114] When considering the influence of kinesiophobia on a host of patient-reported and performance-based outcomes among individuals with ACLR, kinesiophobia may be an important consideration in identifying factors that contribute to patient function and mechanics post-ACLR.

The relationship between kinesiophobia, physical activity engagement, and mechanics may be an especially important consideration for individuals with ACLR who are at in increased risk of knee OA development. When considering the identified relationship between pain and kinesiophobia, it is unsurprising that individuals with symptomatic knee OA report elevated kinesiophobia. Among individuals > 65 years old with bilateral knee OA, kinesiophobia assessed with the TSK-11 significantly predicted pain intensity ($B=1.05$, $p<0.001$).[115] Among individuals with knee OA, nearly 90% have reported elevated kinesiophobia (> 37 using TSK-17) and of this same cohort nearly 65% report engaging in low levels of physical activity.[116] Therefore, fear of activity or movement or related pain may be limiting physical activity engagement among a population where greater time spent in moderate-to-vigorous intensity physical activity has been related to better knee function and decreased pain and symptoms.

Greater kinesiophobia negatively influences self-reported physical activity re-engagement and participation among individuals with musculoskeletal injury such as ACLR and knee pathology such as knee OA. Greater injury-related fear has also been related to aberrant biomechanics, which may be due to avoidance of behaviors that are related to pain or reinjury among this population. Though, it remains unclear whether individuals with ACLR have specific biomechanical and free-living adaptations because of this pain or movement avoidance.

Kinesiophobia and Lower Extremity Biomechanics Following ACLR

The relationship between kinesiophobia and movement biomechanics has been minimally studied across clinical populations. Though, greater kinesiophobia has been negatively associated with lower extremity hopping and jump-landing biomechanics among individuals with ACLR (i.e., underloading). Trigsted et al. identified that among young women who were > 2 years post-ACLR, greater fear of re-injury as assessed with the TSK-11 was significantly and negatively related to knee and hip flexion and significantly and positively related to hip adduction during a jump-landing task. This indicates that women with ACLR with higher injury-related fear demonstrated a stiffened landing strategy related to second ACL injury risk.[117] Noehren et al. identified a relationship between fear of re-injury and ACLR limb underloading during a jump landing task among women who were 6 months post-operative. Specifically, a significant negative association between greater TSK-11 scores and lesser vGRFs of the reconstructed limb were identified ($r=-0.624$, $p=0.003$). This suggests that women with ACLR are demonstrating a weight shift away from their reconstructed limb at this timepoint.[118] This asymmetrical limb loading, especially during landing has been related to contralateral ACL injury risk among this patient population. Injury-related fear may influence lower extremity biomechanics among this patient population and targeting fear as an avenue for intervention may serve as a means to improve landing mechanics.

Among individuals with lateral knee OA following ACLR, a significant association between walking biomechanics and kinesiophobia ($r=0.535$) has been identified.[12] Specifically, greater trunk flexion which is indicative of a movement strategy to reduce knee joint load and pain, has been related to greater levels of injury-related fear. However, among individuals who were 49.35 ± 27.29 months post-ACLR, Luc-Harkey et al. identified weak or nonsignificant associations between measures of kinesiophobia and walking speed, vGRFs and knee joint biomechanics and symmetry indices.[119] It is important to note that ACLR limb peak vGRFs were weakly related to TSK-11 scores (R^2=0.098, p=0.057) among this sample and perhaps further investigation may be warranted. However, when considering the wide range of post-operative time points and the level of physical activity engagement among this sample, and that walking was captured on the treadmill rather than overground, generalizability of these findings may be limited. More recently, a research group has identified that greater levels of kinesiopohbia as measured with the TSK-11 were related to walking gait characteristics and symmetry post-ACLR. Though, in contrast to the previous investigation, authors identified a significant and positive relationship between TSK-11 score and peak vGRF symmetry during the second half of stance (r=0.531, p=0.002) and an nonsignificant relationship between injury-related fear and peak limb loading during the first half of stance (r=0.200, p=0.153).[103] This relationship may be significant as this asymmetry is indicative of ACLR limb underloading as compared to the contralateral limb. ACLR limb underloading has been related to a host of poor long-term knee joint health outcomes including the development of knee OA only 5 years following primary reconstruction. Therefore, addressing elevated injury-related fear may help to also remedy reconstructed limb underloading during the second half of stance. Addressing kinesiophobia may provide a pathway for addressing these psychological deficits as well as aberrant biomechanical adaptations that have been related to the development of knee OA among this patient population.

Measurement of Kinesiophobia

The Tampa Scale of Kinesiophobia (TSK-17) is a 17-item questionnaire developed by Miller et al. to capture patient-reported fear of movement/ activity or re-injury.[120] While the TSK-17 was created and validated in a chronic musculoskeletal pain patient population, it has been applied and widely implemented among individuals with knee pathology.[121] An abbreviated questionnaire, consisting of only 11 items has also been validated and widely implemented among pain and musculoskeletal injury populations, including individuals with ACLR.[120] The TSK asks the patient to respond to the prompts according to their feelings and score the prompts from strongly disagree to strongly agree, with a minimum score of 1 and a maximum score of 4 for each prompt. The total score for the TSK-17 ranges from 17-68 with scores > 37 indicative of elevated kinesiophobia; the total score for the TSK-11, however, ranges from only 11-44 and scores > 17 are indicative of elevated injury-related fear. A change (e.g., reduction) in TSK-11 scores of at least 4 points are indicative of a meaningful reduction of fear of movement or injury-related fear. Though another research group has reported a change of TSK score of at least 6 points is considered a minimal clinically important difference (MCID) or meaningful change in fear.[120] Table 2 includes the 11 items of the TSK-11 questionnaire.

When considering the psychometric properties of the TSK, the TSK-17 and TSK-11 both have acceptable internal consistency and discriminant, concurrent criterion-related and incremental validity. The TSK demonstrates construct validity (moderate correlation) with measures of pain-related fear, fear avoidance, pain catastrophizing, and disability. The TSK also exhibits acceptable test-retest reliability as characterized by ICCs > 0.82-0.89 and demonstrates moderate (r=0.33-0.59) concurrent validity.[120] Lastly, the

TSK-17 and TSK-11 demonstrate good internal consistency (TSK: α=0.76; TSK-11: α=0.79) and responsiveness (TSK: SRM=−1.19; TSK-11: SRM=−1.11).[120] The 11-tem, 2 subscale structure of the TSK was supported with confirmatory factor analysis. The TSK-11 is comprised of two subscales, activity avoidance and somatic focus. The somatic focus subscale is a reflection of beliefs and/ or underlying serious conditions. Activity avoidance is a reflection of beliefs that activity may result in greater pain or cause harm or injury. When controlling for pain severity, the somatic focus subscale is a predictor of perceptions of (dis)ability, and the activity avoidance subscale is a predictor of function or performance.[120] In total, the TSK-11 provides a short, valid and reliable method of evaluating patient fear of re-injury or movement/ activity across a variety of clinical populations.

Table 2. Tampa Scale of Kinesiophobia (TSK-11)

The TSK-11 survey asks for the patient to respond to the following prompts (strongly disagree, disagree, agree, strongly agree) based upon feelings.
1. I'm afraid that I might injure myself if I exercise.
2. If I were to try to overcome it, my pain would increase
3. My body is telling me I have something dangerously wrong.
4. People aren't taking my medical condition seriously enough
5. My accident has put my body at risk for the rest of my life
6. Pain always means I have injured my body.
7. Simply being careful that I do not make any unnecessary movements is the safest thing I can do to prevent my pain from worsening.
8. I wouldn't have this much pain if there weren't something potentially dangerous going on in my body.
9. Pain lets me know when to stop exercising so that I don't injure myself.
10. I can't do all the things normal people do because it's too easy for me to get injured
11. No one should have to exercise when he/she is in pain.

Adapted from: Miller, Robert P.; Kori, Shashidar H.; Todd, Dennis D.. The Tampa Scale: a Measure of Kinisophobia. The Clinical Journal of Pain: March 1991 - Volume 7 - Issue 1 - p 51. Woby, S. R., Roach, N. K., Urmston, M., & Watson, P. J. (2005). Psychometric properties of the TSK-11: A shortened version of the Tampa Scale for Kinesiophobia. *Pain, 117*(1-2), 137–144.

FREE-LIVING CADENCE FOLLOWING ACLR

Cadence, or steps taken per minute, has been related to declines in gait speed among adults at risk for or diagnosed with knee OA.[11,21,21] Declines and slower gait speed have also been related to poor physical function, morbidity and even mortality across clinical populations, including adults with knee OA.[122] Adults who have undergone ACLR within the previous five years engage in fewer minutes of moderate-to-vigorous physical activity and take fewer steps per day as compared to healthy, uninjured age-matched individuals.[26] In addition to these reduced step counts, there is evidence that adults with ACLR in the previous five years also spend less time in greater cadence intensities as compared to uninjured age-matched controls.[24] This indicates that individauls with ACLR take fewer steps per day and demonstrate a lower average cadence as compared to uninjured age-matched adults. When considering that slower gait speeds and reduced physical activity engagement such as taking fewer steps per day, are related to poorer physical function, indicators of knee joint health, and even mortality across clinical populations, assessment of free-living cadence may provide an indication of the intensity of ambulation (i.e., steps per minute) and the frequency of limb loading among individuals with ACLR who are at increased risk of knee OA development.

Assessment of Cadence (Steps per Minute)

Cadence, or steps taken per minute, can be assessed using a variety of techniques. Direct observation or step counting is considered the gold standard for step-count and cadence assessment.[123] However, a variety of wearable devices have been more recently validated that capture steps and can provide time-stamped minute-level step counts from which cadence can be calculated. For example, pedometers and uni-axial and tri-axial accelerometers have been more recently implemented because they are non-invasive and can provide a more comprehensive assessment of frequency and intensity of ambulation and limb loading as compared to laboratory-assessed measures. While volume-based step counts (i.e., daily step counts or number of steps taken) provide an indication of physical activity engagement, cadence may provide an indication of ambulation intensity and mechanics and gait speed. [123]

In overground and treadmill walking laboratory conditions, cadence intensity thresholds have been identified among adults ages 21-40 years old as described in Table 3.[124] Moderate intensity cadence characterized by 100-129 steps per minute, has been directly related to moderate intensity metabolic equivalents (i.e., 3-6 METs) and vigorous intensity cadence is characterized by > 130 steps per minute and has also been related to vigorous intensity METs (i.e., 6 METs). This suggests that these cadence thresholds are related to ambulation intensities. [124]Among these laboratory-based studies, direct observation was primarily used because it is considered the gold standard. However, device-assessed cadence provides an opportunity to assess free-living ambulation, which is more ecologically valid as compared to laboratory-based cadence measurement.

Table 3. Laboratory-based Cadence Intensities

Walking/ Ambulation Cadence Description	Minute-level Cadence	Activity Intensity- Metabolic Equivalents (METs)
Slow walking	60-79 steps per minute	< 2 METs
Medium walking	80-99 steps per minute	< 3 METs
Brisk walking	100-119 steps per minute	3-4 METs
M-V intensity ambulation	≥100-129 steps per minute	3-6 METs
Vigorous intensity ambulation	≥130 steps per minute	≥ 6 METs

M-V = moderate-to-vigorous

Device-Based Assessment of Cadence

For the purposes of this device-based review, we will discuss Actigraph uni-axial and tri-axial accelerometers as they have been most widely implemented to capture cadence under laboratory-based and free-living conditions.

Both uniaxial and triaxial Actigraph accelerometers demonstrate good agreement and both the uniaxial and triaxial counts are correlated with step counts for the Actigraph accelerometers.[125,126] The uniaxial Actigraph 7164 accelerometer is also considered reliable for assessing step counts and cadence (ICCs > 0.80)[124] in laboratory overground and treadmill conditions. In addition, the uniaxial Actigraph 7164 accelerometer demonstrates acceptable to good agreement with direct observation of steps for moderate to vigorous intensity cadences that are 100 to 180 steps per minute. When compared to direct observation step counts, the Actigraph 7164 accelerometer also demonstrates an absolute error of < 1.5% at ambulation speeds ranging from 2 to 4 mph.[127] In addition, wear-time also influences monitor reliability. When worn for 4 days for at least 10 hours per day (>i.e., greater than 600 minutes per wear period), the GT3X triaxial monitor demonstrates acceptable test-test reliability over 1 to 3 week periods (ICCs >0.80-0.90).[128] Therefore, it is recommended that individuals wear activity monitors for at least 4 days to achieve 80% reliability when accessing activity or step counts. Though there are a variety of considerations for length of wear time, at least 1 week of activity monitoring is considered a valid representation of physical activity behavior. When implementing accelerometry-based physical activity monitoring or assessment, it is recommended that adults wear accelerometers on the hip or waist. The accelerometer should be initialized with a sampling frequency of 30, 60 or 90 Hz and Choi et al.

recommend a minimum wear time of 600 minutes over a four-day period that includes 1 weekend day.[129] Though, factors such as seasonal variability due to weather, feasibility of monitor wear and location should be considered when implementing device-based physical activity monitoring.

Actigraph monitors consistently underestimate step counts at lower ambulation speeds (< 1.5-2.0 mph) when compared to the gold standard of direct observation step count. Though, these monitors are considered to have acceptable sensitivity and specificity, 83% and 89.6% respectively, when identifying moderate to vigorous physical activity when compared to indirect calorimetry, which is considered the gold-standard for physical activity intensity assessment.[128] Physical activity intensity has been calculated from accelerometry data across a variety of populations. Specifically, these intensity cut points are based upon device counts per minute (cpm). The Actigraph Gt3X and GT9X Link monitors are both triaxial accelerometers that determine counts based upon an Actigraph-specific algorithm that accounts for changes in acceleration along all three axes of motion. While activity counts are traditionally based upon accelerometer data from the vertical axis such as when using uniaxial accelerometers, newer triaxial Actigraph accelerometers use the vector magnitude (VM). The VM is the square root of the sum of squares of data from all three axes of motion (X, Y, Z). Freedson 1998 cut points utilize counts from the vertical axis to determine sedentary (0-100 cpm), light (101-1951 cpm), moderate (1952-5724 cpm) and vigorous (> 5724 cpm) activity intensities. However, Freedson 2011 VM cut-points utilize the vector magnitude data to determine sedentary (0-200 cpm), light (201-2690 cpm), moderate (2691-6166 cpm) and vigorous (> 6166 cpm) activity intensities.[125] While total activity counts are helpful for identifying the volume of activity in a given wear period, these cut-points are helpful in characterizing the intensity of this physical activity.

When considering calculation of cadence from wearable devices, such as Actigraph accelerometers, these devices provide step counts that can be identified at minute-level epochs. For example, Lisee et al. identified the number of steps completed in every 1-minute epoch on days that participants met adequate physical activity monitor wear time recommendations as described by Choi et al. in order to determine average and peak minute-level cadences and the time spent in various cadence-intensities in free-living conditions.[24] These monitors that are often utilized to assess the volume of physical activity participation may also provide an indication of cadence and cadence intensity which are spatiotemporal parameters of gait speed and may be indicative of free-living ambulation speed and walking mechanics.

Device-assessed Cadence among Adults

Tudor-Locke et al. reported free-living cadence among National Health and Nutrition Examination Survey (NHANES) adult participants from 2005-2006 who were ≥ 20 years old. Average daily time spent (i.e., minutes per day) in 8 cadence bands (i.e., 0 steps per minute, 1-19 steps per minute, 20-39 steps per minute, 40-59 steps per minute, 60-79 steps per minute, 80-99 steps per minute, 100-119 steps per minute, ≥ 120 steps per minute) and total steps per day were reported. Among this sample of 3744 adults, individuals spent approximately 7 minutes per day, or less than 0.5% of their day, in moderate or greater intensity cadence.[127] However, Troiano et al. and other research groups have reported that U.S. adults accumulate approximately 17-45 minutes of moderate-to-vigorous intensity physical activity per day, as determined by triaxial accelerometer activity counts of a similar NHANES adult population.[130] This suggests that assessment of moderate intensity cadence is not perfectly related to accelerometry intensity cut points.[127] However, when considering that walking speed is a function of cadence, and as speed increases, cadence and therefore intensity increases, cadence may serve as an indicator of gait speed and ambulation intensity, as well as mechanics, across populations.

