

THE EFFECTS OF KNEE JOINT LOADING ON DYNAMIC TASKS IN  
INDIVIDUALS SEVERAL YEARS POST-ACL RECONSTRUCTION

by

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DISSERTATION

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## ABSTRACT

### THE EFFECTS OF KNEE JOINT LOADING ON DYNAMIC TASKS IN INDIVIDUALS SEVERAL YEARS POST-ACL RECONSTRUCTION

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Joint loading of the lower extremity is studied to identify risk factors for anterior cruciate ligament (ACL) injuries and to determine limb asymmetries. Asymmetrical loading in the lower extremity during ACL reconstruction (ACLR) rehabilitation and at the time of return to sport or activity will cause compensations during functional movements, which can lead to unwanted joint re-injury or long-term joint damage. Re-injury and/or development and progression of knee osteoarthritis (OA) is prevalent after ACLR; therefore, joint loading measurements at extended time points from reconstruction and after return to play may help to identify how asymmetrical loading and compensatory movement strategies contribute to these occurrences. The joints of the lower extremity experience different stresses when ACLR individuals return to physical activity after clearance from rehabilitation because there are varying intensities and physical demands on individual athletes. Individuals also may actually avoid loading their ACLR knee because of

persistent symptoms, poor perception, or limited knee extensor eccentric control . Therefore, our understanding of the impact of both excessive and limited knee joint loading on knee OA can be developed from an understanding of the normal and abnormal lower extremity movement patterns or strategies during various functional tasks in ACLR individuals.

Study 1 (Chapter 2) takes a comprehensive approach to understand the difference in joint loading by way of energy absorption (EA) and energy absorption contribution (EAC) during three different functional tasks, single-leg squat (SLS), single-leg hop, and gait, in ACLR individuals 2-9 years removed from surgery and healthy, matched control participants. Advanced statistical analyses were used to identify interaction effects between each task within each group and between groups. There were differences between both groups in EA and EAC across all joints when comparing each physical performance task. Knee joint loading was greatest for both groups during the SLS task. ACLR participants utilized strategies with greater hip compensations during hop tasks and greater ankle contribution during gait tasks. These findings suggest the ability of ACLR participants to utilize altered loading strategies when performing different functional tasks and likely represent an avoidance of loading the knee of the surgical limb. The avoidance of knee joint loading in ACLR subjects are likely due to strength and range of motion asymmetries in the surgical limb compared to the non-surgical limb within ACLR subject as well as the matched limb within the healthy controls.

Physical performance on different functional tasks is not only related to physical capacity but it is also related to a patient's self-efficacy related to the task, so it is important to measure a patient's perception of their capabilities as these cannot be objectively proven with lab tests. Self-reported function (SRF) has been utilized in conjunction with other biomechanical measures to explain kinetic and kinematic alterations; however, the comparison to EA and EAC has not

been explored. Study 2 (Chapter 3) used performance on the previously mentioned physical performance tasks to identify an interaction effect with SRF, as measured by the Knee injury and Osteoarthritis Outcome Score (KOOS) and International Knee Documentation Committee (IKDC) forms. Overall, across functional tasks, ACLR subjects with lower SRF also used joint loading strategies that limited knee loading and emphasized hip and ankle compensations. These data support the notion that a lower perception of function will lead to changes in energy absorption. When compared to control subjects, ACLR subjects with SRF in either low or high sub-groups consistently demonstrated altered loading strategies with more ankle and/or hip contribution in an effort to underload the knee.

The findings of these investigations provide insightful information into energy absorption measures of joint loading within a variety of functional tasks in a previously unstudied time frame (2-9 years) following ACLR. Movement asymmetries and deficits in joint loading will impact knee joint health and the inclusion of measures of SRF are a necessary compliment to objective findings as understanding how ACLR individuals perceive their ability to load their surgical knee may help our understanding of asymmetrical loading patterns. Future work should identify EA and EAC across other performance tasks, in addition longitudinal investigations of joint loading and SRF in ACLR patients beyond the typical continuum of care from surgery through rehabilitation and return to activity should be pursued.

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## DEDICATION

This work is dedicated to my most treasured support system: my family. This achievement would not be possible without my parents, Leo and Joann, and my sister, Mallory, who have been a constant source of support and encouragement throughout every stage of my academic career. And most importantly, I attribute my success to the love, patience and stability provided by my wife, Halee.

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## **Chapter 1**

### **INTRODUCTION**

## **ACL Injury Prevalence and Epidemiology**

Knee injuries are common in sport participants of all ages, ranging from youth athletes to older populations. Anterior cruciate ligament (ACL) injuries can be classified as one of the more debilitating knee injuries, which occur primarily in young individuals involved in quick change of direction activities and pivoting sports, such as team handball, soccer, basketball, football, alpine skiing, and tennis.<sup>1-4</sup> ACL tears are estimated to occur in 0.8 per 1,000 individuals in the general population, which is thought to be a slightly lower incidence rate compared to the athletic population.<sup>5</sup> In recent years, the efforts to implement ACL injury prevention programs have increased; however, the number of ACL injuries has risen to roughly 250,000 per year, with a higher rate occurring in individuals younger than 30 years of age.<sup>4,6</sup> This has led to an increase in the number of surgical treatments via ACL reconstruction (ACLR) performed in the United States in patients younger than 20 years from 12.22 per 100,000 persons in 1994 to 17.97 per 100,000 persons in 2006.<sup>7</sup>

ACL injuries occur via two primary mechanisms: contact and non-contact. Contact injuries are somewhat unavoidable in team and collision sports, such as football or soccer, where player on player contact is inevitable and occurs regularly. A primary function of the ACL is to withstand anterior tibial translation forces as external contact is applied. Non-contact mechanisms of injury, in which the ACL ruptures without physical contact by external forces or other individuals, are reported to be more common than contact mechanisms. Non-contact anterior tibial translation at knee flexion angles around 20–30 degrees are potentially the most detrimental isolated force associated with an ACL injury.<sup>8,9</sup> Several studies report that the rate for non-contact ACL injuries ranges from 70 to 84% of all ACL tears in both female and male athletes.<sup>8-10</sup> During these instances of non-contact injury, the ACL is susceptible to rupture when

the knee and lower limb are involved in variety of change of direction or cutting maneuvers combined with deceleration, landing from a jump in or near full extension, and pivoting with the knee near full extension on a planted foot.<sup>8,10</sup>

Surgical treatment via ACLR has become the primary choice of treatment following injury, which has ultimately led to it being one of the most commonly performed orthopedic procedures.<sup>11</sup> Conservative management exists as an additional possibility for treatment following an ACL rupture, but is not always sustainable for individuals aiming to return to highly demanding physical activity and sport. The conservative option involves individuals, classified as ACL-deficient (ACLD) or copers, who have asymptotically returned to all preinjury activities with the complete absence of an ACL.<sup>12</sup> The advantage to receiving ACLR is to theoretically restore joint function by way of a graft placed in the joint to replace the ACL and mimic the function of the torn ligament. Unfortunately, although the graft attempts to restore the normal restraints previously provided by the ACL, it does not completely provide stability to the joint as once was present with the original ACL ligament.<sup>13,14</sup>