While device-based assessment of cadence is valid and reliable, age, sex and height should be considered when reporting outcomes. Across the lifespan, laboratory assessed walking cadence is faster among women (96-138 steps per minute) as compared to men (81-135 steps per minute). Though, Tudor-Locke and colleagues report that among U.S. adults, men spend more time across all cadence intensities from incidental movements to vigorous intensities.[124] This indicates that while women walk at greater cadences, they also spend less overall time in ambulation as compared to men. There is also evidence that time spent in moderate intensity cadences is negatively associated with age. This suggests that older individuals may spend less time in greater intensity cadences as compared to younger individuals. This is supported by additional research that reports declines in gait speed with greater age among adult populations with and without lower extremity pathology. Moreover, as cadence is a spatiotemporal parameter of gait speed, considerations for leg length and/ or height should be accounted for. While there is evidence that step or stride length may influence up to 20% of change in gait speed, it is cadence that contributes the majority 80% of change in ambulation speed. For example, cadence intensities can vary by more than 20 steps per minute for adults 198 cm to 152 cm tall when considering leg/ stride length differences. In addition, there is also evidence that body size may influence cadence, with obese and overweight individuals exhibiting less time spent in higher intensity cadences, even though average daily step counts, and total time spent walking was similar between groups of obese, overweight and normal weight individuals. While age, sex and height/ leg length have been identified as contributors to cadence, it is unknown whether other modifiable or non-modifiable variables influence cadence outcomes, and thus, future investigations are warranted. [127]

Free-living Cadence Following Primary ACLR and Among Individuals with Knee OA

Free-living cadence among young adults (20.9 ± 3.2 years old) with ACLR has been evaluated in a single study by Lisee et al.[24] As compared to uninjured, age matched controls, individuals who were 28.7 ± 17.7 years post-ACLR engaged in fewer weekly minutes of moderate-to-vigorous intensity cadence (175.8 ± 116.5 minutes versus 218.5 ± 137.1 minutes; *P* = .048). These results indicate that individuals > 2 years post-ACLR walked 40 fewer minutes at moderate-to-vigorous intensity cadence each week as compared to individuals without ACLR. Though, there were no statistically significant differences between ACLR and uninjured groups for slow walking, medium walking, brisk walking or vigorous intensity ambulation cadences.[24] Monitoring free-living cadence may provide a clinically feasible avenue of improving physical activity engagement and ambulation intensity, and thus promoting knee joint health and potentially mitigating negative consequences related to knee OA among individuals with ACLR. In addition, when considering that individuals with ACLR also demonstrate aberrant laboratory-assessed walking biomechanics, free-living cadence may offer insight into spatiotemporal gait patterns that have been related to function and mortality across clinical populations, including individuals with knee OA.

Assessment of free-living cadence may be an important consideration for individuals with ACLR that are at increased risk of knee OA development. Fewer weekly minutes spent in moderate-to-vigorous intensity cadence (≥ 100 steps/ minute), reduced daily step counts and reductions in gait speed have been identified among individuals with and at-risk for knee OA development.[21] White et al. reported that among 1788 individuals with or at risk for knee OA from the Multicenter Osteoarthritis Study, walking less than approximately 6000 steps per day was related to declines in gait speed (i.e., walking at < 1.0 m/s) and self-reported function within a 2-year period.[20] This suggests that there is an observed decline in physical activity participation and gait speed which may influence changes in cadence or intensity. Perhaps, walking at least 6000 steps per day can preserve gait speed and prevent declines in ambulation speed and therefore function among adults with knee OA.

Among individuals with and at risk of knee OA, Fenton et al. reported that replacing 20 minutes per day of no ambulation with walking at moderate-to-vigorous intensity cadences (i.e., > 100 steps per minute) reduces risk of exhibiting gait speed less than approximately 1.0 m/ s.[11] Ambulation speeds < 1.0 m/s have been related to mortality and limitations in physical function among older adults and speeds < 1.2 m/s are indicative of functional limitations. In addition, declines in gait speed and slow ambulation speeds have been related to a variety of concerns including poor knee joint health among individuals with ACLR and knee OA, progression of knee OA, and even mortality.[11] Hart and colleagues, who observed aberrant mechanics among individuals with knee OA following

ACLR, suggest that these reductions in physical activity engagement and gait speed, which influence reductions in cadence, may result from aberrant biomechanical adaptations of the patient.[11] These adaptations may be employed to reduce or avoid pain, fear of pain or injury, or to improve other function. Therefore, it may be important to better understand the relationship between free-living cadence characteristics and laboratory assessed walking biomechanics including peak limb loading (i.e., peak vGRFs) and gait speed. Walking, landing and hopping vGRFs assessed with research grade force platforms have been significantly and positively correlated with triaxial accelerometry counts and peak vertical accelerations. In addition, Lisee et al. recently identified that the volume of steps taken per day is positively related to laboratory-assessed walking biomechanics.[131] Individuals that were approximately 8 months post-ACLR and walked the fewest steps per day (< ~6000 steps per day), also exhibited lesser reconstructed limb loading (i.e., lesser vGRFs) during stance as compared to individuals with ACLR that walked > 6000 steps per day.[131] Despite this association, it is unknown how cadence characteristics assessed under free-living conditions relate to laboratory-assessed walking biomechanics and ambulation speed. Assessment of free-living cadence may be an especially important consideration for individuals with history of ACLR that demonstrate aberrant walking biomechanics such as ACLR limb under- or over- loading, or slower gait speed.

CONCLUSION

Individuals with ACLR demonstrate aberrant lower extremity biomechanics such as ACLR limb under- or over- loading during walking which have been related to the development of knee OA. However, there is a critical gap in the literature investigating: 1) Contributors to aberrant walking biomechanics following ACLR such as injury-related fear and 2) The relationship between laboratory-assessed walking biomechanics and free-living cadence.

CHAPTER 3: THE ASSOCIATION BETWEEN LOWER EXTREMITY WALKING BIOMECHANICS AND KINESIOPHOBIA AMONG ADOLESCENTS AND YOUNG ADULTS 6 MONTHS FOLLOWING ANTERIOR CRUCIATE LIGAMENT RECONSTRUCTION

ABSTRACT

Elevated injury-related fear or kinesiophobia is commonly reported following anterior cruciate ligament (ACL) injury and reconstruction (ACLR) and among individuals with knee OA. Elevated kinesiophobia has been associated with aberrant walking biomechanics among individuals with diagnosed lateral knee OA 5 years following primary ACLR. In addition, individuals with ACLR demonstrate aberrant lower extremity walking biomechanics related to knee OA development such as lesser vertical ground reaction forces (vGRFs) of the ACLR limb, asymmetrical vGRFs between limbs, and slower gait speed. However, it is unclear whether elevated kinesiophobia meaningfully contributes to these aberrant walking biomechanics and slower gait speeds that have been related to early changes in articular cartilage health and knee OA development. Therefore, the purpose of this study was to determine the association between kinesiophobia and walking biomechanics among young adults and adolescents who have undergone ACLR 5-7 months prior. Sixty-five participants (age: 19.1 ± 5.4 years old, 55% female, 6.3 ± 1.6 months post-ACLR) underwent a walking biomechanics assessment to determine: 1) ACLR limb peak vGRF during the first 50% of stance, 2) Between-limb symmetry index for peak vGRF during the first 50% of stance, and 3) gait speed. At the same laboratory visit, participants completed the Tampa Scale of Kinesiophobia (TSK-11) to characterize injury-related fear. Participants who scored < 17 were considered to be experiencing "acceptable" injury-related fear and participants who scored ≥ 17 were considered to be experiencing "elevated" injury-related fear. Seventy-two percent of

participants (47/65) were characterized as experiencing elevated injury-related fear 6 months following primary ACLR. Despite this prevalence of elevated injury-related fear, kinesiophobia was not significantly associated with ACLR limb first peak vGRF ($P=0.634$, $F=0.230$, $\Delta R^2=0.0021$), first peak vGRF limb symmetry ($P=0.589$, $F=0.295$, $\Delta R^2=0.0048$), or gait speed ($P=0.856$, $F=0.0333$, $\Delta R^2=.0005$) among our sample. Our findings indicate that kinesiophobia may not have a significant influence on walking biomechanics early following surgery; perhaps other interventions such as real-time gait biofeedback may be more effective in addressing aberrant walking early following primary ACLR.

INTRODUCTION

Incidence of anterior cruciate ligament (ACL) injury among pediatric and adolescent patients < 20 years old and young adults 20-29 years old is more than double when compared to any other age groups.[37] More than 50% of adolescents and young adults who experience ACL injury and undergo surgical reconstruction (ACLR) will develop knee osteoarthritis (OA) within 20 years of surgery. This means that 1 in 2 adolescents will experience incurable, progressive knee OA by the time they are in their 30's or 40's.[5] In comparison, among adults > 45 years old without history of knee injury, less than 30% will be diagnosed with knee OA.[3] Consequently, individuals with history of ACLR experience negative consequences that are detrimental to knee joint health such as slower gait speed and aberrant walking biomechanics that have been related to knee OA development. When considering the incidence of ACL injury among adolescents and young adults and that individuals with ACL injury have a 4-6 times increased risk of developing knee OA as compared to uninjured control limbs, there is a clear need to identify contributors to and indicators of knee OA development. Aberrant walking biomechanics have been consistently identified as contributors to worse knee joint health and knee OA development following ACLR and may serve as an avenue to target individuals that may benefit from gait re-training interventions early following surgery.

Development of posttraumatic and idiopathic knee OA have been related to aberrant limb loading such as such as limb under- or over- loading as characterized by vertical ground reaction forces (vGRFs) that are significantly greater or less than the contralateral or healthy, uninjured control limbs.[87] Individuals with ACLR exhibit aberrant walking gait characteristics that have been related to indicators of poor knee joint health and the development of knee OA.[10,18] For example, 6 months following ACLR, ACLR limb underloading was related to greater T1ρ relaxation time ratios of articular cartilage of the medial femoral (ΔR = 0.24, P = 0.01) and lateral femoral (ΔR = 0.14-0.15, P = 0.05) condyles, which is indicative of detrimental changes in cartilage proteoglycan density that has been related to OA development.[83] In addition to structural changes in the knee joint, within the first year following surgery and up to 2 years post-ACLR, ACLR limb underloading has also been predictive of worse future symptom status up to 10 years post-ACLR.[94,101] It is postulated that individuals may adapt their walking biomechanics and underload their reconstructed limb in response to pain-related or injury-related fear, or kinesiophobia early following primary ACLR. In contrast, ACLR limb overloading has also been observed during overground walking among women approximately 5 years following surgery, and greater rates of loading have been associated with cartilage degradation in both animal and human posttraumatic models. In addition to this evidence for ACLR limb overloading at later post-operative timepoints, individuals with diagnosed lateral knee OA 5 years following ACLR also exhibit aberrant walking biomechanics that are related to elevated injury-related fear.[12] In addition to these considerations for aberrant walking biomechanics, there is also evidence that individuals with knee OA may reduce their walking speed in response to similar injury- or pain- related fear.[21] Among individuals with ACLR, slower walking speed has also been related to greater T1ρ relaxation time ratios of articular cartilage, indicative of poor knee joint health, only 6 months following surgery.[132] However, evidence for the relationship between modifiable characteristics such as injury-related fear, and walking biomechanics and gait speeds related to knee OA development, such as aberrant peak limb loading (i.e., vGRFs), limb loading symmetry and slower gait speed is limited among individuals with ACLR.

Kinesiophobia is characterized by an irrational or debilitating fear to carry out physical movements or activities due to feelings of vulnerability from pain and/ or an injury.[120] Among individuals with ACLR, kinesiophobia has been operationally defined as fear of movement or injury-related fear. It is postulated that pain and unmanaged or poor psychological response following ACLR may contribute to fear avoidance of sport-related movements or activities of daily living among this population. Elevated kinesiophobia is widely reported following ACLR, and up to 50% of individuals report TSK-11 scores ≥ 17 at 6-9 months post-ACLR, a post-operative timepoint that is commonly associated with return to modified activity or sport participation. Elevated kinesiophobia is associated with a 13 times greater likelihood of sustaining an ipsilateral ACL injury within the first 2 years following primary ACLR and has been identified as a primary barrier to return to pre-injury sport or activity levels among this population.[16,111] In addition, greater kinesiophobia has been related to reduced physical activity engagement, including lower levels of self-reported physical activity engagement using the Tegner Activity Scale among individuals with ACLR.[13,116] It is likely that individuals with ACLR with elevated kinesiophobia are altering their physical activity patterns (e.g., intensity, volume, type) or mechanics in response to this injury- or pain- related fear.[12] Therefore, a better understanding of how kinesiophobia influences lower extremity biomechanics may be an especially important consideration 6-months post-ACLR when kinesiophobia is reported to be elevated.

We hypothesize that 6 months following ACLR, individuals may adapt their movement biomechanics to underload their affected limb in response to injury-related fear or fear of pain during walking. While Luc-Harkey et al. did not report a statistically significant association between kinesiophobia and gait speed (ΔR^2 0.038, P = 0.319) and walking biomechanics (ΔR^2 = 0.001-0.098) among individuals 49.35 ± 27.29 months post-ACLR,[119] other research groups have identified significant associations between kinesiophobia and lower extremity biomechanics within the first year of ACLR.[103,118] For example, Noehren et al. identified a significant association between kinesiophobia and ACLR limb underloading during a jump landing task among women who were 6 months post-ACLR. A significant negative association between greater TSK-11 scores and lesser vGRFs of the reconstructed limb was identified (r=-0.624, p=0.003). These findings indicate that at 6-months post-ACLR, patients who underload their ACLR limb also report elevated kinesiophobia.[118] Despite these significant associations, it is unclear whether elevated kinesiophobia significantly influences walking biomechanics and gait speed in the same manner that it influences landing mechanics at this post-operative timepoint and walking biomechanics among individuals with knee OA. It is critical to investigate the association between walking biomechanics and kinesiophobia 6 months following primary ACLR because it is a timepoint that is often associated with elevated kinesiophobia and return to modified sports and physical activity.

Elevated kinesiophobia is commonly reported following ACLR and individuals with ACLR demonstrate aberrant lower extremity biomechanics related to knee OA development. However, it is unclear whether elevated kinesiophobia is meaningfully contributing to aberrant walking biomechanics and slower gait speeds that have been related to early changes in articular cartilage health and knee OA development. Therefore, the purpose of this study was to determine the association between kinesiophobia and walking biomechanics among young adults and adolescents who have undergone ACLR 5-7 months prior. Specifically, we will examine the associations between kinesiophobia, captured by the Tampa Scale of Kinesiophobia (TSK-11), and 1) peak ACLR limb loading (i.e., first peak vGRF), 2) peak limb loading symmetry (i.e., first peak vGRF symmetry indices) during walking, and 3) gait speed. We hypothesize that greater injury-related fear (i.e., greater TSK-11 scores) will be related to lesser ACLR limb peak loading, greater ACLR limb underloading asymmetry (i.e., vGRF symmetry indices < 90%), and slower gait speed among patients 5-7 months post-ACLR.

METHODS

This investigation is a cross-sectional analysis of data obtained from individuals who have sustained an ACL injury and undergone ACLR. The study was approved by the Michigan State University Institutional Review Board for Human Subjects Research (Approval #00002816 and #00002234). Enrolled participants ≥ 18 years old provided written informed consent and participants <18 years old provided written assent and at least 1 parent or legal guardian provided written consent prior to engagement in any study-related activities.

Participants

Participants were recruited from a university-affiliated sports medicine clinic from one of four fellowship-trained orthopaedic surgeons. Participants were eligible for this study if they were ≥ 13 years old at the time of study enrollment, had recently undergone ACLR and did not have any chronic medical condition or prescribed medications that would put them at risk of adverse outcome. Participants were included in the present analysis if they were 13-35 years old at the time of biomechanical assessment and had undergone ACLR 6 months (± 2 months) ago. Adults > 35 years old were excluded from the present analysis due to the elevated idiopathic knee OA incidence (> 0.13-0.25) among individuals over the age of 35 years old.[133] If more than one post-operative study visit was completed, the visit closest to six months post-ACLR was used for analysis. Only participants with complete surgical reports that could be verified via formal medical chart review were included.

Walking Gait Biomechanics

We determined habitual walking speed by asking participants to walk down a six-meter walkway in their own athletic shoes 5 times at a natural, comfortable pace. Gait speed was computed by dividing the distance covered (6 meters) by the time it took the participant to cover the distance (meters/ second, m/s) using a pair of timing gates (TracTronix, TF 100). Gait speed is reported as the average across five trials. During the subsequent biomechanics assessment trials, we ensured that participants walked within ± 5% of their habitual walking speed as changes in ambulation speed are associated with alterations in kinetics, kinematics and symmetry indices.[134]

Vertical ground reaction force (vGRF) data were collected at a sampling frequency of 1200 Hz using two embedded force platforms (Advanced Medical Technology Inc., Watertown, MA, USA). We acquired data from 5 trials that successfully captured one stride. A trial was considered successful if a participant's entire foot landed on two force platforms during subsequent foot strikes without normal gait being disrupted. vGRFs were assessed using Motion Monitor xGen software (Innovative Sports Training Inc., Chicago, IL, USA) and a custom Matlab code (R2022a, MathWorks Inc., Natick, MA, USA). Force plate data were lowpass filtered with a cutoff frequency of 12 Hz. First peak vGRF (i.e., peak loading) was identified as maximum limb loading (N) during the first 50% of stance, where initial contact was defined as > 20 N and terminal stance was defined as < 20 N. vGRFs were normalized to body weight ($N*(BW)^{-1}$) and reported as the average force across 5 trials.