Following injury, several kinematic changes occur at the knee, including increased anterior-posterior translation of the tibia relative to the femur, increased tibial internal rotation, and decreased external rotation of the tibia during knee range of motion.<sup>15</sup> Of those kinematic changes, an increase in anterior tibial shift and position relative to the femur is most common and is present in functional movements following ACLR, such as gait.<sup>16</sup> This abnormal tibial position creates slight dissociation at the tibiofemoral joint, which places the tibia at new, unwanted positions, which has been found to contribute to the development of post-traumatic osteoarthritis (PTOA).<sup>17</sup>

ACL injury is a long and challenging process due to the joint trauma suffered from the injury and reconstruction. A summit of orthopedic surgeons from various countries collectively identified that patients generally return to modified sport activity or practice after an average of 6 months, with return to full athletic competition after an average of 8 months.<sup>18</sup> Unfortunately, the milestone of returning to sport or activity often does not happen. At 12 months post ACLR, Ardern et al.<sup>19</sup> found that 33% of patients had returned to competitive sport, while the return-to-competitive-sport rate was only 46% at 39 months' follow-up. An additional study conducted by this group revealed that 40% of subjects that did not return to pre-injury level of activity cited poor knee function as a major reason for failure to return.<sup>20</sup> Psychological factors, such as fear of reinjury or a lack of confidence, are major deterrents for individuals lacking full return to sport status.<sup>18,21</sup> Additional factors related to the knee, such as persistent instability, pain and/or swelling, and re-rupture, sideline individuals indefinitely following ACLR.<sup>18</sup>

One particular risk that receives a significant amount of focus for individuals returning to sport or activity following ACLR is the likelihood of re-tear of the ipsilateral or contralateral ACL. Several factors are related to this increased risk; however, time to return to activity following surgery is a major contributor to the likelihood of re-injury. In a study identifying return to sport criteria after ACLR, Paterno et al.<sup>22</sup> found that 35 out of 159 adolescent and young adult subjects suffered a 2<sup>nd</sup> ACL injury, with 74% of those participants experiencing this re-injury within the first 12 months following the initial surgery. A similar report of incidence rates of a second ACL injury following an initial ACLR found the rate to be 15 times greater within the first 12 months following surgery.<sup>23</sup> This report went on to determine that 25% of the athletes with a history of ACLR suffered a second injury to either their original graft or their contralateral knee upon returning to activity.<sup>23</sup>

Delaying return to full sport and activity participation may be a viable mechanism to attempt to reduce the re-injury rate, especially within the first year following reconstruction. Grindem et al.<sup>24</sup> found that the reinjury rate following ACLR was significantly reduced by 51% for each month return to full sport activity was delayed until 9 months after surgery. Although the evidence clearly indicates the greatest risk of re-injury during the first year post-ACLR, there still continues to be a significant risk of re-tear present in the second year, which has sparked debate about delaying return to sport until the 2-year mark.<sup>25</sup> Despite the optimism related to decreasing injury risk with a delay in sport participation, the risk of re-tearing is a reality that all ACLR individuals face, no matter the time frame from surgery. Although time can be favorable when dictating decisions to return to activity from ACL surgery and might prevent re-tearing or contralateral injury, within roughly 5-15 years after the initial injury, over 50% of individuals who suffer an ACL injury will go on to develop knee osteoarthritis (OA).<sup>12,26,27</sup>

### **Development of Post-Traumatic Osteoarthritis Following ACL Injury**

An ACL injury is often associated with long-term functional impairments and disabilities, beyond rehabilitation and return to activity, due to knee joint laxity, meniscal injuries, reduced quadriceps strength, and changes in knee joint loading, with subsequent development of knee OA.<sup>28</sup> Osteoarthritis is the pathophysiological response of a synovial joint to mechanical insult.<sup>29</sup> OA is classified as total joint failure driven by abnormal joint loading, with a prominent inflammatory component.<sup>30,31</sup> The OA process was previously thought of as a degenerative disorder, only impacting cartilage within the joint; however, in advanced stages the presence of joint contractures, muscle atrophy, and limb deformity magnify the disease presence.<sup>32</sup> Interestingly as science has developed more sophisticated approaches to understanding

pathology, it is now believed that OA is not purely a degenerative disease as previously thought and that it is a part of an active repair process.<sup>29,31</sup>

Osteoarthritis represents the entire process of the joint attempting to repair the damage and adjust to any resultant abnormal mechanical stresses. Increased levels of cytokines, degradative enzymes, and toxic oxygen radicals in the articular cartilage have mistakenly been considered as the common cause of primary OA.<sup>29</sup> However, recent evidence indicates that these altered levels are the result of attempts by the chondrocytes to break down damaged tissue and actually actively repair the joint.<sup>33</sup> Because many different forms of joint loading can trigger the OA process, the clinical expressions that can be associated with the joint's response may vary.

A clinical diagnosis of knee OA is done via radiographic and/or symptom reports. Radiographic presence of tibiofemoral OA includes one or more findings of a loss of articular cartilage, osteophyte formation, subchondral bone deformities, or a narrowing of joint space. Radiographic joint changes occur in both medial and lateral compartments of the tibiofemoral joint, but are more commonly detected in the medial compartment.<sup>34</sup> Clinical or symptomatic OA is determined based on the presence of pain, stiffness and/or functional deficiencies.<sup>35</sup> Individuals following ACLR may experience radiographic knee OA without the presence of associated symptoms, whereas other individuals may have symptomatic OA without any significant radiographic findings.

While the prevalence of knee OA typically peaks around the age of 50 years,<sup>36</sup> research has shown that the greatest risk factor predicting the development of knee OA in young and middle-aged people is previous traumatic knee joint injury.<sup>37</sup> However within the vast amount of research detailing the radiographic, symptomatic and time-based progression of knee OA, there has been limited data to pinpoint the exact cause of disease onset. Johnson et al.<sup>38</sup> found that both

complete and partial ACL tears showed structural OA changes on MRIs despite whether the knee was reconstructed or not. There was a predominance for medial tibiofemoral damage and individuals who suffered a complete ACL rupture also exhibited an increased risk of posterior tibial cartilage damage and bone marrow lesion formation.<sup>38</sup>

Because traumatic joint injury, like ACL rupture, will likely create suboptimal joint mechanics, the theoretical goal of anatomically reconstructing the knee is to decrease joint incongruity, malalignment, and instability.<sup>32</sup> The surgery attempts to decrease focally elevated contact stresses, which are thought to be in large part responsible for the development of post-traumatic osteoarthritis (PTOA). However, the potential for cartilage to repair and remodel itself physiologically and its tolerance to both acutely or chronically increased stress is still not fully understood.<sup>32</sup>