To evaluate limb loading symmetry, we calculated and reported a Limb Symmetry Index (LSI %) for first peak vGRF as described in Equation 1 below:

$$LSI\ (\%) = (\frac{ACLR\ Limb\ Peak\ vGRF}{Contralateral\ Limb\ Peak\ vGRF}\, x\ 100\%)$$

Kinesiophobia

To characterize kinesiophobia, participants completed the Tampa Scale of Kinesiophobia (TSK-11) at the same visit as their walking assessment. Administration of the TSK-11 was not standardized to before or after the walking assessment. The TSK-11 is an 11-item questionnaire that asks the patient to respond to prompts from strongly disagree to strongly agree. Total scores range from 11-44, with higher total scores indicative of greater or elevated injury-related fear. The TSK-11 is a valid (r=0.33-0.59) and reliable (ICCs > 0.82-0.89) questionnaire to evaluate injury-related fear/ fear of movement among individuals with musculoskeletal and/ or chronic pain. [120,121] In accordance with *Chmielewski et al.,* participants who score < 17 will be characterized as experiencing "low" or "acceptable" injury-related fear and participants who score ≥ 17 will be characterized as experiencing "elevated" injury-related fear.

Power Analysis

We completed our power analysis based upon findings from Hart and colleagues, who reported a moderate association between walking biomechanics and kinesiophobia among individuals with diagnosed lateral knee OA 5 years following primary ACLR. Assuming this moderate correlation (r=0.535) and in order to obtain 80% statistical power with alpha set to 0.05, we determined that we would require at least 25 participants (G*Power Statistical Power Analysis v 3.1.9.7).

Statistical Analysis

Descriptive statistics (means and standard deviations) were calculated, and demographics were compared between groups with independent samples t-tests. Graft type was compared between groups using χ^2 tests of association and sex was compared between groups using Fisher's Exact test. All walking data were evaluated for normality; any participant data > 3 standard deviations from the mean were characterized as outliers and excluded from analysis.

Three linear regression models were developed to determine the association between injury-related fear as captured by TSK-11 score and 1) ACLR limb first peak vGRF, 2) peak vGRF LSI, and 3) gait speed. For the vGRF models, time since ACLR was entered at step 1, gait speed was entered at step 2, and TSK-11 group was entered at step 3. Time since ACLR and gait speed will be entered in these models because of their known influence on walking biomechanics. For example, greater gait speed is related to greater asymmetry and net forces as described above and greater time since ACLR is related to greater symmetry during walking. For the gait speed model, time since ACLR was entered at the first step, then TSK-11 group was entered at the second step. R^2 were calculated and used to identify overall model explained variance. ΔR^2 were calculated to determine the unique associations between the predictor and dependent variable, if significant. We also calculated and reported the unstandardized coefficient (β), 95% confidence intervals, F-statistics, and p-values. Significance was adjusted to $P < 0.0167$ (0.05/3) to account for three regression models included in analysis. We performed all statistical analyses using an open-source statistical software (v 2.2.5, *jamovi*).

RESULTS

Six months following primary ACLR, 18 participants (28%) were characterized as experiencing low or acceptable injury-related fear and 47 participants (72%) were characterized as experiencing elevated injury-related fear. There were no statistically significant differences in patient demographics between groups as reported below in Table 4.

After accounting for time since surgery and gait speed, kinesiophobia was not significantly associated with ACLR limb first peak vGRF (P=0.634, F=0.230, ΔR^2=0.0021), first peak vGRF limb symmetry (P=0.589, F=0.295, ΔR^2=0.0048), or gait speed (P=0.856, F=0.0333, ΔR^2=.0005). A summary of gait outcomes is included in Table 5, and linear regression models are outlined in Table 6 and Figure 3.

Table 4. Participant demographic characteristics (N=65)

	Acceptable Injury-Related Fear (n=18)	Elevated Injury-Related Fear (n=47)	P-Value
Age (years)	19.2 ± 5.9	19.1 ± 4.9	0.928
Sex (M/F(%F) *	9/9(50.0%)	20/27 (57.4%)	0.589
Graft type (BTB/HAS/QUAD) (n (%)) *	5/ 13/ 0 (27.8%/ 72.2%/ 0%)	11/ 35/ 1 (23.4%/ 74.5%/ 2.1%)	0.782
Time between ACLR and biomechanical assessment (months)	6.5 ± 1.6	6.1 ± 1.6	0.448

Data are presented as mean ± standard deviation, unless otherwise indicated
*Data are presented as frequency
† Indicates statistical significance at P<0.05
BTB= bone patellar tendon bone, HAS= hamstring, QUAD= quadriceps tendon, ACLR= anterior cruciate ligament reconstruction

Table 5. Participant Walking Biomechanics Characteristics (N=65)

	Acceptable Injury-Related Fear (n=18)	**Elevated Injury-Related Fear (n=47)**
*ACLR 1st Peak vGRF (x BW)	1.10 ± 0.08	1.11 ± 0.09
*LSI 1st Peak vGRF (%)	98.0 ± 5.3	98.9 ± 6.0
*Gait speed (m/s)	1.27 ± 0.15	1.26 ± 0.16

ACLR = Anterior cruciate ligament reconstruction limb, LSI= Limb symmetry index, vGRF= Vertical ground reaction force

Data are presented as mean ± standard deviation.

Table 6. Linear Regression Models for ACLR Limb First Peak vGRF, First Peak vGRF LSI, and Gait Speed (N=65)

ACLR Limb First Peak vGRF						
	Predictor Variables	**β (95% CI)**	**R^2**	**Adjusted R^2**	**F**	**P-Value**
Model 1			0.115	0.101	8.21	0.006*
	Time Since Surgery	0.0186 (0.00563, 0.0316)				0.006*
Model 2			0.444	0.426	24.73	<0.001*
	Time Since Surgery	0.0163 (0.00593, 0.0268)				0.003*
	Gait Speed	0.3167 (0.21209, 0.4214)				< 0.001*
Model 3			0.446	0.419	16.36	< 0.001

Table 6 (cont'd)

	Predictor Variables	β (95% CI)	R^2	Adjusted R^2	F	P-Value
	Time Since Surgery	0.01658 (0.00605, 0.0271)				0.003*
	Gait Speed	0.31732 (0.21196, 0.4227)				< 0.001*
	TSK-11	0.00879 (-0.02788, 0.0455)				0.634
First Peak vGRF LSI						
	Predictor Variables	**β (95% CI)**	**R^2**	**Adjusted R^2**	**F**	**P-Value**
Model 1			0.0001	-0.0157	0.00810	0.929
	Time Since Surgery	-0.0419 (-0.972, 0.888)				0.929
Model 2			0.0007	-0.0315	0.02141	0.979

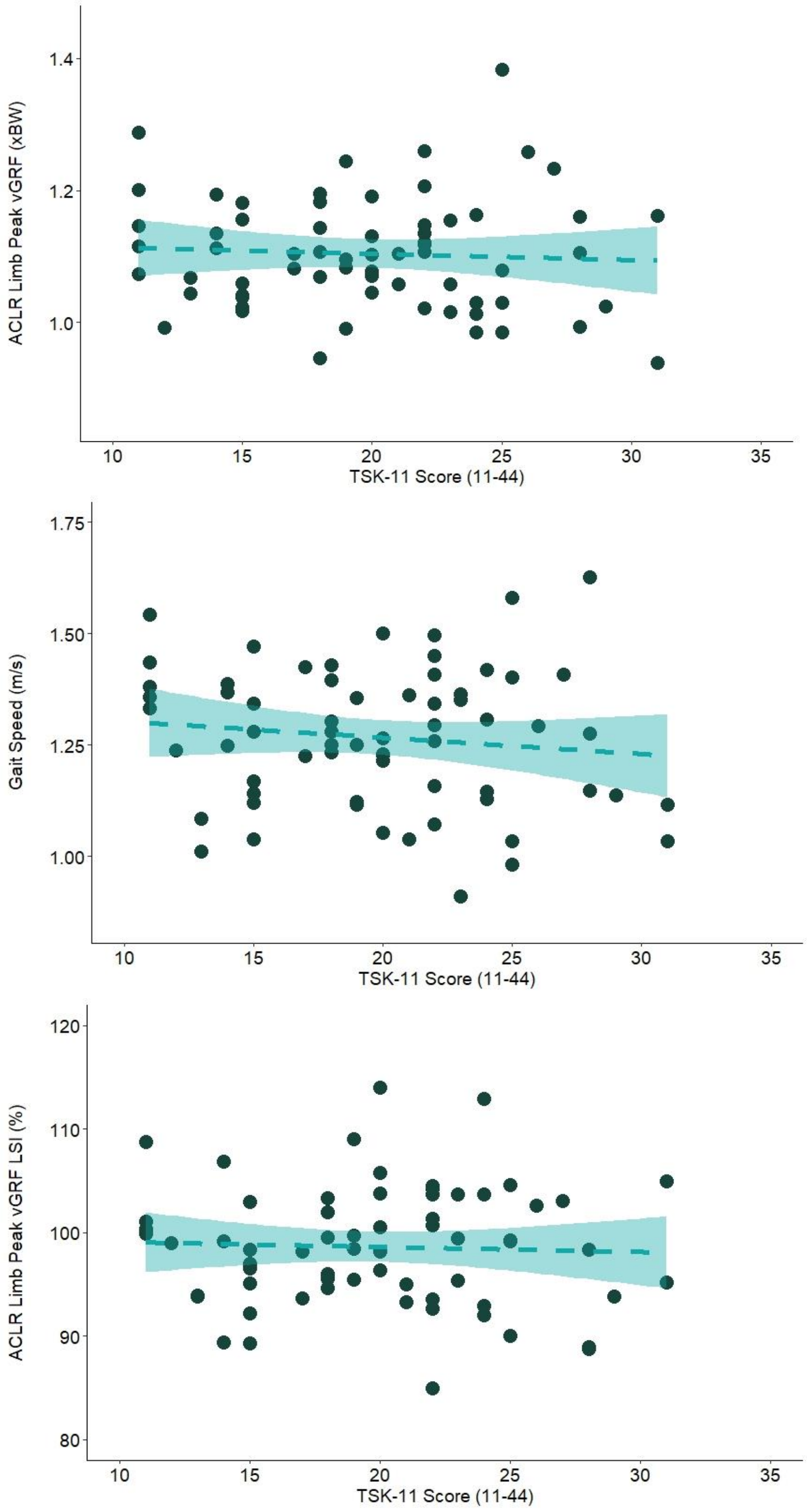
Table 6 (cont'd)

	Time Since Surgery	-0.0482 (-0.988, 0.891)				0.919
	Gait Speed	0.8816 (-8.559, 10.322)				0.853
Model 3			0.0055	-0.0434	0.11238	0.953
	Time Since Surgery	-0.0240 (-0.974, 0.925)				0.960
	Gait Speed	0.9414 (-8.559, 10.442)				0.844
	TSK-11	0.8978 (-2.409, 4.204)				0.589
Gait Speed						
	Predictor Variables	**β (95% CI)**	**R^2**	**Adjusted R^2**	**F**	**P-Value**
Model 1			0.00524	-0.0105	0.332	0.567

Table 6 (cont'd)

	Time Since Surgery	0.00721 (-0.0178, 0.0322)				0.567
Model 2			0.00578	-0.0263	0.180	0.836
	Time Since Surgery	0.00699 (-0.0183, 0.0323)				0.583
	TSK-11	-0.00806 (-0.0964, 0.0803)				0.856

Figure 3. Associations Between Kinesiophobia and Walking Biomechanics and Gait Speed 6 Months Following Primary ACL Reconstruction



DISCUSSION

This is the first study to examine the relationship between kinesiophobia and walking biomechanics among patients 6 months following primary ACLR. We evaluated the relationship between kinesiophobia and walking biomechanics at this specific post-operative timepoint because patients may still be engaged in formal rehabilitation, which may serve as an avenue for meaningful and clinically feasible intervention delivery. Seventy-two percent (47/65) of participants included in our sample were characterized as experiencing elevated injury-related fear. Despite the prevalence of kinesiophobia in our sample, it appears that elevated injury-related fear did not influence ACLR limb first peak vGRF, first peak vGRF LSI or gait speed within our sample of patients with ACLR. Therefore, our primary hypothesis was not supported. These findings indicate that management of kinesiophobia may not be effective in addressing aberrant walking biomechanics early following surgery.

Seventy-two percent of participants included in our sample were characterized as experiencing elevated kinesiophobia 6 months following ACLR. This is a much greater prevalence of kinesiophobia in comparison to Paterno and colleagues who reported that only 47.5% of patients had elevated TSK-11 scores at the time of return to sport, approximately 7-8 months following ACLR. Our sample demonstrated elevated TSK-11 scores (19.8 ± 5.2) at 6 months following ACLR. This is particularly concerning because Paterno and colleagues reported that those patients with a TSK-11 score of 19 or greater at the time of return to sport (7-8 months post-ACLR) were 13 times more likely to experience a second, ipsilateral ACL injury within only 2 years of return to sport. While the sample of participants from the Paterno study were 3 years younger (16.2 ± 3.4 years old), they were also, on average, 7.6 months post-ACLR, in comparison to our sample that was only 6 months post-ACLR (Table 4). Management of elevated kinesiophobia may be an important consideration at this postoperative timepoint because 6-months post-ACLR is often associated with return to modified sports or physical activity engagement. When considering the negative consequences associated with elevated kinesiophobia including reduced self-reported physical activity engagement, aberrant biomechanics and second ACL injury risk, management of kinesiophobia early following surgery may be beneficial to enhancing long-term post-operative outcomes.

Our analysis revealed that after accounting for time since surgery and gait speed, kinesiophobia was not associated with ACLR limb first peak vGRFs, first peak vGRF limb symmetry indices, or gait speed among individuals 6 months following primary ACLR. In our sample, ACLR limb first peak vGRFs were similar to previous reports of peak limb loading during the first 50% of stance (1.05-1.11 x BW). Our sample demonstrated lesser peak limb loading in early stance when compared to reports of uninjured healthy control or uninjured contralateral limbs (1.12 x BW) and the contralateral limbs included in our sample, though this was not directly reported or compared between groups. However, these findings do not support our hypothesis that elevated injury-related fear would be associated with lesser ACLR limb peak loading. These findings are in accordance with Luc-Harkey and colleagues who reported that walking biomechanics, including first peak vGRF in early stance, were not significantly associated with kinesiophobia among individuals 4 years post-ACLR ($P=0.057$, $\Delta R^2=0.098$).

Contrary to our hypothesis, elevated kinesiophobia was not associated with first peak vGRF LSIs indicative of ACLR limb underloading (i.e., LSI < 90%). Our sample demonstrated first peak vGRF LSIs that were indicative of acceptable between limb symmetry and on average > 98%. All but 3 participants demonstrated symmetry indices > 90%, which indicates that patients are exhibiting similar peak limb loading in early stance of both the ACLR and contralateral limbs. In comparison with previous findings, Luc-Harkey and colleagues reported similar LSI values (98.73 ± 2.62 %) and also concluded that peak limb loading symmetry in early stance was not associated with kinesiophobia 4 years post-ACLR ($P=0.415$, $\Delta R^2=0.024$). However, 37% of participants (24/65) included in our sample exhibited LSIs > 100%, indicative of greater ACLR limb loading relative to the contralateral limb, which is not commonly reported within the first year of surgery. The high symmetry and between-limb function demonstrated by our sample may have limited associations with kinesiophobia. This greater between-limb symmetry exhibited by our sample may be attributed to the number of adolescents included in our sample in comparison with previous literature that included adults only (46/65; 70.7%). While kinesiophobia was not cross-sectionally related to walking biomechanics post-ACLR, future investigations may be warranted to better understand if elevated kinesiophobia at other timepoints (e.g., pre-operative) may be indicative of walking post-ACLR.

Contrary to our hypothesis, elevated kinesiophobia was also not associated with slower gait speed among individuals 6 months post-ACLR. Our sample demonstrated gait speeds of 1.27 m/s which is like previous cohorts of individuals with ACLR and is 0.045 m/s slower than the free-living walking speed commonly reported among uninjured adults (i.e., 1.3 m/s). It is postulated that individuals with knee pathology such as knee OA or ACLR may reduce their walking speed in response to injury- or pain- related fear.[21]

However, the primary findings of this study did not support our primary hypothesis that greater kinesiophobia would be associated with aberrant overground walking biomechanics such as ACLR limb underloading and slower gait speed. Perhaps, tasks such as walking are not demanding or “risky” enough to elicit task-related fear or these underloading or slower gait strategies associated with elevated kinesiophobia.

Time since ACLR was entered as the first covariate in all models and was significantly associated with ACLR limb first peak vGRFs (Table 6) which is supported by previous literature describing that time since ACLR influences walking biomechanics up to 2 years post-operatively. However, time since ACLR was not associated with all other outcomes included in this analysis. Likely, time since ACLR did not significantly contribute to these other models because time since ACLR was relatively similar between groups (Table 4). However, it may be important to monitor the association between changes in walking biomechanics and changes in kinesiophobia at additional timepoints following ACLR.