Despite the lack of concrete evidence to detail the onset of knee OA following a traumatic joint injury, several authors<sup>12,26,27</sup> suggest that the result of initial trauma itself is likely what causes the permanent joint changes leading to OA because studies demonstrate that over time, knee OA is present in patients who are both ACL-deficient and those that had ACLR. For example, fifty percent of ACLD individuals will go on to develop PTOA within 5-15 years following injury<sup>12,26,27</sup> and Daniel et al<sup>12</sup> found an increased prevalence of OA in ACLR patients compared with conservatively treated patients.<sup>12</sup> Further evidence from magnetic resonance imaging (MRI) and recently established OA criteria has revealed the presence of early-onset structural knee OA in approximately one third of young adults (median age, 26 years) as early as 1 year after ACL reconstruction.<sup>39</sup> Several studies have supported this finding by identifying significant cartilage degeneration on MRI scans within the first year following ACL injury,<sup>40-43</sup> with one study<sup>41</sup> detecting increased cartilage signals on MRI scans in 100% of acutely injured



ACL subjects. Furthermore, radiographic OA changes are as high as 50% to 90% a decade after sustaining an ACL rupture, with the highest rates reported for people with combined ACL and meniscal injuries.<sup>35,44,45</sup> Unfortunately, the likelihood of developing knee OA following ACLR increases as time passes. Cinque et al<sup>46</sup> revealed that the presence of radiographic knee OA increased at 5, 10, and 20 year time points from 11.3% to 20.6% and eventually to 51.6% at a 20 year follow up point.

The efficacy of ACLR in delaying the progression of OA has not been fully substantiated.<sup>47</sup> However, the relative risk for developing radiographic OA was greater in individuals who did not undergo surgery as compared to those that did and there was also a risk for developing signs of OA in the contralateral, uninjured limb of these individuals.<sup>48</sup> These findings, while conflicting in some regard, provide insight into the notion that the initial traumatic mechanism during injury is a major factor in which joint changes are triggered. Despite best efforts to restore joint function either through ACLR and rehabilitation or as a coper undergoing exercise-based management, joint changes that persist from the initial injury may contribute to the development of OA. Therefore, the exercise activities that ACL individuals participate in following surgery or conservative management may be an important factor to examine.

A return to predominately cutting and pivoting sports may have an influence on the development of knee OA. von Porat et al<sup>49</sup> found a 41% prevalence of radiographic OA changes in male soccer players 14 years after ACL injury. Similarly, in a study conducted by Lohmander et al<sup>50</sup> over 50% of former female soccer players (12 years post ACLR) were determined to have radiographic knee OA with over 80% having general radiographic changes. Among these structural changes, 75% of female soccer players reported having symptoms that affected their

knee-related quality of life and daily activities including knee pain, stiffness and swelling.<sup>50</sup> Jarvela et al<sup>51</sup> found that 50% of patients 5-9 years post ACLR had either radiographic patellofemoral OA or tibiofemoral OA, whereas, patients without knee OA had no pain or swelling and also had significantly better knee range of motion (ROM) than their counterparts with radiographic OA.

ACLR surgery involves the use of either an autograph or allograft and it has been thought to influence the development of OA. Graft types in ACLR patients have been examined as it relates to the development of knee OA, 45% patients treated with patellar tendon autograft demonstrated radiographic evidence of OA and 14% of patients treated with a hamstring tendon autograft after seven years.<sup>52</sup> Similarly, two studies found a greater prevalence of OA after using patellar autografts at 5 and 10 years.<sup>53,54</sup> Conversely, Liden et al<sup>55</sup> found that regardless of graft type, 23% of the patients had degenerative changes according to the Ahlbäck OA ranking system and 74% had degenerative changes according to the Fairbank OA ranking system. More importantly it was associated meniscal injuries, coupled with ACL injury, and not the graft type that was the factor that increased the prevalence of OA.<sup>55</sup>

The presence of OA following these traumatic knee injuries is accompanied by alarming estimated health care related costs. One in three people with an ACL injury and concomitant meniscal injury are likely to develop symptomatic knee OA in their lifetime, with an estimated lifetime risk of total knee replacement at 22% for this patient group.<sup>56,57</sup> More than one-half (54%) of knee OA patients underwent TKA an average of 13 years after diagnosis.<sup>58</sup> In a population-based study, Ackerman and colleagues<sup>59</sup> found that sports-injured individuals who sustained a knee injury were twice as likely to undergo a total knee arthroplasty (TKA) within 15 years, compared to those who had not. The rate of primary knee replacement for people aged 20

to 49 years increased by 76% in the United States from 2001 to 2007, while the surgery rate for this age group almost doubled in the province of Ontario, Canada.<sup>60</sup> With pain and disability as the driving force for individuals seeking treatment for their knee OA, the United States Bone and Joint Decade found that lifetime cost attributed to knee OA in 2013 was \$140,300. Additional costs related to OA can encompass resource utilization; time lost, either in a work or leisurely setting, and general pain and suffering incurred by the patient themselves.<sup>61</sup> Therefore, major societal burdens exist in the United States and Canada that are related to OA and the health care costs associated with hospital admission for joint replacements and arthroscopic procedures.

Throughout the last several decades, population-based studies have been performed in the United States to examine the prevalence of radiographic and symptomatic knee OA in adults. The prevalence of radiographic knee OA in adults aged  $\geq 45$  was 19.2% in the Framingham study<sup>62</sup> and 27.8% in Johnston County study.<sup>63</sup> In adults aged 60 and older, the prevalence was 37.4% in the National Health and Nutrition Examination Survey (NHANES III) study during the early 1990's.<sup>56</sup> Symptomatic knee OA was also prevalent in adults in all three studies at 4.9%,<sup>62</sup> 16.7%,<sup>63</sup> and 12.1%.<sup>56</sup> In a group of adults, age 54 years and older with a diagnosis of knee OA, van der Esch et al<sup>64</sup> found that activity limitations and self-reported knee instability were significantly present in addition to knee pain and a lack of muscular strength. These numbers are consistent with reports that roughly a quarter of people with knee OA have difficulty walking and doing activities of daily living, with some having to use assistive devices, such as canes or crutches.<sup>56</sup>

In addition to the financial burden of an arthroscopy or knee joint replacement, health related quality of life and knee function are also severely impacted in individuals who develop OA. Ackerman et al<sup>65</sup> studied 147 people with hip or knee OA aged 20 to 55 years and found

that this group had markedly impaired health-related quality of life compared with age- and sex-matched population norms. The physical and emotional burden due to OA since 1990 has demonstrated a steady growth among people aged 15 to 49 years, with the greatest burden evident for females.<sup>36</sup> The knee accounts for the most healthcare related OA visits at roughly one-third (31%) of OA visits in hospital and outpatient settings, with females making up 78% of the population with OA.<sup>58</sup> Advanced and late stage OA typically leads to joint replacement procedures, which contributes to a significant percentage of the high direct healthcare costs related to all forms of OA.<sup>36</sup> Unfortunately, the number of individuals returning to competitive sport or activity following ACLR is significantly declining both within the first year following surgery and over subsequent years. A major contributor to this lack of participation in former athletes is related to the self-reported decreased function of their surgical knee at various time points after surgery including at long-term follow-up.<sup>19</sup>

While ACL rupture is somewhat inevitable, especially in populations and sport activities with a higher risk, perhaps the identification of risk factors for the development of knee OA following ACL injury can help prevent or delay the development of OA. Contrasting reports have been published regarding sex as a risk factor to developing knee OA. Although females have had a higher likelihood for developing primary knee OA and PTOA,<sup>35,66</sup> males have also been shown to be at a greater risk for such developments.<sup>40</sup> In addition to sex,<sup>67-69</sup> several other risk factors have already been identified in the literature such as race,<sup>63,69-71</sup> age,<sup>56,67</sup> body mass index,<sup>27,43,67,68,72,73</sup> and meniscectomy<sup>43,71</sup> at the time of ACL reconstruction; however, most of these factors are unalterable throughout the development process of OA.

Clinicians and researchers should be privy to the information about risk factors for the development of OA to help facilitate positive outcomes in individuals with one or more of these

risk factors. Of particular importance is the need to fully understand and apply knowledge regarding any risk factors that could potentially influence the trajectory of joint changes. Although concurrent meniscectomy at the time of ACLR and having a BMI >25kg/m are predictive of tibiofemoral OA and osteophytes as early as one year following ACLR<sup>43</sup>, there is limited influence that can be made related to these findings on the trajectory of further OA development and progression. Therefore, we need to expand our knowledge and awareness of more modifiable risk factors within the progression of PTOA. Several tangible and modifiable indicators to the development of OA have been identified, such as decreased performance during a single legged hop test, loss of knee extension range of motion, and increased knee joint laxity.<sup>53,71</sup> Attention to these modifiable risk factors will allow clinicians to address the disease before onset or at its earlier stages.

### **Alterations in Joint Loading Following ACL Injury**

Asymmetrical joint loading may exist in various activities and movements, as well as at various time points following ACLR. Therefore, it can be a critical, objective finding in patients at risk of developing knee OA. Joint loading encompasses several different mechanisms and measurements to understand how force is dissipated during functional tasks and movements. One such measurement is the pattern and magnitude of mechanical loading in the vertical direction, which has been demonstrated to be lower in the ACL limb in tasks such as squatting and hopping.<sup>74-76</sup> Reduced loading at the knee joint has been shown to alter chondrocyte synthesis and catabolic activities, thus changing the composition of articular cartilage.<sup>77</sup> Often asymmetries in joint loading have the ability to be corrected through extensive rehabilitation; however, some may continue to persist, including during high intensity activities, such as

jumping.<sup>78</sup> Risk of a second ACL injury is significantly higher in individuals who demonstrate these asymmetric biomechanical alterations.<sup>79</sup> In addition to limiting the risk of re-injury, information regarding asymmetries should be applied in an effort to modify a patient's trajectory towards PTOA following injury.

Individuals who have sustained a traumatic knee joint injury, specifically an ACL injury, are prone to long-term biomechanical and self-reported deficits several years after injury that are similar to that of individuals experiencing OA.<sup>80</sup> An improved understanding of lower extremity movement strategies and the influence of knee joint loading on PTOA is critical in developing treatment plans for individuals following a knee joint injury. Limited evidence exists to understand how to alter the degenerative process of articular cartilage and overall joint breakdown following ACL injury. Wellsandt et al<sup>81</sup> determined that reduced knee joint loading forces 6 months after ACLR were associated with the subsequent development of knee OA at 5 years following surgery. Therefore, an improvement in knee joint loading across functional tasks, especially in individuals returning to physical activity following ACLR, may be important in patients in an attempt to prevent progressive OA and a subsequent TKA. However, the link between increased joint loading and OA has also been explored by some researchers who connect excessive compressive loading during ambulatory tasks to the development and progression of knee osteoarthritis<sup>82</sup> which is contrary to the finding of decreased loading leading to changes in cartilage composition. Knee adduction moments, during functional movement tasks, such as gait, have been shown to influence the pathogenesis of OA after ACL injury, primarily in the medial compartment of the knee, which is most susceptible to joint breakdown.<sup>66,81,83,84</sup> Further explanation can be provided through the abnormal kinematics of the knee as demonstrated by an increase in anterior tibial shift and tibial rotation during gait.<sup>16,17</sup>

The ability to determine joint loading during more physically demanding tasks, such as jumping and landing, is important in patients that intend to or have returned to sport or activity which require these movements. An insight into the multi-joint strategy (hip, knee, and ankle) during these movements may provide vital information about the overall functional capacity. A measurement of joint loading that has garnered more attention in the ACL injured population in the last 10 years is the concept of energy absorption (EA) and energy absorption contribution (EAC) throughout the lower extremity.

Energy absorption is influenced by eccentric muscle action of the lower extremity musculature and is calculated by combining kinematic (joint angular velocity) and kinetic (net joint moment) data to quantify the energy at each joint that is responsible for producing the observed movement.<sup>85,86</sup> EA is primarily quantified in regards to extensor muscles of the lower extremity and is based on the integration of the negative portion of the power curve.<sup>86</sup> This interpretation of eccentric muscle action and the presence of a negative power curve exists when the direction of joint motion is opposite to that of the internal joint moment (knee is flexing but the quadriceps are active as extensors).<sup>86</sup> The individual contributions of each joint within the lower extremity during a specific task can be interpreted as a sum of 100%, which is identified as EAC.

Sex differences in energy absorption during landing strategies have been previously documented in healthy subjects. Males contributed 22% of ankle plantarflexors, 41% of knee extensors and 38% of hip extensors to overall energy absorption during a flexed landing task.<sup>87</sup> When observed completing a similar landing task, females have used 40%, 41% and 19%, respectively, compared to their male counterparts.<sup>88</sup> The distal-to-proximal strategy and/or “knee-dominant” strategy often used by females is similar to what has been identified in

biomechanical literature as increasing their risk for an ACL injury, whereas males tend to use more of a proximal or hip and knee focused strategy to dissipate energy.<sup>89,90</sup> Norcross and colleagues<sup>89</sup> further examined energy absorption and biomechanical factors linked to ACL injury risk and determined that greater values for peak vertical ground reaction force (VGRF), knee flexion angle, external hip flexion moment, and knee valgus angle during the first 100ms of landing were the biomechanical factors that were most linked to ACL injury. But ultimately, only greater knee energy absorption and greater peak knee flexion during landing were significantly related to ACL injury risk.<sup>89</sup>

The examination of joint loading by way of energy absorption has also been documented in ACLR subjects. Decker et al<sup>91</sup> demonstrated that ACLR individuals used greater energy absorption from the knee and ankle compared with the hip during a vertical drop landing, whereas, healthy subjects presented with no energy absorption differences between the lower-extremity joints. These findings elude to compensations in functional movements and altered strategies to accomplish tasks in ACLR individuals. Garrison et al<sup>92</sup> found that ACLR individuals utilized a greater percentage of hip EAC and less knee EAC during a double-leg squat task compared to healthy controls at 3 months post-surgery. This group also examined EAC during landing from a lateral vertical jump task at time of return to sport following ACLR in female patients. No significant findings were demonstrated for knee EAC, but ACLR subjects used greater hip EAC of both the involved and uninvolved limbs, as well as a lower percentage of EAC at the involved ankle compared to healthy controls.<sup>93</sup>