Gait speed was entered as the second covariate in all models and was significantly associated with ACLR limb first peak vGRFs (Table 6). These results are in accordance with previous reports that gait speed is a significant contributor to walking biomechanics, including vGRFs. Gait speed was not significantly associated with first peak vGRF LSI (Table 6). There is evidence that individuals with ACLR exhibit greater kinetic and kinematic asymmetries during walking at faster gait speeds, but this is not supported by the vGRF LSIs included in our study. However, as described above and in Table 7, this may be due to the influence of age on walking symmetry in our sample. Collectively, however, time since ACLR and gait speed explained up to 50% of the variance in walking biomechanics among our sample, supporting the importance of the inclusion of these variables in biomechanical analyses.

Table 7. Linear Regression Models for ACLR Limb First Peak vGRF, First Peak vGRF LSI, and Gait Speed with Additional Covariates (Sex, Age)

ACLR Limb First Peak vGRF						
	Predictor Variables	**β (95% CI)**	**R^2**	**Adjusted R^2**	**F**	**P-Value**
Model 1			0.115	0.101	8.21	0.006*
	Time Since Surgery	0.0186 (0.00563, 0.0316)				0.006*
Model 2			0.444	0.426	24.73	<0.001*
	Time Since Surgery	0.0163 (0.00593, 0.0268)				0.003*
	Gait Speed	0.3167 (0.21209, 0.4214)				< 0.001*
Model 3			0.454	0.427	16.91	< 0.001*

Table 7 (cont'd)

	Time Since Surgery	0.0166 (0.00616, 0.0270)				0.002*
	Gait Speed	0.3111 (0.20606, 0.4162)				< 0.001*
	Sex	-0.0176 (-0.05041, 0.0152)				0.286
Model 4			0.476	0.441	13.62	< 0.001*
	Time Since Surgery	0.01717 (0.00685, 0.0275)				0.001*
	Gait Speed	0.32121 (0.21661, 0.4258)				< 0.001*
	Sex	-0.01056 (-0.04417, 0.0230)				0.532

Table 7 (cont'd)

	Age	-0.00260 (-0.00589, 0.00007)				0.118
Model 5			0.478	0.433	10.79	<0.001*
	Time Since Surgery	0.01738 (0.00694, 0.0278)				0.001*
	Gait Speed	0.32194 (0.21654, 0.4273)				< 0.001*
	Sex	-0.01005 (-0.04397, 0.0239)				0.556
	Age	-0.00261, (-0.00592, 0.00007)				0.119
	TSK-11	0.00801 (-0.02829, 0.0443)				0.660

Table 7 (cont'd)

First Peak vGRF LSI						
	Predictor Variables	β (95% CI)	R^2	Adjusted R^2	F	P-Value
Model 1			0.0001	-0.0157	0.00810	0.929
	Time Since Surgery	-0.0419 (-0.972, 0.888)				0.929
Model 2			0.0007	-0.0315	0.02141	0.979
	Time Since Surgery	-0.0482 (-0.988, 0.891)				0.919
	Gait Speed	0.8816 (-8.559, 10.322)				0.853
Model 3			0.0071	-0.0417	0.14549	0.932

Table 7 (cont'd)

	Time Since Surgery	-0.0357 (-0.981, 0.910)				0.940
	Gait Speed	0.5843 (-8.953, 10.122)				0.903
	Sex	-0.9343 (-3.910, 2.042)				0.533
Model 4			0.1378	0.0803	2.3964 6	0.060
	Time Since Surgery	0.0612 (-0.830, 0.952)				0.891
	Gait Speed	2.2424 (-6.790, 11.274)				0.621
	Sex	0.2272 (-2.674, 3.129)				0.876
	Age	-0.4278 (-0.712, -0.144)				0.004*
Model 5			0.1427	0.0701	1.9643 6	0.097
	Time Since Surgery	0.0854 (-0.815, 0.985)				0.850

Table 7 (cont'd)

	Predictor Variables	β (95% CI)	R^2	Adjusted R^2	F	P-Value
	Gait Speed	2.3263 (-6.763, 11.416)				0.610
	Sex	0.2860 (-2.639, 3.211)				0.846
	Age	-0.4292 (-0.715, -0.144)				0.004*
	TSK-11	0.9140 (-2.217, 4.045)				0.561
Gait Speed						
	Predictor Variables	**β (95% CI)**	**R^2**	**Adjusted R^2**	**F**	**P-Value**
Model 1			0.00524	-0.0105	0.332	0.567
	Time Since Surgery	0.00721 (-0.0178, 0.0322)				0.567
Model 2			0.01505	-0.0167	0.474	0.625
	Time Since Surgery	0.00755 (-0.0175, 0.0326)				0.550

Table 7 (cont'd)

	Sex	-0.03098 (-0.1098, 0.0478)				0.435
Model 3			0.02966	-0.0181	0.621	0.604
	Time Since Surgery	0.00657 (-0.01863, 0.0318)				0.604
	Sex	-0.04091 (-0.12248, 0.0407)				0.320
	Age	0.00383 (-0.00416, 0.0118)				0.342
Model 4			0.03063	-0.0340	0.474	0.755
	Time Since Surgery	0.00628 (-0.01924, 0.0318)				0.625

Table 7 (cont'd)

Sex	-0.04157 (-0.12398, 0.0408)	0.317
Age	0.00384 (-0.00421, 0.0119)	0.344
TSK-11	-0.01089 (-0.09980, 0.0780)	0.807

Limitations

First, this study is limited because it is cross-sectional; therefore, we cannot determine cause-and-effect relationships between kinesiophobia and walking among patients 6-months post-ACLR. Second, level of physical activity engagement and rehabilitation data were not consistently collected or standardized among participants which may have influenced gait biomechanics and kinesiophobia. Our groups were also unbalanced with more than 70% of participants characterized with elevated injury-related fear.

Due to limitations in sample size and number of statistical comparisons, we did not include several potential covariates in this analysis. For example, women consistently reported elevated injury-related fear and there is evidence that walking biomechanics may differ between men and women, but frequency of sex distribution did not differ between kinesiophobia groups, therefore sex was not included as a covariate in our primary analysis. In addition, age is known to influence kinesiophobia and there is emerging evidence that walking biomechanics may differ between adolescents and adults post-ACLR (Collins et al., under review, MSSE). However, groups were of a similar age, therefore, age was not included as a covariate in our primary analysis. Acknowledging these limitations, we have completed a secondary analysis that includes time since ACLR, gait speed, sex, and age as covariates in the vGRF linear regression models and time since ACLR, sex and age as covariates in the gait speed linear regression model. The results of this additional analysis are outlined in Table 7. Sex was not a significant contributor to any vGRF or gait speed models; however, age was a significant contributor to first peak vGRF LSI, which is in accordance with emerging evidence that age may influence walking post-ACLR.

Finally, this study did not include kinematic or kinetic variables that have been previously reported to characterize walking post-ACLR. However, vGRFs are commonly reported and have been related to indicators of knee joint health and symptom status post-ACLR and among individuals with knee OA. Due to the ease and relative affordability of vGRF assessment, walking can be assessed in the laboratory, free-living or clinical environment.

Conclusions

Seventy-two percent of participants reported elevated injury-related fear 6 months following primary ACLR. Greater kinesiophobia or injury-related fear was not associated with ACLR limb first peak vGRFs, first peak vGRF LSIs or gait speed among individuals 6 months post primary ACLR. When considering the negative consequences associated with elevated kinesiophobia, management of kinesiophobia early following surgery may be beneficial to enhancing post-operative outcomes but may not be a primary influence on walking.

CHAPTER 4: THE ASSOCIATION BETWEEN LABORATORY-ASSESSED WALKING BIOMECHANICS AND GAIT SPEED WITH FREE-LIVING CADENCE CHARACTERISTICS FOLLOWING ANTERIOR CRUCIATE LIGAMENT RECONSTRUCTION

ABSTRACT

Individuals with anterior cruciate ligament reconstruction (ACLR) exhibit aberrant walking biomechanics including vertical ground reaction forces (vGRFs) and slow walking speeds that have been related to indicators of poor knee joint health and knee osteoarthritis (OA) development within only 5 years of surgery. However, walking biomechanics and gait speed are often assessed in laboratory conditions with limited ecological validity. Cadence, or steps taken per minute, is a spatiotemporal component of gait speed. Cadence can be measured in free-living conditions using wearable devices such as smartwatches, which may provide an ecologically valid avenue to assess and intervene on free-living ambulation. When considering the ubiquity of physical activity or step count monitoring through research-grade and commercially available devices, assessment and manipulation of cadence may serve as a feasible avenue to influence gait speed and walking biomechanics. Therefore, the purpose of this study was to assess the associations between laboratory-assessed gait speed, ACLR limb peak vGRF, and peak vGRF symmetry with free-living cadence characteristics among individuals with ACLR. We hypothesized that laboratory-assessed gait speed, peak vGRF, and vGRF symmetry will be associated with free-living cadence characteristics, including: 1. average daily cadence, 2. average light cadence (60-100 steps per minute), 3. average light-to-moderate cadence (60-130 steps per minute), and 4. peak cadence, among individuals with ACLR. Participants with ACLR completed a single laboratory visit to assess walking speed and ACLR limb vGRFs. Laboratory gait speed was measured using a pair of timing

gates (TracTronix, TF 100) and is reported as the average across 5 trials. vGRFs were collected using 2 embedded force platforms (Advanced Medical Technology Inc., Watertown, MA). ACLR limb peak vGRF was identified during the first 50% of stance and normalized to participant body weight. ACLR limb peak vGRF is reported as the average across 5 trials. ACLR Limb peak vGRF LSI is also reported as the average across 5 trials. For the next 7 days, participants wore an Actigraph GT9X Link monitor (Actigraph, LLC, Pensacola, FL) on their right hip. Monitor data were collected at 30 Hz and wear-time was validated with a minimum of 600 minutes of wear time per day for at least 4 days, including 1 weekend day. Non-wear time was removed from analysis and remaining data were analyzed in minute-level epochs. Peak cadence is reported as the maximum number of steps taken during any 1-minute period of wear time. Average daily cadence is reported as the average steps taken per minute across all valid wear-time. Partial correlations were used to determine the association between laboratory gait: 1) ACLR limb peak vGRF, 2) peak vGRF LSI, and 3) gait speed and free-living cadence: 1) mean light cadence, 2) mean light-to-moderate cadence, 3) mean daily cadence, and 4) peak cadence. Total monitor wear time and participant height were entered as control variables for all partial correlations. Forty-eight participants (age: 21.3 ± 6.0 years old, sex: 26 F/ 22 M (54% F), height: 174.0 ± 8.0 cm, mass: 77.5 ± 20.0 kg, time since ACLR: 13.9 ± 15.9 months, total monitor wear time: 5910 ± 2372 minutes) met inclusion criteria and had adequate free-living and laboratory gait data. Laboratory-assessed gait speed was positively and moderately associated with peak 1-minute free-living cadence (r=0.444, P=0.002). Laboratory-assessed gait speed was not significantly related to free-living average daily cadence (r=-0.172, P=0.253), mean light cadence (r=0.011, P=0.940), or mean light-to-moderate cadence (r=0.280, P=0.059). ACLR peak vGRF was positively and weakly associated with peak 1-minute free-living cadence (r=0.331, P=0.025). ACLR limb peak vGRF was not significantly related to average daily free-living cadence (r=0.075, P=0.622), mean light cadence (r=0.158, P=0.294), or mean light-to-moderate cadence (r=0.092, P=0.093). Peak vGRF LSI was not significantly related to average daily free-living cadence (r=0.011, P=0.945), peak 1-minute cadence (r=0.090, P=0.550), mean light cadence (r=0.104, P=0.494), or mean light-to-moderate cadence (r=-0.104, P=0.490). Our hypotheses were only partially supported. The findings of this study indicate a disconnect between average laboratory gait and average free-living gait. However, our results also suggest that participants who demonstrated greater walking speeds and vGRFs in the laboratory environment also exhibited greater peak minute-level cadences in free-living conditions. Targeting peak cadence outside of the laboratory environment using wearable devices may serve as an avenue to modify or intervene on laboratory walking speeds and vGRFs that have been previously related to poor knee joint health and knee OA development following ACLR.

INTRODUCTION

Incidence of anterior cruciate ligament (ACL) injury is greatest among individuals 15-35 years old.[37] Despite a common goal of return to pre-injury level of physical activity participation, there are reports that less than 1 in 4 individuals who have undergone ACLR will return to pre-injury levels of physical activity within 2 years of surgery. In addition, more than 50% of individuals who opt to undergo ACLR following ACL injury will develop knee osteoarthritis (OA) within 2 decades of surgery. In fact, individuals who experience ACL injury have a 4.2 times greater risk of developing knee osteoarthritis (OA) in the affected knee when compared to the contralateral limb knee or the knees of uninjured individuals.[4] As a consequence of this knee injury and surgery, individuals with ACLR will demonstrate slower walking speeds and aberrant walking biomechanics that have been related to indicators of poor knee joint health and knee OA development.

Repetitive, aberrant mechanical loading of the knee is a known contributor to development of idiopathic and posttraumatic knee OA.[6–9] Aberrant ACLR limb loading has been significantly associated with clinical-imaging and biomarker indicators of poor knee joint health only 6 months following ACLR and the development of radiographic evidence of knee OA within 5 years of surgery.[9,132] For example, adults within the first year following primary ACLR demonstrate ACLR limb underloading relative to the contralateral limb as characterized by peak vertical ground reaction force (vGRF) limb symmetry indices (LSIs) < 100%. These underloading LSIs during walking have been related to cartilage matrix protein degradation only 6 months following primary ACLR. In addition, at the same post-operative timepoint, lesser ACLR limb loading, as characterized by lower peak vGRFs, has been related to greater T1ρ relaxation time ratios of articular cartilage, which is indicative of detrimental changes in cartilage proteoglycan density that has been related to OA development.[83] While under- and lesser- loading of the ACLR limb early following surgery has been widely reported, ACLR limb over- loading has also been observed 2-5 years following surgery. In fact, greater loading rates of the involved limb have been associated with cartilage degradation in animal and human posttraumatic knee OA models. However, these aberrant walking biomechanics that have been related to poor knee joint health and knee OA development are most commonly evaluated in research laboratory environments, with limited ecological validity.

In addition to aberrant laboratory-assessed walking biomechanics, individuals with ACLR and knee OA demonstrate slower laboratory walking speeds as compared to uninjured healthy control groups. For example, among individuals who had undergone ACLR 6 months prior, slower laboratory walking speed was related to MRI-indicators of poor knee joint health, including lesser proteoglycan density, and biomarkers of poor knee joint health, including greater collagen breakdown of the articular cartilage.[132] In addition to these mechanical considerations, declining and slower gait speeds have also been related to poor physical function, morbidity and even mortality across clinical populations, including adults with knee OA.[122] Gait speed may serve as not only an important indicator of knee joint health and physical function, but also serves as an avenue to influence mechanics.

Gait speed can influence joint kinematics and kinetics, and symmetry, as well as ground reaction forces, with greater ambulation speeds associated with greater net forces and torques and larger asymmetries across injured and uninjured populations.[134–138]

Modifying ambulation speeds, such as increasing walking speed at the time of assessment, has been used to manipulate laboratory walking and running biomechanics among uninjured populations, including runners and injured populations, especially in individuals with knee OA. When considering these findings, increasing or manipulating walking speed may provide an avenue to influence limb loading among individuals who demonstrate lesser involved limb loading. However, laboratory gait has low external validity, and it is unclear how these laboratory gait speeds are related to free-living ambulation.

Cadence, or steps taken per minute, is a spatiotemporal component of gait as described by the following equation:

$$Gait\ Speed = Step\ Length * Cadence.$$ [139]

While cadence is not a direct indictor of gait speed as described above, assessment of cadence has many advantages because it can be measured under free-living conditions using wearable devices (e.g., triaxial accelerometers). Therefore, cadence measured outside of the laboratory environment may provide an ecologically valid avenue to evaluate free-living ambulation and gait.[123] Free-living cadence among individuals with ACLR has been evaluated by Lisee et al. using research grade triaxial accelerometers.[24] As compared to uninjured controls, individuals who were on average more than 2 years post-ACLR spent 40 fewer weekly minutes in moderate-to-vigorous intensity cadence (175.8 ± 116.5 minutes versus 218.5 ± 137.1 minutes; $P = .048$) and had slower average daily cadences (11.3 ± 3.4 steps per minute versus 10.0 ± 3.0 steps per minute).[24] These findings indicate that individuals with ACLR are spending less time in cadences > 100 steps per minute, which has also been observed among individuals with and at-risk for knee OA. In addition, these results indicate that individuals with ACLR are, on average, ambulating at slower cadences as compared to uninjured controls, which is also like reports of individuals with and at risk for knee OA. Moreover, Lisee and colleagues recently identified that individuals 6-10 months post-ACLR who took approximately 3326-6042 steps per day demonstrated ACLR limb underloading as characterized by lesser vertical ground reaction forces during the stance phase, as compared to individuals with ACLR that walked more than 6043 steps per day. These findings suggest a potential link between free-living step counts and laboratory-assessed walking biomechanics among this population. Despite these identified associations between laboratory vGRFs and free-living step counts, and the potential benefits of evaluating free-living cadence among a population that demonstrates reduced cadences, there has not been an investigation of the relationship between laboratory-assessed gait speed and mechanics with free-living cadence characteristics.