The difference in mechanical demands of high-impact landing tasks is evident in healthy individuals compared to those with an ACL injury. When examining EA in ACLR individuals the angular velocity and joint positions at ground contact and throughout the entirety of the



motion during landing must be analyzed. The stresses placed on internal knee structures are effected by distance of landing height because of its influence on the peak joint moments and power.<sup>87</sup> Eccentric strength and neuromuscular control are critical during functional movements as they control landing and energy dissipation across joints. Individuals with an injury history may be challenged to meet those demands if there are any changes in hip extensors, knee extensors, or ankle plantarflexors joint moments and power.<sup>87</sup>

A limitation to quantifying EA during functional tasks is the variability in findings at the lower extremity joints based off of the type task (i.e., single leg hop vs. drop jump landing). Despite the changes in joint contributions across tasks<sup>93-96</sup>, these data can help to contribute to the body of knowledge regarding eccentric muscle actions and the ability to dissipate energy to decelerate the body effectively during various functional tasks. Larger eccentric muscle actions and greater EA at certain joints may help identify the type of individual or functional task that experiences greater loads to the ACL. Further work in this area is needed to examine the consistency of these findings among ACLR individuals who are more than 1 year from surgery.

### **Self-Reported Function in Individuals with ACLR History and OA**

Patient reported outcomes (PROs) and measures of self-reported knee function are widely used with individuals that have sustained a traumatic knee injury, such as an ACL injury and subsequent ACLR. Subjective measures of knee function are valuable aspects of the rehabilitative process and serve as a means along with objective measures to determine readiness to return to sport in physically active populations following ACLR. Knee function is commonly

measured through the use of PROs throughout a patient's rehabilitation but are also beneficial to quantify self-reported function beyond the point of return to play. Two common instruments used to identify factors related to knee function and the development of OA post ACLR are the International Knee Documentation Committee (IKDC) Subjective Knee Evaluation Form and the Knee Injury and Osteoarthritis Score (KOOS).

The IKDC was formed in 1987 by a committee of international orthopedic surgeons to develop a standardized international documentation system for knee conditions. The IKDC Standard Knee Evaluation Form, which was designed for knee ligament injuries, was subsequently published in 1993 by Hefti et al.<sup>97</sup> and revised in 1994 by Anderson.<sup>98</sup> The IKDC Subjective Knee Evaluation Form was developed as a revision of the Standard Knee Evaluation Form in 1997. It has undergone successive revisions since its publication in 2001 to be inclusive to patients with a variety of knee conditions.<sup>99</sup> The IKDC form is used to detect improvement or deterioration in symptoms, function, and sports activities due to knee impairment from a variety of knee conditions, including ligament injuries, meniscal injuries, articular cartilage lesions, and patellofemoral pain.<sup>100</sup>

The KOOS questionnaire was developed in the 1990s and first published in 1998. The KOOS is used to measure patients' opinions about their knee and associated problems over short and long-term follow-up.<sup>99,101</sup> The KOOS targets young and middle-aged people with post-traumatic osteoarthritis, as well as those with injuries that may lead to posttraumatic OA (e.g., ACL, meniscal, or chondral injury).<sup>102</sup> An advantage of the KOOS is the inclusion of multiple subscales (pain, symptoms, activities of daily living, sport/recreation, and knee related quality of life) to measure physical function relating to daily life and physical activity.<sup>101</sup>

The IKDC and KOOS tools are used widely through the process following ACL injury, from initial injury to return to sport. These measures of knee function provide important information about patient status throughout the rehabilitation process and are used to make important decisions regarding patient subjective progress. The questionnaires can also be used to determine the status and success of recovery throughout the post-operative phases during rehabilitation and beyond return to play. Ardern et al,<sup>20</sup> found that those who returned to their pre-injury status had more positive psychological responses, reported better knee function in sport and recreational activities, perceived a higher knee-related quality of life, and were more satisfied with their current knee function. Gathering this subjective information at the return to play time point and once an athlete has been back to activity is vital for the clinician to understand overall knee function.

Several authors have continued to gather these data beyond the point of return to sport and activity to understand how knee function persists over time. In a group of elite handball and football players who had a previous history of an ACL injury 1-6 years prior to the study, Myklebust and colleagues<sup>103</sup> indicated that ACLR players reported significantly lower subscores in all 5 KOOS domains compared to their healthy counterparts, although none had developed OA at the time of the study.

The association between radiographic knee OA and subjective outcomes have also been examined in ACLR subjects. Jarvela et al<sup>51</sup> examined the presence of OA and used the IKDC to evaluate self-reported function in 100 patients between 5-9 years post-ACLR. While the number of patients with radiographic changes was over 50%, they additionally found that these patients had IKDC scores significantly lower than subjects without radiographic OA. At a later time point of 14 years following ACLR, Barenus et al<sup>104</sup> examined similar findings when using the KOOS

scale, with results showing that patients with OA in any compartment in any knee had significantly worse scores than patients without OA. Øiestad et al<sup>105</sup> findings were consistent with the aforementioned studies, which demonstrated that patients 10-15 years removed from ACLR with any radiographic knee OA changes also had significantly increased symptoms scores using the KOOS scale.

These findings suggest that through the use of multiple valid and reliable tools, the psychological impact of OA is substantial and must be addressed in conjunction with physical limitations to provide holistic care to patients that have or will develop knee OA. Conversely, Salmon et al<sup>71</sup> found evidence of radiographic knee OA changes at a 13 year follow-up point, but less than half of the subjects with OA reported abnormal findings using the IKDC scale. Despite the lack of significant findings,<sup>71</sup> those participants that identified as having abnormal self-reported function justify the importance of examining these factors after ACLR across various time points. Collectively, these studies suggest the presence of diminished self-reported function at various time points following ACLR, which increase the need to gather these data to understand subjective factors related to the development of knee OA.

Measures of health-related quality of life (HRQOL) are of important following ACLR as patients that may participate in various levels of activity from recreational participation to competitive sports, but all participate in activities of daily living. Identifying overall HRQOL can help practitioners and researchers gather the complete picture regarding their patients' health, beyond just their joint function. When using the Assessment of Quality of Life (AQoL) instrument, 147 people examined with hip or knee OA aged 20 to 55 years had markedly impaired HRQOL compared with age- and sex-matched population norms.<sup>65</sup> Whittaker et al<sup>80</sup> found a moderately high correlation between the KOOS symptoms subscale and AQoL subscale,

which suggests that knee related symptoms influence knee related quality of life. The inclusion of the quality of life subscale in the KOOS questionnaire allows users to gather important general health data, in conjunction with more focused subscales for activity, sport and recreation, and symptoms. Combining this data with objective measures of physical function is of substantial importance to understand the totality of knee OA following ACL injury.

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## Chapter 2

### **Energy absorption and energy absorption contribution during functional tasks in ACL reconstructed individuals**

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## Abstract

**Background:** Knee osteoarthritis (OA) is highly prevalent in individuals who have a previous history of traumatic knee injury, including anterior cruciate ligament (ACL) injuries. Although data exists to identify persistent physical deficits several years following ACL injury, evidence is lacking in regard to how functional alterations during joint loading can progress an individual towards the development or worsening of OA. The purpose of this study was to measure how knee, hip and ankle joint loading, via EA and EAC, change across physical performance tasks on the involved limb of ACL reconstructed (ACLR) individuals, compared to healthy matched control limb. The hypothesis was that ACLR individuals will show alterations in knee, hip and ankle joint loading during physical performance tasks, compared to healthy matched controls.

**Methods:** Twenty ACLR participants (11 females, 9 males; Age =  $21.9 \pm 2.1$ ; Years since ACLR =  $5.2 \pm 2.5$ ) were compared to 20 age, sex, limb and activity-matched healthy controls (11 females, 9 males; Age =  $22.2 \pm 1.9$ ). Lower extremity biomechanical data was collected during single leg squat (SLS), single leg hop and gait tasks. Energy absorption (EA) and energy absorption contribution (EAC) were calculated at the knee, hip and ankle joints during all tasks. Linear mixed effects models were used to model the interaction between group and performance task when compared to joint loading via EA and EAC. **Results:** A significant two-way interaction effect was found between group and task for all EA and EAC joint loading measures ( $p < .0001$ ). Several significant findings resulted from the post-hoc analyses between tasks for EA and EAC in both the ACLR and control groups. Accordingly, significant between-task differences were found in both the ACLR and control groups for certain EA and EAC joint loading measures. For example, both the ACLR and control groups showed that the Gait-2 task was associated with a lower mean Hip EA than other tasks (Hop100:  $\Delta = 2.44$ ,  $p < .0001$ ; Hop50:

$\Delta=1.26$ ,  $p < .0001$ ; Stance:  $\Delta=0.53$ ,  $p=0.01$ ; SLS:  $\Delta=1.96$ ,  $p < .0001$ ), with the mean for ACL group being generally lower than the control group (Hop100:  $\Delta=.82$ ,  $p < .0001$ ; Hop50:  $\Delta=1.04$ ,  $p < .0001$ ; Stance:  $\Delta=0.88$ ,  $p < .0001$ ; SLS:  $\Delta=.74$ ,  $p < .0001$ ). In contrast, for both the ACL and control groups, the Hop100 task was associated with a higher mean Hip EA than other tasks (Hop150:  $\Delta=-2.39$ ,  $p < .0001$ ), with the mean for ACL group being generally higher than the control group (Hop150:  $\Delta=-1.1$ ,  $p < .0001$ ). **Conclusion:** ACLR participants use joint loading strategies that differ based on the type of dynamic task that is being completed. Specifically, when compared to control participants, ACLR participants utilize less knee EA and EAC, while compensating at the ankle and/or hip to complete various dynamic tasks. **Word Count: 434**

## Introduction

An anterior cruciate ligament (ACL) injury is often associated with long-term functional impairments and disabilities, which extend beyond rehabilitation and return to activity. These deficiencies may be due to knee joint laxity, meniscal injuries, reduced quadriceps strength, and changes in knee joint loading, along with the subsequent development of knee osteoarthritis (OA).<sup>1</sup> Joint loading of the lower extremity has been studied to identify risk factors for ACL injuries<sup>2</sup> and is also a useful measurement to determine asymmetries<sup>3-5</sup> or increased risk of re-injury<sup>6</sup> following ACL reconstruction (ACLR). Asymmetrical loading of the surgical limb during functional tasks has been identified across the continuum of care after ACLR,<sup>7,8</sup> throughout rehabilitation and to the time of return to sport or activity. In some cases these asymmetries may begin to normalize as healing progresses and time since surgery increases,<sup>9</sup> however, in more demanding physical tasks the differences in joint loading continue to persist up to and beyond the one-year time point from surgery,<sup>10-14</sup> which suggests continued risk of joint re-injury and long-term damage.

While the prevalence of knee OA peaks around the age of 50 years,<sup>15</sup> research has shown that the greatest risk factor predicting the development of knee OA in young and middle-aged people is previous traumatic knee joint injury.<sup>16</sup> ACLR individuals inherently have an elevated risk of developing post-traumatic OA (PTOA),<sup>16,17</sup> with roughly 50% of individuals who suffer an ACL injury developing radiographic or symptomatic knee OA within 5-15 years after the initial injury.<sup>18-20</sup> The increased likelihood of developing OA after ACL injury is likely due to several factors, including alterations in knee joint kinematics and kinetics. Reduced loading at the knee joint has been shown to alter chondrocyte synthesis and catabolic activities, thus physiologically changing the composition of articular cartilage.<sup>21</sup> Wellsandt et al<sup>3</sup> determined

that reduced knee joint contact forces 6 months after ACLR were associated with the subsequent development of knee OA at 5 years following surgery. Several studies demonstrate a decreased knee extensor moment during various functional tasks following ACLR,<sup>12,14,22,23</sup> which suggests the inability of the knee extensors to eccentrically control movement and dissipate forces at the knee joint. In addition to these findings, ACLR individuals often rely on the ankle and hip to control the limb during functional movement in order to compensate for an inadequate knee extensor moment.<sup>6,24</sup>

The ability to determine the influence of each lower extremity joint on overall joint loading during functional activities is imperative to understand the implications of ACLR and future joint status. Examining more physically demanding tasks, such as jumping and landing, is important in patients that intend to or have returned to sport or activity which require these movements. An insight into the strategy during these movements may provide vital information about the overall functional capacity of all joints of the lower extremity, especially the knee. A measurement of joint loading that has garnered more attention in the ACL injured population recently is the concept of energy absorption (EA) and energy absorption contribution (EAC). Energy absorption is influenced by eccentric muscle action of the lower extremity musculature and is calculated by combining kinematic (joint angular velocity) and kinetic (net joint moment) data to quantify the energy at each joint that is responsible for producing the observed movement.<sup>25,26</sup> EA is primarily quantified in regards to extensor muscles of the lower extremity and is based on the integration of the negative portion of the power curve.<sup>26</sup> This interpretation of eccentric muscle action and the presence of a negative power curve exists when the direction of joint motion is opposite to that of the internal joint moment.<sup>26</sup> As a measure of EAC, joints are



analyzed according to their overall contributions, totaling a sum of 100, or often represented as 100%.