Fenton and colleagues suggest that reductions in gait speed among individuals with knee OA, which influence reductions in cadence, may result from aberrant biomechanical adaptations.[11] Despite this postulated relationship, it is unclear how free-living assessed cadence characteristics are related to laboratory-assessed walking biomechanics and gait speed among a clinical population that is at increased risk of knee OA development. When considering the ubiquity of physical activity or step count monitoring through research-grade and commercially available smartwatches (e.g., Fitbit Charge 5, Apple Watch Series 7), manipulation of cadence (e.g., spend 20 more minutes per day taking at least 100 steps per minute)[11] may serve as a feasible avenue to influence gait speed and therefore walking biomechanics in both laboratory and free-living conditions,[136,137] which may enhance likelihood of clinical application. Therefore, the purpose of this study was to assess the associations between laboratory-assessed gait speed, ACLR limb peak vGRF, and peak vGRF symmetry with free-living cadence characteristics among individuals with history of ACLR. We hypothesized that slower laboratory-assessed gait speed, lesser peak vGRF, and vGRF underloading asymmetry would be associated with slower free-living cadence characteristics, including lesser 1. average daily cadence, 2. average light cadence (60-100 steps per minute), 3. average light-to-moderate cadence (60-130 steps per minute), and 4. peak 1-minute cadence, among individuals with ACLR.

METHODS

This investigation is a cross-sectional analysis of individuals who have sustained an ACL injury and undergone ACLR. The study was approved by the Michigan State University Institutional Review Board for Human Subjects Research. Enrolled participants ≥ 18 years old provided written informed consent and participants ≤ 17 years old provided written assent and at least 1 parent or legal guardian provided written consent prior to engagement in any study-related activities.

Participants

Participants were recruited from a university-affiliated sports medicine clinic from one of three fellowship-trained orthopaedic surgeons. Participants were eligible for this study if they were ≥ 13 years old at the time of study enrollment and had undergone ACLR anytime within the previous 4 months to 5 years. Participants were included in the present analysis if they were 13-35 years old at the time of biomechanical assessment. Adults > 35 years old were excluded from the present analysis due to idiopathic knee OA incidence (> 0.13-0.25) among individuals over the age of 35 years old.[133] If more than one post-operative study visit was completed, the visit closest to six months post-ACLR was used for analysis.

Walking Gait Biomechanics

We determined habitual walking speed by asking participants to walk down a six-meter walkway 5 times at a natural, comfortable pace in their own athletic shoes. Laboratory gait speed was computed by dividing the distance covered (6 meters) by the time it took the participant to cover the distance (m/s). Laboratory gait speed was assessed using a pair of timing gates (TracTronix, TF 100) and is reported as the average across five trials.

During the subsequent biomechanics assessment trials, we ensured that participants walked within ± 5% of their habitual walking speed as changes in ambulation speed are associated with alterations in kinetics, kinematics and symmetry indices.[134]

Vertical ground reaction force (vGRF) data were collected at a sampling frequency of 1200 Hz using two embedded force platforms (Advanced Medical Technology Inc., Watertown, MA, USA). We acquired data from 5 successful walking trials. A trial was considered successful if a participant's entire foot landed on a force platform during subsequent foot strikes without normal gait being disrupted. vGRFs were calculated using Motion Monitor xGen software (Innovative Sports Training Inc., Chicago, IL, USA) and a custom Matlab code (R2022a, MathWorks Inc., Natick, MA, USA). Force plate data were lowpass filtered with a cutoff frequency of 12 Hz. Peak vGRF (i.e., peak loading) was identified as maximum limb loading (N) during the first 50% of stance, where initial contact was defined as > 20 N and terminal stance was defined as < 20 N. Peak vGRF was normalized to body weight ($N^*(BW)^{-1}$) and is reported as the average peak force across 5 trials. To evaluate between-limb symmetry, we calculated and reported a Limb Symmetry Index (LSI %) for peak vGRF across 5 trials as described in Equation 1 below:

$$LSI\ (\%) = (\frac{ACLR\ Limb\ Peak\ vGRF}{Contralateral\ Limb\ Peak\ vGRF}\, x\ 100\%)$$

Free-living Cadence

For 7 days following their laboratory-based walking assessment, participants were asked to wear an Actigraph GT9X Link monitor (Actigraph, LLC, Pensacola, FL) for all hours, except for water and sleep activities, and as described in Table 8. The Actigraph GT9X Link monitor is a triaxial accelerometer that determines counts per minute (cpm) based upon an Actigraph-specific algorithm that accounts for changes in acceleration along all three axes of motion. Importantly, these activity counts are strongly correlated with step counts.[128] The threshold for step detection for Actigraph GT9X Link monitors is based upon the previously described algorithm and a minimum acceleration amplitude of 0.07g.[140] Finally, the Actigraph GT9X Link monitor has been previously implemented to evaluate steps, physical activity intensities and cadence intensities in free-living conditions among individuals with ACLR.[24,26,131]

Activity and step counts were collected and analyzed in accordance with recommendations from Montoye et al. as described in Table 4.[141] Wear-time validation was based upon criteria from Choi et al. and non-wear time was removed from analysis as also described by this research group.[129] All acceleration data were processed in ActiLife software (version) and minute-level (i.e., 60-second epoch) step counts were exported during all validated wear-times. Cadence variables of interest were calculated and reported as described below in Table 8.

Table 8. Summary Table for Device-Based Activity Data Collection and Analysis

Accelerometer Model	GT9X Link Actigraph Monitor
Data Collection Sampling Rate	30 Hz
Data Analysis Epoch Length	60 s
Accelerometer Placement/ Location	Right ASIS
Validation Criteria	≥ 4 valid days (3 weekday and 1 weekend day) ≥ 600 minutes per day
Variables of Interest	
Peak Cadence (steps/min)	Maximum number of steps taken in any single 60 second epoch
Average Daily Cadence	Average steps taken across all 60 second epochs of valid wear time
Average Light Cadence (60-100 steps/min)	Average minute-level cadence during epochs of 60-100 steps/min
Average Light-to-Moderate Cadence (60-130 steps/min)	Average minute-level cadence during epochs of 60-130 steps/min

*ASIS= anterior superior iliac spine

Power Analysis

We completed our power analysis based upon Adams and colleagues who reported moderate and strong positive correlations between laboratory peak vGRF variables and low cadences during running (r=0.865) among injured and uninjured runners. Assuming a positive and moderate correlation, and to obtain 80% statistical power with alpha set to 0.0167 (0.05/3), we determined that we would require at least 35 participants (G*Power Statistical Power Analysis v 3.1.9.7).

Statistical Analysis

Descriptive statistics were calculated for all participant demographic information, laboratory gait, and free-living cadence outcomes. Laboratory gait and free-living cadence data were evaluated for normality, and any participant data > 3 standard deviations from the mean were characterized as an outlier and therefore excluded from analysis. Partial correlations were used to determine the association between laboratory gait and: 1) ACLR limb peak vGRF, 2) peak vGRF LSI, and 3) gait speed and between free-living cadence and: 1) mean light cadence, 2) mean light-to-moderate cadence, 3) mean daily cadence, and 4) peak cadence, as reflected in Table 11. Activity monitor wear time and height will be entered as control variables because monitor wear time and height are known to influence cadence and device-based activity characteristics. Associations between free-living cadence and laboratory gait outcomes were interpreted using Pearson's r as: < 0.39: weak, 0.40-0.69: moderate, and > 0.70 strong.[142] We performed all statistical analyses using an open-source statistical software (v 2.2.5, *jamovi*).

RESULTS

Fifty-one participants had adequate monitor wear time and 5 complete walking trials. Three participants' laboratory walking and/ or free-living cadence data were considered outliers and were excluded from analysis. Forty-eight participants with history of primary, unilateral ACLR were included in this analysis and their demographic characteristics are described in Table 9. Participant laboratory gait and free-living cadence characteristics are summarized in Table 10 and partial correlations included in Table 11. Scatterplots of partial correlations are included in Figures 4-6.

Laboratory-assessed gait speed was positively and moderately associated with peak 1-minute free-living cadence (r=0.444, P=0.002). Laboratory-assessed gait speed was not significantly related to free-living average daily cadence (r=-0.172, P=0.253), mean light cadence (r=0.011, P=0.940), or mean light-to-moderate cadence (r=0.280, P=0.059).

ACLR peak vGRF was positively and weakly associated with peak 1-minute free-living cadence (r=0.331, P=0.025). ACLR limb peak vGRF was not significantly related to average daily free-living cadence (r=0.075, P=0.622), mean light cadence (r=0.158, P=0.294), or mean light-to-moderate cadence (r=0.092, P=0.093).

Peak vGRF LSI was not significantly related to average daily free-living cadence (r=0.011, P=0.945), peak 1-minute cadence (r=0.090, P=0.550), mean light cadence (r=0.104, P=0.494), or mean light-to-moderate cadence (r=-0.104, P=0.490).

Table 9. Participant demographic characteristics (N=48)

Age (years)	21.3 ± 6
Sex (M/F(%F) *	22/26 (54%)
Height (cm)	174.0 ± 8.0
Weight (kg)	77.5 ± 20.0
Time between ACLR and assessment (months)	13.9 ± 15.9

Data are presented as mean ± standard deviation, unless otherwise indicated
*Data are presented as frequency
ACLR= anterior cruciate ligament reconstruction

Table 10. Participant Laboratory Gait and Free-living Cadence Characteristics

Laboratory Gait Variables	
Gait Speed (m/s)	1.26 ± 0.14
ACLR Limb Peak vGRF (x BW)	1.10 ± 0.08
vGRF LSI (%)	99.9 ± 6.0
Free-Living Cadence Variables	
Mean Light Cadence (60-100 steps/min)	77.4 ± 6.7
Mean Light-to-Moderate Cadence (60-130 steps/min)	86.7 ± 6.8
Mean Daily Cadence (steps/min)	8.2 ± 2.5
Peak Cadence (steps/min)	145.0 ± 25.0
Valid Monitor Wear Time (average minutes/ day)*	827 ± 134

Data are presented as mean ± standard deviation, unless otherwise indicated
ACLR= anterior cruciate ligament reconstruction, LSI= limb symmetry index
*control variable

Table 11. Associations of Laboratory Gait and Free-living Cadence Characteristics

Laboratory Gait Variable	Free-Living Cadence Variables	Pearson Correlation (r)	P-Value
Gait speed	Mean Light	0.011	0.940
	Mean Light-to-Moderate	0.280	0.059
	Mean Daily	-0.172	0.253
	Peak	0.444	0.002*
ACLR peak vGRF	Mean Light	0.158	0.294
	Mean Light-to-Moderate	0.092	0.093
	Mean Daily	0.075	0.622
	Peak	0.331	0.025*
vGRF LSI	Mean Light	0.104	0.494
	Mean Light-to-Moderate	-0.104	0.490
	Mean Daily	0.011	0.945
	Peak	0.090	0.550

ACLR= anterior cruciate ligament reconstruction, vGRF= vertical ground reaction force, LSI= limb symmetry index
*indicates statistical significance
Height and total monitor wear time were entered as control variables

Figure 4. Association of Laboratory-assessed Gait Speed and Free-living Cadence Characteristics

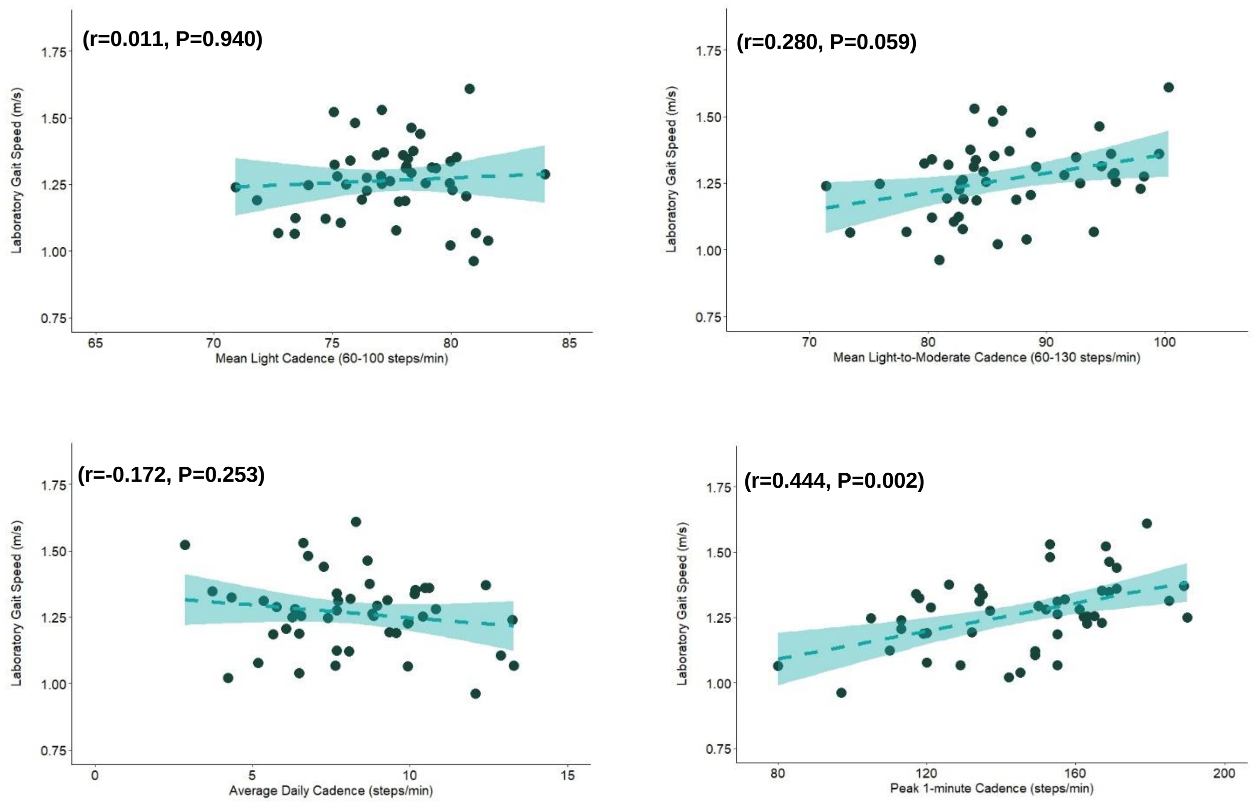


Figure 5. Association of Laboratory-assessed ACLR Limb Peak vGRF and Free-living Cadence Characteristics