Sex differences in energy absorption during landing strategies have been previously documented in healthy subjects. Males contributed 22% of ankle plantarflexors, 41% of knee extensors and 38% of hip extensors to overall energy absorption during a landing task.<sup>27</sup> When observed completing a similar landing task, females have used 40%, 41% and 19%, respectively, compared to their male counterparts.<sup>28</sup> The distal-to-proximal strategy and/or “knee-dominant” strategy often used by females is similar to what has been identified in biomechanical literature as increasing their risk for an ACL injury, whereas males tend to use more of a proximal or a hip and knee focused strategy to dissipate energy.<sup>29,30</sup> Norcross and colleagues<sup>29</sup> further examined energy absorption and biomechanical factors linked to ACL injury risk and determined that greater values for peak vertical ground reaction force (VGRF), knee flexion angle, external hip flexion moment, and knee valgus angle during the first 100ms of landing were the biomechanical factors that were most linked to ACL injury. But ultimately, only greater knee energy absorption and greater peak knee flexion during landing were significantly related to ACL injury risk.<sup>29</sup>

The examination of joint loading by way of energy absorption has also been documented in ACLR subjects.<sup>7,10,31-33</sup> Decker et al<sup>31</sup> demonstrated that ACLR individuals used greater energy absorption from the knee and ankle compared with the hip during a vertical drop landing, whereas healthy subjects presented with no energy absorption differences between the lower-extremity joints. These findings elude to compensations in functional movements and altered strategies to accomplish tasks in ACLR individuals. Garrison et al<sup>32</sup> found that ACLR individuals utilized a greater percentage of hip EAC and less knee EAC during a double-leg squat task compared to healthy controls at 3 months post-surgery. This group also examined

EAC during the same task across multiple time points from preoperative to return to sport testing.<sup>7</sup> As time progressed, knee EAC increases with each time point, but ultimately does not return to preoperative thresholds, even at time of return to sport.<sup>7</sup> Boo et al<sup>10</sup> expanded observations of functional tasks to the frontal plane with EAC assessment during landing from a lateral vertical jump task at time of return to sport following ACLR in female patients. No significant findings were demonstrated for knee EAC, but ACLR subjects used greater hip EAC of both the involved and uninvolved limbs, as well as a lower percentage of EAC at the involved ankle compared to healthy controls.<sup>10</sup>

The difference in mechanical demands of high-impact landing tasks is evident in healthy individuals compared to those with an ACL injury. When examining EA in ACLR individuals the angular velocity and joint positions at ground contact and throughout the entirety of the motion during landing must be analyzed. The stresses placed on internal knee structures<sup>27</sup> are effected by distance of landing height because of its influence on the peak joint moments and power.<sup>27</sup> Eccentric strength and neuromuscular control are critical during functional movements as they control landing and energy dissipation across joints. Individuals with an injury history may be challenged to meet those demands if there are any changes in hip extensors, knee extensors, or ankle plantarflexors joint moments and power<sup>27</sup> as they control landing and energy dissipation.<sup>27</sup>

A limitation to quantifying EA during functional tasks is the variability in findings at the lower extremity joints based off of the type task (i.e., single leg hop vs. drop jump landing). Despite the changes in joint contributions across tasks<sup>10,34-36</sup>, these data can help to contribute to the body of knowledge regarding eccentric muscle actions and the ability to dissipate energy to decelerate the body effectively during various functional tasks. Larger eccentric muscle actions

and greater EA at certain joints may help identify the type of individual or functional task that experiences greater loads to the ACL.

ACLR individuals return to physical activity of varying intensities and physical demands after clearance from rehabilitation, which can place different stressors on the joints of the lower extremity. An understanding of the normal and abnormal strategies or movement patterns of each lower extremity joint during various functional tasks can influence our understanding of PTOA. Therefore, the purpose of the study was to compare the involved limb of ACLR individuals several years removed from surgery to healthy matched controls across various functional tasks including gait, single leg squat, and single leg hop using measures of knee, hip and ankle joint loading, via EA and EAC. We hypothesized that ACLR individuals will show alterations in joint loading when (a) comparing within functional tasks and (b) when comparing to healthy matched controls.

## **Methods**

Participants: Forty individuals who met the inclusion criteria were enrolled into this study. Twenty participants had a prior history of an ACLR, and twenty participants were age, sex, limb and activity-matched healthy controls. ACLR participants were an average of  $5.2 \pm 2.5$  years removed from ACL reconstruction (males =  $5.8 \pm 3$  and females =  $4.7 \pm 2$ ). The injured limb of the ACLR group was matched to the limb of the control group based upon the side of dominance. Physical activity level was quantified and matched using the Tegner Activity Scale. Table 1 details participants' demographics. For both groups, participants were considered eligible if they were between the ages of 18 and 25. For the ACL group, eligible participants

were enrolled if they had a history of a unilateral ACL reconstruction and were at least 2 years removed from the time of the surgery. Participants were excluded if they had a follow-up procedure to their original ACL limb, suffered a second ACL injury to either the ipsilateral or contralateral limb, or had any lower extremity injury within the last 6 months. For the control group, eligible participants were enrolled if they were not experiencing an active lower extremity orthopedic injury and had not been injured within the last six months.

Following the screening process, if the participants were eligible, they were invited to participate in the study. All participants gave informed consent for the study and the rights of each person were protected. The Institutional Review Board of UT Southwestern (affiliate of Texas Health Resources) and The University of Texas at Arlington approved the research procedures. Following enrollment in the study, each participant completed a demographic information sheet that included injury history and sports participation.

Procedures: A between group, observational case control laboratory-based study was conducted. Data collection took place during a single visit to either the Texas Health Sports Medicine (THSM) Laboratory or the Biomechanics Laboratory at the University of Texas at Arlington (UTA). Participants were prepared for 3D motion capture analysis using reflective markers that were adhered to participants' skin and clothing with double-sided tape. Marker placement consisted of 33 total markers including C7, T12, manubrium, acromion processes, bilateral posterior superior iliac spine, bilateral anterior superior iliac spine, bilateral superior sacral poles, inferior sacrum, bilateral greater trochanters, bilateral mid-thigh, bilateral medial and lateral femoral condyles, bilateral mid tibia, bilateral medial and lateral malleoli, bilateral first and fifth metatarsal heads, and bilateral calcaneus. Markers at ASISs, medial femoral

condyles, and medial malleoli were used only for a static calibration trial. Participants then completed the static trial and three tasks while being recorded using a motion capture system. Single-leg squat (SLS), single-leg hop and gait tasks were performed by each participant, with all trials starting on the participants' non-dominant or non-surgical limb, followed by the dominant or surgical limb.

### *Single-leg squat (SLS)*

Participants were asked to stand on a single limb on the force plate, with hands on their lower ribs and the contralateral leg raised to 90 degrees of hip and knee flexion during the single leg squat task. Participants performed the single leg squat while keeping their hands on their lower ribs and their feet flat on the floor. A metronome set at 60 bpm was used to ensure consistent pace across testing as participants completed five consecutive single limb squats without touching down on each leg. Participants were given a brief practice period to familiarize with the testing position and the metronome before capturing the data.

### *Single-leg hop*

During the single leg hop task, participants stood on their testing leg at a distance of 50% of their height from the force plate with their hands unrestricted and moving freely. Participants were instructed to take off on one leg and land on same leg, while stabilizing the landing position for 1-2 seconds. A failed attempt was counted if accessory movement is present on landing, the participant fell or was not able to stabilize their landing for 1-2 seconds. Participants were given unlimited practice trials until they felt comfortable with the task, followed by three captured trials on each leg.

### *Gait*

Gait was the last task completed, where participants were instructed to walk an approximately 10-meter runway at their self-selected speed through the capture space over the embedded force plates. Foot placement on the force plate and identification of an acceptable range of walking speeds were determined during 3-5 practice trials. Speed was monitored for consistency and was accessed based off of the practice trials using 2 infrared photocells (DashR Timing System, Lincoln, Nebraska) placed 2m apart. Gait trials were accepted if the participant maintained a consistent speed, avoided visual targeting of the force plate, and made isolated foot contact without altering the natural gait pattern. These procedures were repeated until three acceptable trials were collected for both limbs.