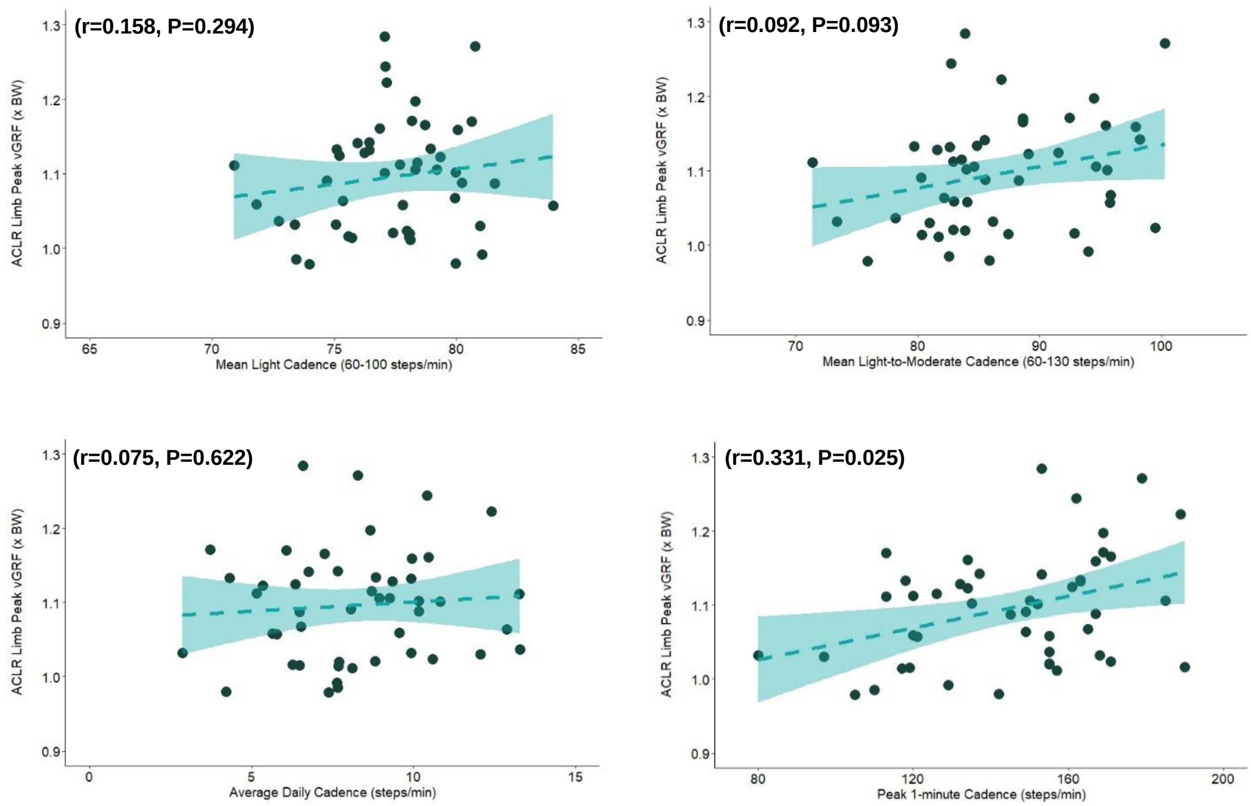
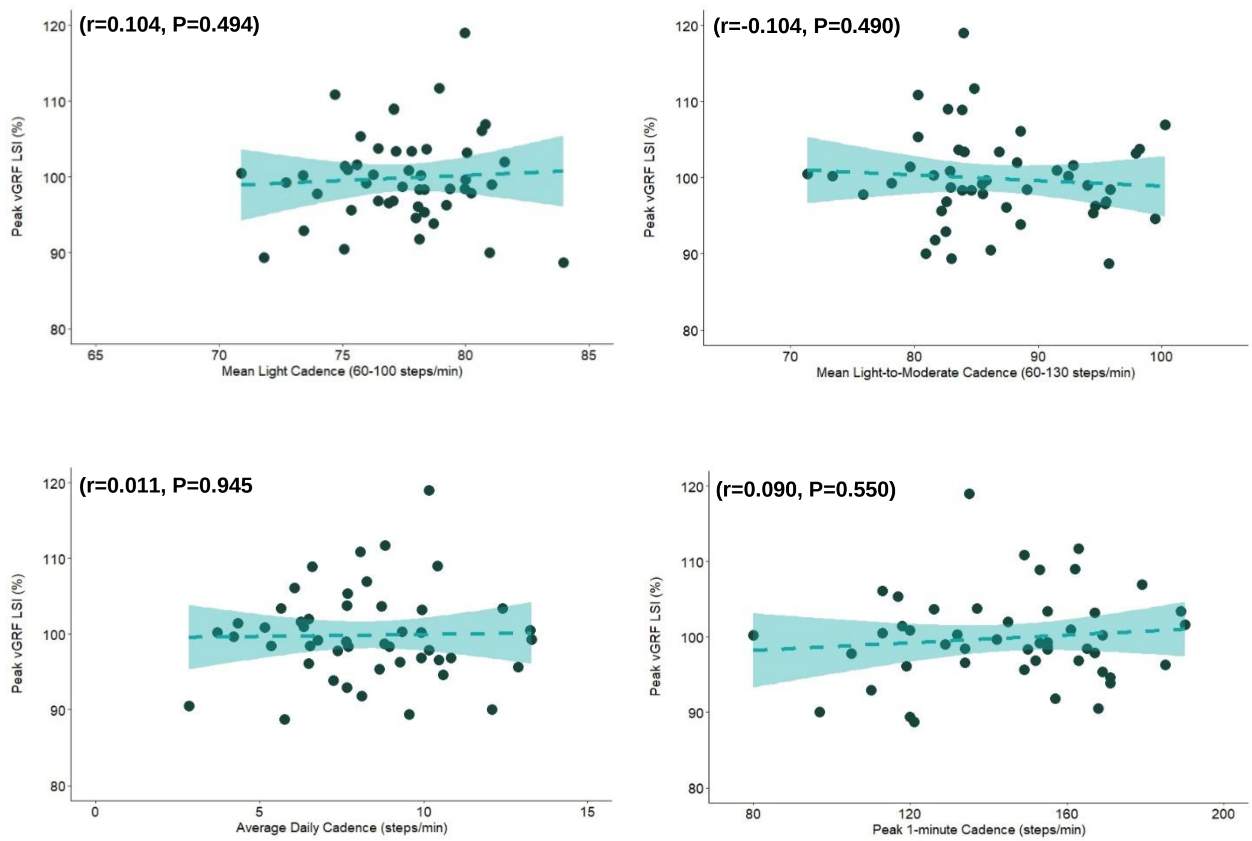


Figure 6. Association of Laboratory-assessed Peak vGRF LSI and Free-living Cadence Characteristics



DISCUSSION

To the authors' knowledge this is the first study to examine the association between laboratory-assessed walking speed, peak vGRF, and peak vGRF LSI with free-living cadences among individuals with history of ACLR. This is also the first study to the authors' knowledge to report free-living mean light and light-to-moderate cadences among individuals with ACLR. The findings of this study indicate that laboratory assessed walking speed, ACLR limb peak vGRF and peak vGRF LSI were not significantly associated with average daily, light, or light-to-moderate cadences. However, laboratory gait speed and ACLR limb peak vGRF were moderately and weakly associated with peak 1-minute cadence. Therefore, our hypotheses were only partially supported. These findings primarily indicate a disconnect between average laboratory-assessed gait characteristics and average free-living gait characteristics. This highlights that one-time laboratory assessments of gait speed and mechanics are not necessarily representative of free-living ambulation in which individuals spend the bulk of their time. However, these findings also suggest that targeting peak 1-minute cadence outside of the laboratory environment using wearable devices may serve as an avenue to modify or intervene on laboratory walking speeds and vGRFs that have been previously related to poor knee joint health and knee OA development following ACLR.

Contrary to our hypothesis, average laboratory gait speed was not significantly associated with free-living mean light or light-to-moderate cadences. The results of this study highlight a discrepancy between average laboratory gait speed and average free-living cadences, which has been previously reported in uninjured adults and clinical populations. Participants were instructed to walk in the laboratory at a comfortable, natural pace and demonstrated similar laboratory walking speeds as compared to previous reports of adults with ACLR (i.e., 1.1-1.3 m/s). Therefore, we anticipated that this average laboratory gait speed would be related to average free-living cadences (i.e., light and light-to-moderate cadences). Specifically, we hypothesized that laboratory gait speeds would be related to light and light-to-moderate cadences because these cadences identify purposeful light walking (60-100 steps per minute) and purposeful light-to-moderate walking (60-130 steps per minute). However, while individuals included in our sample spent, on average, 98.8% of their time each day in cadences < 100 steps per minute, most of this time (96.48%) was spent in cadences < 60 steps per minute. Therefore, these findings highlight both the large amount of time participants spent in non-purposeful ambulation and sedentary activities, and that the average walking cadences exhibited in free-living conditions are not related to average laboratory gait speeds.

Average daily cadence was also not significantly related to average laboratory gait speed. Average daily cadences were low due to the large amount of time spent in low cadence or sedentary activities (i.e., 0 step counts), but are similar to Lisee and colleagues who reported average daily cadences of individuals with and without ACLR (6-10 steps/ minute). When excluding sedentary activity from analysis (i.e., remove 0 step counts), average daily cadences increased to 16.6 ± 3.5 steps per minute. Though, upon supplemental analysis, these average daily cadences were also not related to laboratory-assessed gait speed or vGRFs (Table 12). To the authors' knowledge, previous literature has not reported daily cadences with 0s removed. However, we aimed to evaluate the association between ambulation in the laboratory and free-living environment, and not sedentary periods. Collectively, these findings suggest that the gait speeds that individuals with ACLR exhibit in the lab are not related to the average daily cadences exhibited by these same individuals in free-living conditions.

Table 12. Associations of Laboratory Gait Characteristics and Free-living Mean Daily Cadence with 0s Removed

Laboratory Gait Variable	Pearson Correlation (r)	P-Value
Gait Speed	-0.091	0.546
ACLR peak vGRF	0.196	0.193
vGRF LSI	0.048	0.753

ACLR= anterior cruciate ligament reconstruction, vGRF= vertical ground reaction force, LSI= limb symmetry index
Height and total monitor wear time were entered as control variables
Mean daily cadence is reported as the average cadence (steps/minute) across all non-zero 60-second epochs of valid wear-time

Our analysis revealed that those individuals who exhibited faster average laboratory gait speeds also exhibited faster peak minute-level cadences under free-living conditions. This finding was surprising because we had anticipated a relationship between average laboratory gait speed and average cadences, which was not observed. The peak 1-minute cadences exhibited by our sample were slower as compared to reported peak cadences of adults 2 years post-ACLR. Lisee and colleagues reported peak cadences of 152.2 ± 23.4 steps/min among adults with ACLR, which was similar to healthy, uninjured controls. However, our sample demonstrated peak cadences of 145.0 ± 25.0 per minute, which is considerably slower. Peak cadence is indicative of a 'best natural effort', and lesser peak cadences in free-living conditions have been related to poor general health outcomes among older adults. Targeting peak 1-minute cadence in free-living conditions may provide several benefits. Based upon the results of this study, increasing peak 1-minute cadence may serve as an avenue to influence laboratory-assessed gait speeds that have been previously related to indicators of poor knee joint health after ACLR. In addition, increasing peak 1-minute cadence may improve or increase the patient's 'best natural effort,' which may be beneficial for knee-specific and general health outcomes. Future research is needed to determine the feasibility and efficacy of peak 1-minute cadence interventions delivered in free-living conditions on laboratory gait speeds.

Laboratory-assessed ACLR limb peak vGRF was not significantly associated with free-living average daily cadence, light cadence, or light-to-moderate cadence. These findings did not support our primary hypothesis and indicate that the average peak vGRFs of 5-10 steps in the laboratory environment are not related to the average cadences that participants spent > 98% of their time each day. Our results provide greater evidence for the disconnect between average laboratory walking mechanics and average free-living walking characteristics. Similar to the laboratory gait speed findings, participants who demonstrated greater ACLR limb loading (i.e., greater peak vGRFs) also demonstrated faster peak 1-minute free-living cadences. This association is in accordance with Lisee and colleagues who reported that individuals with ACLR who took the greatest number of steps per day also demonstrated greater ACLR limb vGRFs during overground walking. Findings from Lisee and colleagues provide insight into the relationship between the frequency of steps taken (i.e., how many) and the magnitude of ACLR limb loading (i.e., peak vGRF), but not free-living cadence. While this is a similar, positive association between laboratory and free-living mechanics, Lisee and colleagues reported steps taken per day and not minute-level cadence, so comparisons are limited. However, this positive association between vGRF and minute-level cadence is not in accordance with previous reports of laboratory cadence and vGRFs among individuals with and without knee OA. Increasing cadence at the time of biomechanical assessment has been shown to reduce loading (e.g., vGRFs and vGRF loading rates) in uninjured populations. Moreover, Hart and colleagues reported that among individuals with knee OA, those who demonstrate higher cadences at the time of biomechanical assessment also demonstrate lower knee joint loading, including knee adduction moments and vGRFs. However, these relationships were observed concurrently in the laboratory environment and are not representative of real-world mechanics or related to free-living cadences. Also, it is important to note that both research groups controlled for concurrent gait speed, which is known to impact vGRF outcomes. We did not include gait speed as a covariate in the

ACLR limb correlations; we ensured participants walked within 5% of their previously determined habitual walking speed during subsequent biomechanics trials in order to reduce the impact of variability in gait speed. When considering the potential impact of changes in cadence on walking biomechanics, manipulation of peak cadence may serve as a potentially promising avenue to intervene on ACLR limb vGRFs that have been previously related to indicators of poor knee joint health following surgery. However, future research is needed to determine the feasibility and efficacy of wearable-device interventions manipulating peak free-living cadence on laboratory walking biomechanics. In addition, laboratory-based cadence interventions that manipulate step rate at the time of vGRF assessment could provide further insight into the relationship between laboratory ACLR limb peak vGRFs with cadence, as the present results do not support that increasing free-living cadence would decrease vGRFs among this population.

This study is the first to the authors' knowledge to report the association between laboratory vGRF LSI and free-living cadence outcomes. No free-living cadence outcomes were significantly associated with laboratory-assessed peak vGRF LSI among individuals with history of ACLR. These findings did not support our primary hypothesis that greater free-living cadences would be associated with greater vGRF asymmetry due to the reported association between greater gait speed and asymmetry during laboratory walking following ACLR. Our findings may have been impacted by the highly symmetrical walking demonstrated by our sample (average LSI: 99.9%). Only two participants demonstrated LSIs < 90% and more than 50% of our sample demonstrated LSIs > 99%. In summary, similar to the laboratory gait speed and vGRF findings, these results support that there is a large disconnect between free-living cadence and laboratory-assessed gait characteristics. These findings indicate that interventions manipulating free-living cadence will likely not influence walking symmetry among individuals with ACLR. Therefore, other interventions, such as laboratory or clinic based real-time biofeedback gait retraining may be needed to restore walking symmetry among patients following ACLR.

Manipulating peak 1-minute cadence may influence laboratory walking speeds and vGRFs that have been previously related to deleterious changes in knee joint health and knee OA development. Due to the ubiquity of step count monitoring using smartwatches or smartphones, wearable-device interventions targeting peak 1-minute cadence may provide a feasible avenue for influencing gait outcomes. Providing step goals to increase peak cadence or time spent in peak cadence may provide a clinically feasible avenue to intervene on free-living cadences. In addition, Perry and colleagues have also suggested using music to help individuals meet cadence goals, which may be helpful for greater intensities, such as vigorous or peak cadences. Intervening on peak minute-level free-living cadence may provide an avenue to influence walking biomechanics and slow gait speeds that have been previously related to poor knee joint health following primary ACLR. In addition, increasing peak 1-minute cadence may have general health benefits for a population that is at-risk of experiencing the negative consequences and limitations associated with knee OA. However, future research is needed to determine the feasibility and efficacy of cadence interventions delivered under free-living conditions on influencing laboratory walking mechanics and speeds.

Limitations

We cannot determine cause-and-effect relationships due to the cross-sectional design of this study. Due to limitations in sample size and number of statistical comparisons, we did not include several potential control variables in this analysis. For example, we did not control for participant sex or age in our primary analysis, both of which research groups have reported may influence walking biomechanics and cadence outcomes. However, previous literature assessing cadence post-ACLR did not include these control variables. In addition, upon completing a supplemental analysis with total monitor wear time, height, participant sex, and age all entered as control variables, no correlations were meaningfully impacted (Table 13). Finally, we included participants from a large post-operative range (4 months to 5.5 years), which may have influenced laboratory gait outcomes. In fact, 72.9% (35/48) of participants included in our analysis were < 12 months post-ACLR when gait is consistently reported to be aberrant as compared to uninjured controls. There is evidence that individuals walk with underloading LSIs and lesser ACLR limb peak vGRFs early following primary ACLR, but this may be restored by 2-5 years post-operative. There is also evidence that laboratory gait speeds among individuals within the first year of primary ACLR are slower when compared to uninjured peers, but speeds are similar 3 years post-ACLR. However, there is minimal longitudinal data to support these claims.

Table 13. Associations of Laboratory Gait and Free-living Cadence Characteristics with Additional Control Variables

Laboratory Gait Variable	Free-Living Cadence Variables	Pearson Correlation (r)	P-Value
Gait speed	Mean Light	0.042	0.789
	Mean Light-to-Moderate	0.241	0.116
	Mean Daily	-0.112	0.471
	Peak	0.445	0.002*
ACLR peak vGRF	Mean Light	0.164	0.288
	Mean Light-to-Moderate	0.215	0.160
	Mean Daily	0.132	0.391
	Peak	0.351	0.019*
vGRF LSI	Mean Light	0.105	0.499
	Mean Light-to-Moderate	-0.111	0.473
	Mean Daily	0.015	0.922
	Peak	0.089	0.565

ACLR= anterior cruciate ligament reconstruction, vGRF= vertical ground reaction force, LSI= limb symmetry index
*indicates statistical significance
Height, total monitor wear time, age and sex were entered as control variables

Conclusions

Average laboratory gait speeds and vGRFs are not associated with average free-living cadences (daily, light, light-to-moderate); however, faster laboratory gait speed and greater ACLR limb peak vGRF are associated with greater (i.e., faster) free-living peak cadences. These findings indicate a disconnect between laboratory-assessed average gait speed and vGRF with free-living average cadences. However, these findings also suggest that wearable-device interventions delivered in free-living conditions that target peak 1-minute cadence may serve as an avenue to modify or intervene on walking speeds and vGRFs that have been previously related to poor knee joint health and knee OA development following ACLR.

CHAPTER 5: FREE-LIVING CADENCE CHARACTERISTICS OF ADOLESCENTS REPORTING ELEVATED AND ACCEPTABLE INJURY-RELATED FEAR 6 MONTHS FOLLOWING ANTERIOR CRUCIATE LIGAMENT RECONSTRUCTION

ABSTRACT

Elevated injury-related fear, also known as kinesiophobia, is commonly reported following anterior cruciate ligament (ACL) injury and reconstruction (ACLR) and among individuals with knee OA. Elevated kinesiophobia is related to an increased risk of second ACL injury and has been identified as a primary barrier to return to pre-injury sport and physical activity participation. This is an important consideration for adolescents who are at risk of experiencing the negative consequences of knee OA early in the lifespan. It is postulated that individuals with knee OA may reduce their walking speed and therefore cadence in response to similar injury- or pain- related fear. As a result, it is critical to investigate the association between free-living cadence and physical activity (i.e., step counts) with kinesiophobia 6 months following primary ACLR because it is a timepoint that is often associated with elevated kinesiophobia and a return to modified or unrestricted sport and physical activity participation. Therefore, the purpose of this study was to compare free-living cadence characteristics and step counts between adolescents who report elevated and acceptable injury-related fear 6-9 months post-ACLR. Specifically, we will examine the association between kinesiophobia, captured by the Tampa Scale of Kinesiophobia (TSK-11), and: 1. average steps per day, 2. mean light cadence, 3. mean light-to-moderate cadence, 4. mean daily cadence, and 5. peak cadence. We hypothesized that adolescents reporting elevated injury-related fear (i.e., TSK-11 scores ≥ 17) would take fewer steps per day and have slower mean light cadences, mean light-to-moderate cadences, mean daily cadences, and peak cadences, as compared to adolescents who

report acceptable injury-related fear 6-9 months post-ACLR. Adolescents who were 6-9 months post primary, unilateral ACLR completed the Tampa Scale of Kinesiophobia (TSK-11) to characterize injury-related fear. Participants who scored < 17 were considered to be experiencing “acceptable” injury-related fear and participants who scored ≥ 17 were considered to be experiencing “elevated” injury-related fear. For one week following their lab visit, participants wore an Actigraph GT9X Link monitor (Actigraph, LLC, Pensacola, FL) on their right hip. Monitor data were collected at 30 Hz, and wear-time was validated with a minimum of 600 minutes of wear time per day for at least 4 days, including 1 weekend day. Non-wear time was removed from analysis, and remaining data were analyzed in minute-level epochs. Mean light cadence is reported as the average number of steps taken each minute during wear periods of 60-100 steps per minute. Mean light-to-moderate cadence is reported as the average number of steps taken each minute during wear periods of 60-130 steps per minute. Peak cadence is reported as the maximum number of steps taken during any 1-minute period of wear time. Average daily cadence is reported as the average steps taken per minute across all valid wear-time. Average steps per day is reported as the average steps taken per day of valid wear-time. We utilized 5 separate ANCOVAs to compare steps per day and cadence characteristics between adolescents with elevated and acceptable injury-related fear following ACLR, while controlling for total monitor wear time and participant height. Six months following primary ACLR, 19 participants (63.3%) were characterized as experiencing elevated injury-related fear and 11 participants (36.7%) were characterized as experiencing acceptable or low injury-related fear. Adolescents who reported elevated injury-related fear demonstrated slower mean light cadences ($F=9.518$, $P=0.005$,

η_p^2=0.268) as compared to adolescents who reported acceptable injury-related fear. There were no statistically significant differences between adolescents with elevated and acceptable injury-related fear for mean light-to-moderate (F=2.95, P=0.098, η_p^2=0.102), mean daily (F=1.357, P=0.294, η_p^2=0.594), and peak cadences (F=0.2382, P=0.630, η_p^2= 0.009), or average steps per day (F=1.4257, P=0.243, η_p^2=0.052). Management of elevated kinesiophobia 6-9 months following primary ACLR may provide an avenue to intervene on free-living light cadences among adolescents, with the goal of improving long-term knee joint health and general health comes.

INTRODUCTION

The incidence of anterior cruciate ligament (ACL) injury among pediatric and adolescent patients < 20 years old is more than double when compared to any other age groups.[37] ACL injury rates have been consistently increasing over the previous two decades, and these greater injury rates are largely attributed to increased organized sport participation at younger ages and have been linked to changes in somatic growth and pubertal maturation among children and adolescents.[143,144] Despite a common goal of return to pre-injury level of physical activity or sport participation, only 24- 50% of patients who opt to undergo surgical reconstruction (ACLR) return to pre-injury level of sport participation within 2 years of surgery.[64] This is an important consideration for adolescents because sport participation serves as a primary source of physical activity engagement among individuals < 20 years old.[145] Losing a source of physical activity early in the lifespan may have negative consequences,[146,147] such as reduced daily step counts and less time spent in moderate-to-vigorous intensity activities, both of which have been linked to indicators of poor knee joint health and worse general health outcomes.

Elevated kinesiophobia is widely reported following primary and second ACLR and at 6-9 months post-ACLR.[16,118,148] In fact, nearly 50% of adults and adolescents will report elevated kinesiophobia as characterized by Tampa Scale of Kinesiophobia (TSK-11) scores ≥ 17 within the first year of surgery.[16] Elevated kinesiophobia is associated with a 13 times greater likelihood of sustaining a second ACL injury and has been identified as a primary barrier to return to pre-injury sport or activity levels among this clinical population.[16,111] In addition, greater kinesiophobia has been related to lower levels of self-reported physical activity engagement using the Tegner Activity Scale among individuals with ACLR.[13,116] Meaning, it is likely that individuals with ACLR with elevated kinesiophobia are altering their physical activity patterns (e.g., intensity, volume, type) in response to this injury- or pain- related fear.[12] This is important when considering that individuals with knee osteoarthritis (OA) may also reduce their walking speed and physical activity engagement in response to injury- or pain- related fear.[21] However, it is unclear if adolescents with history of ACLR who are at increased risk of experiencing limitations of knee OA early in the lifespan also exhibit elevated kinesiophobia that is related to free-living activity and ambulation.

Adults who have undergone ACLR take 1,611 fewer steps per day as compared to age-matched uninjured controls.[26] This is concerning because reduced step counts have been associated with negative consequences including poor quality of life and morbidity among adults with and without knee OA. In fact, reduced step counts (< 6000 steps per day) have been predictive of incident slow gait speed among adults with knee OA.[149] This may be an important consideration for adolescents with ACLR, who are reported to take an average of only 6153 steps per day.[67] In addition to reduced step counts only 9% of adolescents with ACLR are reported to have met United States Department of Health and Human Services (USDHHS) aerobic physical activity guidelines within the first year of surgery.[67] This is concerning because adolescents with ACLR who are exhibiting reduced physical activity engagement are at risk of adapting poor physical activity behaviors early in the lifespan that are predictive of physical activity into adulthood.[146,147] When considering the risk for knee OA development early in the lifespan among adolescents with ACLR and the reduced step counts and physical activity engagement demonstrated by this clinical population, it may be important to better understand how barriers to return to pre-injury physical activity, such as elevated kinesiophobia, influence free-living step counts and ambulation intensities.

Cadence (i.e., steps taken per minute), is a spatiotemporal component of gait speed (i.e., distance covered per second) and can be used to simply characterize intensity of activity or ambulation.[139] Gait speed can be computed as the product of cadence and step length as described by the following equation:

$$Gait\ Speed = Step\ Length * Cadence.$$ [139]

While cadence is not a direct indicator of gait speed as described above, assessment of cadence may provide many advantages because it can be measured under free-living conditions using wearable devices (e.g., triaxial accelerometers) and may provide insight into free-living gait and physical activity intensities.[123] Adults who were 2 years post-ACLR spent 40 fewer weekly minutes in moderate-to-vigorous intensity cadences (175.8 ± 116.5 minutes versus 218.5 ± 137.1 minutes; P =0.048) as compared to uninjured adults. [24] This is concerning because fewer weekly minutes spent in moderate-to-vigorous intensity cadences (≥ 100 steps/ minute) and reduced daily step counts have also been identified among individuals with and at-risk for knee OA development.[11,21,130] Despite these identified associations, there has not been an investigation of the relationship between free-living cadence characteristics and potentially modifiable factors like injury-related fear among a clinical population that demonstrates inadequate physical activity participation, elevated kinesiophobia, and is at increased risk of knee OA development early in the lifespan.

As a result, it is critical to investigate the association between free-living cadence and step counts with kinesiophobia 6 months following primary ACLR because it is a timepoint that is often associated with elevated kinesiophobia and a return to modified or unrestricted sport and physical activity participation.[16,19] Therefore, the purpose of this study was to compare free-living cadence characteristics between adolescents who report elevated and those who report acceptable injury-related fear 6-9 months post-ACLR. Specifically, we will examine the association between kinesiophobia, captured by the Tampa Scale of Kinesiophobia (TSK-11), and: 1. average steps per day, 2. mean light cadence, 3. mean light-to-moderate cadence, 4. mean daily cadence, and 5. peak cadence. We hypothesized that adolescents reporting elevated injury-related fear (i.e., TSK-11 scores $\geq$ 17) would take fewer steps per day, and have slower mean light cadences, mean light-to-moderate cadences, mean daily cadences, and peak cadences, as compared to adolescents who report acceptable injury-related fear 6-9 months post-ACLR.

METHODS

This investigation was a cross-sectional analysis of data obtained from adolescents who have experienced an ACL injury and undergone surgical reconstruction. This study was approved by the Michigan State University Institutional Review Board for Human Subjects Research. All enrolled participants 13-17 years old provided written assent and at least 1 parent or legal guardian provided written consent and all participants who were 18 years old provided written consent prior to engagement in any study-related activities.

Participants

Participants were recruited from a single university-affiliated sports medicine clinic from one of three fellowship-trained orthopaedic surgeons. Participants were eligible for this study if they were 13-18 years old at the time of study enrollment and had undergone ACLR 6-9 months prior. If participants had any complication or delay during their ACLR or rehabilitation, they were not able to participate in this study. In addition, if participants had history of a neurological, cardiovascular, or other medical condition that would make it unsafe for them to participate, they were excluded from study enrollment. Participants were not excluded from this study based upon surgical demographics, including graft type or concomitant injury or surgical procedure. If more than one post-operative study visit was completed, the visit closest to six months post-ACLR was used for analysis.

Kinesiophobia

To characterize kinesiophobia, participants completed the Tampa Scale of Kinesiophobia (TSK-11) within 7 days of their free-living cadence assessment. The TSK-11 is an 11-item questionnaire that asks the patient to respond to prompts from strongly disagree to strongly agree. Total scores range from 11-44, with higher total scores indicative of greater or elevated injury-related fear. The TSK-11 is a valid (r=0.33-0.59) questionnaire to evaluate injury-related fear and fear of movement among individuals with musculoskeletal injury or chronic pain.[120,121] It has been widely implemented to characterize injury-related fear post-ACLR. Participants who scored < 17 were characterized as experiencing "low" or "acceptable" injury-related fear and participants who scored ≥ 17 were characterized as experiencing "elevated" injury-related fear.

Free-living Cadence

Participants were asked to wear an Actigraph GT9X Link monitor (Actigraph, LLC, Pensacola, FL) for a minimum of 7 days for all waking hours, except for water activities. Activity and step counts were collected and analyzed in accordance with Montoye and colleagues as described in Table 14.[141] Wear-time validation was based upon criteria from Choi and colleagues, and non-wear time was removed from analysis.[129] All acceleration data were processed in ActiLife software and minute-level (i.e., 60-second epoch) step counts were exported during all validated wear-times. Average minute-level daily cadence was calculated for each participant across all valid wear time by reporting steps taken for each 60 second epoch divided by the total number of 1-minute epochs, including 0s. Mean light cadence was identified by removing wear periods < 60 steps per minute and > 100 steps per minute from analysis and reporting the mean steps taken for each 60 second epoch divided by the total number of epochs. Mean light-to-moderate cadence was identified by removing wear periods < 60 steps per minute and > 130 steps per minute from analysis and reporting the mean steps taken for each 60 second epoch divided by the total number of epochs. The light and light-to-moderate cut-offs identify purposeful light walking (60-100 steps per minute) and purposeful light-to-moderate walking (60-130 steps per minute). Peak minute-level cadence is reported as the maximum number of steps taken during any 1-minute period of valid wear time.

Table 14. Summary Table for Device-Based Activity Data Collection and Analysis

Accelerometer Model	GT9X Link Actigraph Monitor
Data Collection Sampling Rate	30 Hz
Data Analysis Epoch Length	60 s
Accelerometer Placement/ Location	Right ASIS
Validation Criteria	≥ 4 valid days (3 weekday and 1 weekend day) ≥ 600 minutes per day

*ASIS= anterior superior iliac spine

Power Analysis

We completed our power analysis based upon findings from Lisee and colleagues who reported a moderate difference in steps taken per day (η_p^2=0.079), average daily cadences(η_p^2=0.040), and time spent in moderate to vigorous intensity cadences (η_p^2=0.040) between adults with ACLR and uninjured adults. Assuming these moderate differences, and in order to obtain 80% statistical power with alpha set to 0.05, we determined that we would require at least 31 participants (G*Power Statistical Power Analysis v 3.1.9.7).

Statistical Analysis

Descriptive statistics (means and standard deviations) were calculated for participant demographics and compared between adolescents with elevated and acceptable injury-related fear using independent samples t-tests. Participant sex and Tegner Activity Scale scores were compared between groups using χ^2 tests of association and Mann Whitney U tests, respectively. All cadence data were evaluated for normality; any participant data > 3 standard deviations from the mean were characterized as outliers and excluded from analysis.

We used 5 separate ANCOVAs to compare average steps per day, mean light cadence, mean light-to-moderate cadence, mean daily cadence, and peak cadence. Activity monitor wear time and height were entered as covariates because monitor wear time and height are known to influence cadence characteristics. Wear time can influence step count accumulations and cadence outcomes; for example, greater wear time will result in greater step count accumulations and may influence means related to steps per time period. In addition, height can influence moderate intensity cadence outcomes;

Rowe and colleagues reported that taller height is related to decreased free-living cadence, by reports of nearly 20 steps per minute. Partial eta squared effect sizes (η_p^2) were calculated to account for covariates included in this analysis. Effect sizes were interpreted as small = 0.01, moderate = 0.06, and large = 0.14. Alpha was set *a priori* to $\leq$ 0.01 (=0.05/5) to account for multiple ANCOVA models. Statistical analysis was completed using an open-source statistical package (v 2.2.5, *jamovi*).

RESULTS

Thirty-one participants completed the TSK-11 within 7 days of adequate monitor wear time. One participants' cadence data was > 3 standard deviations from the mean and was therefore characterized as an outlier. Six months following primary ACLR, 19 participants (63.3%) were characterized as experiencing elevated injury-related fear and 11 participants (36.7%) were characterized as experiencing acceptable or low injury-related fear. There were no statistically significant differences in patient-reported outcomes or demographics between groups except for TSK-11 and TAS scores (Table 15).

After controlling for participant height and monitor wear time, adolescents who reported elevated injury-related fear demonstrated slower mean light cadences ($F=9.518$, $P=0.005$, $\eta_p^2=0.268$) as compared to adolescents who reported acceptable injury-related fear. However, there were no statistically significant differences between adolescents with elevated and acceptable injury-related fear for mean light-to-moderate cadence ($F=2.95$, $P=0.098$, $\eta_p^2=0.102$), mean daily cadence ($F=1.357$, $P=0.294$, $\eta_p^2=0.594$), peak cadence ($F=0.2382$, $P=0.630$, $\eta_p^2= 0.009$), or average steps taken per day ($F=1.4257$, $P=0.243$, $\eta_p^2=0.052$). A summary of cadence characteristics is included below in Table 16 and boxplots comparing group cadence outcomes are included in Figure 7.

Table 15. Participant demographic characteristics (N=31)

	Acceptable Injury-Related Fear (n=11)	Elevated Injury-Related Fear (n=19)	P-Value
Age (years)	16.0 ± 1.5	16.0 ± 1.1	0.999
Sex (M/F(%F) *	2/9(81.8%)	8/11 (57.9%)	0.180
Height (cm)	168.1 ± 14.0	174.3 ± 8.1	0.134
Weight (kg)	69.0 ± 11.7	76.2 ± 21.1	0.310
Time since ACLR (months)	6.2 ± 2.1	6.0 ± 1.6	0.797
TSK-11 score†	14.0 [11, 16]	22.0 [17, 28]	<0.001
TAS score†	6.0 [5,9]	5.0 [3, 9]	0.064
Total monitor wear time	6695 ± 2566	5515 ± 1394	0.181

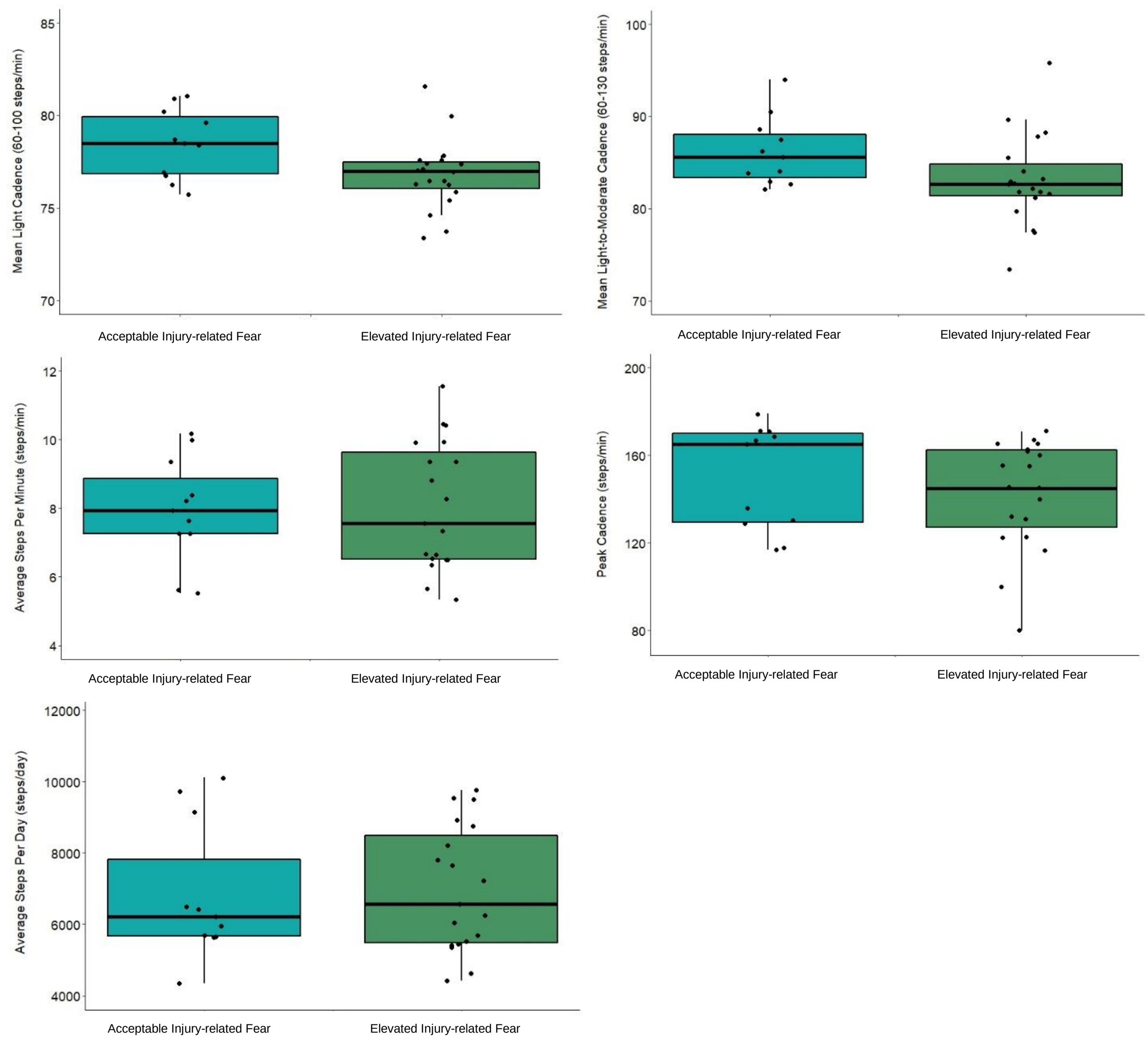
Data are presented as mean ± standard deviation, unless otherwise indicated
*Data are presented as frequency
† Data are presented as median [minimum, maximum]
ACLR= Anterior Cruciate Ligament Reconstruction, TSK-11= Tampa Scale of Kinesiophobia, TAS= Tegner Activity Scale

Table 16. Participant Free-living Cadence Outcomes

	Acceptable Injury-Related Fear (n=11)	Elevated Injury-Related Fear (n=19)
Mean Light Cadence (60-100 steps/min)	78.5 ± 1.9	76.8 ± 1.9
Mean Light-to-Moderate Cadence (60-130 steps/min)	86.2 ± 3.7	83.1 ± 4.9
Mean Daily Cadence (steps/min)	7.9 ± 1.5	8.1 ± 1.9
Peak Cadence (steps/min)	150.0 ± 24.0	142.0 ± 25.0
Average Steps Per Day (steps/day)	6854 ± 1903	6990 ± 1750

Data are presented as mean ± standard deviation, unless otherwise indicated

Figure 7. Comparisons of cadence outcomes and steps per day between adolescents with elevated and acceptable injury-related fear 6 months post-ACLR.



DISCUSSION

To the authors' knowledge, this is the first investigation to examine free-living cadence and step counts among adolescents with elevated and acceptable injury-related fear 6-9 months post-ACLR. The primary finding of this study is that adolescents with elevated injury-related fear demonstrated slower mean light cadences as compared to adolescents with acceptable injury-related fear. However, injury-related fear did not influence mean light-to-moderate cadences, average daily cadences, peak cadences, or average daily step counts. Therefore, our primary hypothesis was only partially supported. These findings indicate that treatment of unacceptable kinesiophobia at 6-9 months post-ACLR may serve as an avenue to improve free-living light cadences. Light cadences of 60-100 steps per minute are the cadence intensity that individuals spend the bulk of their purposeful ambulation time and there is evidence that increasing time spent in light cadences may help to mitigate consequences related to knee OA such as incident slow gait speed and worse general health outcomes.

Sixty-one percent of participants included in our sample were characterized as experiencing elevated injury-related fear 6-9 months following ACLR. Similarly, Paterno and colleagues reported that 47.5% of adolescent patients (16.2 ± 3.4 years old), experience elevated injury-related fear at the time of return to sport, approximately 7-8 months following ACLR.[16] Management of elevated kinesiophobia may be an important consideration at this postoperative timepoint because 6-9 months post-ACLR is often associated with return to modified or unrestricted sport or physical activity engagement.[19] When considering the negative consequences associated with elevated kinesiophobia among this population, including reduced self-reported physical activity levels and second

ACL injury risk, management of kinesiophobia early following surgery may be beneficial to enhancing long-term post-operative outcomes.

Adolescents with elevated injury-related fear demonstrated slower mean light cadences (60-100 steps per minute) when compared to adolescents with acceptable injury-related fear. The step difference was relatively small between groups (i.e., 1.5 steps/min). However, this is still concerning because our sample spent most of their purposeful ambulatory (i.e., 60+ steps per minute) monitor wear time each day in light cadences of 60-100 steps per minute (76.8 ± 11.7 %). Meaning, adolescents with elevated injury-related fear are demonstrating slower mean cadences during the bulk of their purposeful ambulation throughout the day, as compared to adolescents with acceptable injury-related fear. Increasing average light cadence or time spent in light cadence may have several knee-related and general health benefits.[11] For example, replacing sedentary activity with light physical activity has been related to a 17% reduced risk for developing slow gait speed within 2 years among individuals with diagnosed knee OA.[20] When considering the negative consequences associated with slow gait speed among individuals with ACLR and knee OA, replacing sedentary activity with light intensity cadences may serve as an avenue to mitigate functional limitations and disability related to knee OA among a population that is at increased risk. To manage elevated kinesiophobia following ACLR, Kuenze and colleagues previously suggested motivational interviewing to better determine the cause of this fear and then to develop a plan of patient-centered care to address this fear.[67] As reported by Baez and colleagues, goal setting or exposure therapy may be useful patient-centered techniques to help manage elevated injury-related fear. However, future research is needed to determine the feasibility and efficacy of interventions that aim to reduce kinesiophobia and influence free-living light cadences among adolescents with ACLR.

Adolescents with elevated injury-related fear demonstrated similar light-to-moderate cadences as compared to adolescents with acceptable injury-related fear. These findings suggest that while there are differences in light cadence, moderate cadence may be similar, regardless of injury-related fear. This was not in accordance with our hypothesis due to previous reports of the association between moderate intensity physical activity and patient-reported outcomes such as quality of life post-ACLR.[150] Davis-Wilson and colleagues reported that among individuals who were characterized as experiencing clinically significant knee symptoms post-ACLR, those who reported worse quality of life on the Knee injury and Osteoarthritis Outscores Score Quality of Life (KOOS-QOL) subscale, engaged in fewer weekly minutes of moderate-to-vigorous physical activity as compared to individuals without significant symptoms post-ACLR.[150] This is an important consideration because quality of life is strongly related (Adjusted R^2=0.39, $P<0.001$ and Adjusted R^2=0.56, $P=0.01$) to injury-related fear post-ACLR and among individuals with knee OA[14]; therefore, we had hypothesized that those individuals with elevated injury-related fear would similarly engage in less intense moderate to vigorous intensity cadences as compared to individuals with acceptable injury-related fear. However, it is important to note that the comparative study was a cohort of adults with ACLR who were, on average, more than 2 years post-operative. Future investigations are needed to better understand what modifiable characteristics may be contributing to free-living cadences among adolescents post-ACLR.

Both groups also demonstrated similar average daily and peak minute-level cadences, regardless of self-reported injury-related fear. These findings were also not in accordance with our primary hypothesis. Reductions in average daily cadence are widely reported among individuals with knee OA and have been reported by a single study among individuals with ACLR. Lisee and colleagues reported that adults with ACLR exhibited reduced daily cadences as compared to uninjured, matched controls.[24] While the average daily cadences of our sample were similar to Lisee and colleagues, these cadences were not influenced by injury-related fear as we had hypothesized. In addition, peak minute-level cadences were similar between groups, which did not support our primary hypothesis. We had anticipated that greater intensity cadences and activities may elicit an injury- or pain- related fear response that would have resulted in reduced peak intensity cadence. However, both groups demonstrated similar peak cadences. The peak cadences exhibited by out sample of adolescents with ACLR were modestly lower as compared to the adults with ACLR included in Lisee's study (152.2 ± 23.4).[24] While we did not statistically compare peak cadences between adults and adolescents with ACLR, future investigations may be warranted in order to better understand these reduced peak cadences exhibited by adolescents with ACLR. In order to intervene on these reduced free-living cadences, there is a critical need to identify if other potentially modifiable factors such as patient-reported symptoms or pain that may influence free-living cadence and activity engagement among this at-risk population.

Average daily step counts were similar among adolescents with and without elevated injury-related fear. Step counts were similar to Kuenze and colleagues who reported that adolescents with ACLR took an average of 6153 steps per day.[67] However, it is important to note that there are no daily step count recommendations for adolescents. The United States Department of Health and Human Services provides aerobic recommendations for adolescents who are between the ages of 6 and 17 years old participate in 60 minutes of moderate or vigorous intensity activity each day, with at least 3 days including vigorous intensity activity. To meet daily MVPA recommendations, Tudor-Locke and colleagues suggest that adolescents take between 10,000 and 11,700 steps per day.[151] However, only 1 participant included in our sample, who reported acceptable injury-related fear, met these step count recommendations by walking an average of 10,110 steps per day. Regardless of injury-related fear, adolescents with ACLR exhibited low step counts that have been related to unfavorable slow gait speeds among individuals with knee OA.[20] In order to mitigate slow walking, it is recommended that individuals with knee OA take at least 6000 steps per day. Of concern, 42% of our sample of adolescents walked fewer than 6000 steps per day. While kinesiophobia was not related to daily steps post-ACLR, these findings highlight the critical need to identify contributors to inadequate step counts post-ACLR in order to reduce the long-term consequences of insufficient activity engagement early in the lifespan.

Limitations

There are several limitations that should be considered when interpreting the findings of the present study. First, this study is cross-sectional and included a relatively small, heterogenous sample of adolescents 6-9 months post-ACLR. Also, rehabilitation data were not consistently available or standardized across participants. In addition, due to limitations in sample size, we could not include sex as a covariate in analysis. While sex is reported to potentially influence cadence and injury-related fear, frequency of sex distribution did not differ between injury-related fear groups, so it was not included as a covariate in our primary analysis. Similarly, age is reported to influence cadence, but was not different between groups, so we did not include it as a covariate in our primary analysis. However, we included sex and age as covariates in a secondary analysis and both modestly impacted mean light cadence, but no other cadence outcomes (Table 17). Though, group differences in mean light cadence did not reach statistical significance after controlling for age and sex. In addition, we are limited because our injury-related fear groups were unbalanced with more than 60% of participants reporting elevated injury-related fear.

Table 17. ANCOVA Models Describing Differences in Steps and Cadences Between Adolescents with Elevated and Acceptable Injury-Related Fear (Additional Covariates)

Covariates and Predictor Variable (TSK-11 Group)	P-Value	Effect Size (η_p^2)
Steps Per Day		
Total Monitor Wear Time	0.011	0.239
Height	0.933	<0.001
Age	0.721	0.005
Sex	0.781	0.003
TSK-11 (Elevated, Low)	0.334	0.039
Average Daily Cadence		
Total Monitor Wear Time	0.312	0.043
Height	0.576	0.013
Age	0.683	0.007
Sex	0.528	0.017
TSK-11 (Elevated, Low)	0.635	0.010
Peak Cadence		
Total Monitor Wear Time	0.880	0.001
Height	0.280	0.049
Age	0.155	0.083
Sex	0.808	0.003
TSK-11 (Elevated, Low)	0.577	0.03
Mean Light Cadence		
Total Monitor Wear Time	0.690	0.007
Height	0.083	0.120
Age	0.078	0.124
Sex	0.024	0.194
TSK-11 (Elevated, Low)	0.026	0.190
Mean Light to Moderate Cadence		
Total Monitor Wear Time	0.813	0.002
Height	0.581	0.013
Age	0.704	0.006
Sex	0.088	0.117
TSK-11 (Elevated, Low)	0.302	0.044

Height, total monitor wear time, age and sex were entered as covariates

Finally, dichotomizing participants as experiencing elevated or acceptable injury-related fear using the previously applied cut-off score of 17 may have failed to capture patients who are experiencing meaningful fear of injury or fear of knee symptoms/ movement that may be considered a barrier to return to physical activity. The cut-off score of 17 was identified as elevated kinesiophobia that may negatively influence patient-reported knee function (i.e., IKDC score) among patients with history of ACLR. Despite the postulated relationship between kinesiophobia and physical activity engagement among individuals with ACLR (i.e., Fear Avoidance Model), it is important to note that the TSK-11 has not been validated to characterize injury-related fear among individuals post-ACLR. Using available data from the Face Validation of the ACL Reasons Survey completed by our lab group, 52 individuals who identified as being 'as active,' 'as active but more challenging' or 'less active' following their ACLR identified fear of knee symptoms/ movement, or fear of injury as a top 3 barrier to return to physical activity. Of those individuals who identified fear of knee symptoms/ movement or fear of injury as a top 3 barrier to physical activity, 86.5% (45/52) would be characterized as experiencing elevated kinesiophobia as described by TSK-11 score cutoffs employed in this study and in previous investigations of the ACLR population (Table 18). It is important to note that through further reliability analysis, our data supports that the TSK-11 demonstrates poor reliability with identification of fear of injury that is a barrier to return to physical activity ($\omega = 0.419$) and poor reliability with identification of fear of knee symptoms of movement that is a barrier to return to physical activity ($\omega = 0.388$). In conclusion, by utilizing the TSK-11, we may have failed to capture elevated injury-related fear that meaningfully impacts free-living cadence and activity among adolescents with ACLR. This highlights the need for additional approaches such as patient interviews that can more adequately determine the cause of injury-related fear that may be free-living ambulation post-ACLR. Finally, inconsistency in the timing of administration of the TSK-assessment (i.e., before- or after-physical assessment) may have influenced reported TSK scores due to anticipation or resultant performance on physical assessments.

Table 18. ACL Reason Face Validation TSK Scores

	All Participants	As Active	More Challenging	Less Active
TSK-11 Score	19.4 ± 5.6	16.1 ± 4.2	20.9 ± 5.2	22.6 ± 5.3
Fear of Knee Symptoms/ Movement	22/ 78 (28.2%)	0 / 32 (0%)	7/ 24 (29.2%)	15/ 22 (68.2%)
Fear of Injury	23/ 78 (29.5%)	0/ 32 (0%)	7/ 24 (29.2%)	16/22 (72.7%)

ACL= Anterior Cruciate Ligament, TSK= Tampa Scale of Kinesiophobia

Conclusions

Six to nine months post-ACLR, which is a timepoint often associated with return to modified or unrestricted sports and activity participation, 61% of adolescents reported elevated injury-related fear. Adolescents with elevated injury-related fear demonstrated slower mean light cadences in free-living conditions; however, injury-related fear did not influence greater intensity free-living cadences including light-to-moderate and peak cadences, or average daily step counts. Management of elevated kinesiophobia 6-9 months following primary ACLR may provide a feasible avenue to intervene on free-living light cadences among adolescents, with the goal of mitigating the long-term consequences of experiencing a knee injury early in the lifespan.

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