Data Capture and Reduction: Marker data was captured at 120 Hz using 8 motion-capture cameras at THSM (Qualisys AB, Göteborg, Sweden) or 16 motion-capture cameras at UTA (Vicon Motion Systems, Oxford, United Kingdom) surrounding in-ground force plates (Optima Human Performance System, Advanced Mechanical Technology, Inc., Watertown, MA) sampling GRF data at 1200 Hz. After marker identification and labeling, trials were transferred to Visual 3D v6 Professional software (C-Motion, Inc., Germantown, MD) for data processing and reduction.

Energy absorption (EA) of the hip, knee, and ankle was calculated during descending phase of SLS and single-leg hop tasks and stance phase during gait. Gait trials were analyzed at three specific time points relative to the stance phase of the foot contacting the force plate: (a) the first 50% of the stance phase (Gait-1 in the results and analysis), (b) the second 50% of the stance phase (Gait-2) and (c) the entire stance phase of the gait cycle (Stance). Similarly, the hop trials were analyzed at three specific time points during the landing, relative to the time after initial foot contact on the force plate: 50ms (Hop50 in the results and analysis), 100ms (Hop100),

and 150ms (Hop150). The kinematic and kinetic data were used to calculate EA by integrating the negative part of the net power (product of angular velocity and moment; Watts) curve during the entirety of the tasks and normalizing it to the product of height and weight ( $Ht * BW$ ). EA values across all joints and tasks were multiplied by 100 prior to statistical analyses. Energy absorption contribution (EAC) of each joint was calculated relative to the total EA (sum of hip, knee, and ankle EA) and is expressed as a percentage or value out of 100.

Statistical Analysis: A linear mixed effects analysis was performed using SAS version 9.4 (SAS Institute, Cary NC) to model the interaction between group (ACLR and healthy control) and performance task (SLS, Single leg hop, and Gait) to compare the joint loading via EA and EAC between the ACLR case and control groups for each performance task. If a significant interaction effect was found, the Tukey multiple comparison test was conducted to test the between-task difference for each group. Alpha levels were set at 0.05.

## **Results**

A significant interaction effect was found for all EA and EAC joint loading measures when comparing the groups across the seven performance tasks (Hip EA,  $F = 48.60$ ,  $p < .0001$ ; Knee EA,  $F = 62.24$ ,  $p < .0001$ ; Ankle EA,  $F = 92.03$ ,  $p < .0001$ ; Hip EAC,  $F = 22.40$ ,  $p < .0001$ ; Knee EAC,  $F = 56.83$ ,  $p < .0001$ ; Ankle EAC,  $F = 46.96$ ,  $p < .0001$ ). Several significant findings resulted from the post-hoc analyses between tasks for EA and EAC in both the ACLR and control groups, as outlined in Table 2 and Table 3.

Hip EA (Table 2 & Figure 1a): ACLR participants demonstrated the least Hip EA during Gait-1 and Gait-2 tasks compared to all other performance tasks, whereas Hop100 exhibited the greatest amount of Hip EA. For example, the mean differences in ACLR participants' Hip EA between Gait-1 and other tasks were 2.52 ( $p < .0001$ ) for Hop 100, 1.34 ( $p < .0001$ ) for Hop50, 0.6 ( $p < .0024$ ) for Stance, and 2.04 ( $p < .0001$ ) for SLS. Control participants experienced the least amount of Hip EA during Hop150 and Gait-2 and the greatest Hip EA during Hop50. ACLR participants exhibited greater Hip EA during the SLS task compared to all other tasks, except for Hop100. Conversely, control participants only experienced greater Hip EA during the SLS compared to Hop150, Gait-1 and Gait-2. Both ACLR and control groups experienced greater Hip EA during Hop50 and Hop100 tasks compared to Gait-1 and Gait-2 tasks. Upon analyzing a within task comparison, both groups exhibit the greatest amount of Hip EA during Stance. ACLR participants experience the least amount of Hip EA in Gait-1, whereas control participants experience the lowest Hip EA values with Gait-2. When comparing Hip EA between hop tasks, both groups experience the least amount of EA at Hop150. ACLR participants exhibit the most EA at Hop100, while control participants report the highest value at Hop50.

Knee EA (Table 2 & Figure 1b): Both groups demonstrated the greatest amount of Knee EA across all tasks during the SLS task, followed by the Hop100 task. Gait-1 was the task with the least amount of Knee EA for ACLR participants, while control participants experienced the least amount in Gait-2 compared to all other tasks. All hop tasks exhibited greater Knee EA than all gait tasks for ACLR participants, with the greatest differences exhibited between Hop100 and Gait-1 at 2.72 ( $p < .0001$ ) and Hop100 and Gait-2 at 2.21 ( $p < .0001$ ). This finding was comparable for control participants, except for Hop150, which exhibited less Knee EA than Stance. A within task comparison demonstrated that for both groups, the greatest amount of



Knee EA was present during Hop100, while the least amount occurred during Hop150. When comparing time points within the gait task, stance exhibited the greatest amount of Knee EA for both groups.

Ankle EA (Table 2 & Figure 1c): ACLR participants demonstrated the greatest amount of Ankle EA during Hop50, followed by the SLS. Conversely, control participants experienced the greatest Ankle EA during SLS, with the Hop50 task as the second greatest task. Later time points in hopping exhibited the least amount of Ankle EA across all tasks for both groups, with the ACLR group experiencing the least Ankle EA in the Hop150 task and the control group at Hop100. ACLR participants had greater Ankle EA during Hop50 and Hop100 compared to Gait-1 and Gait-2. Alternatively, control participants experienced more Ankle EA with all gait tasks than both Hop100 and Hop150. The greatest difference existed with Hop50 and Gait-1 at 0.87 ( $p < .0001$ ) and Hop50 and Gait-2 at 0.79 ( $p < .0001$ ). A within group comparison of gait tasks revealed that both groups exhibited the greatest amount of Ankle EA with Stance and the least amount with Gait-1.

Hip EAC (Table 3 & Figure 2a): ACLR participants displayed the greatest Hip EAC during the Hop100 task and the lowest Hip EAC during the Gait-1 task. Control participants experienced the most Hip EAC with the Gait-1 task and the lowest amount during the SLS task. Further contrasting findings were noted between groups when grouping the tasks comparatively. ACLR participants had greater Hip EAC during all hop tasks compared to all gait tasks and SLS. Specifically, the greatest difference between tasks for the ACLR group was Hop100 having an estimate of 16.55 more units of Hip EAC than in Gait-1 ( $p < .0001$ ). Control participants had the opposite outcome with the greatest Hip EAC being experienced during all gait tasks compared to all hop tasks and SLS. Among these findings, control participants had 24.31 less units of Hip

EAC during Hop150 compared to the Gait-1 task ( $p < .0001$ ). When comparing within the hop task, ACLR and control participants experienced the lowest Hip EAC during Hop150. ACLR participants had the highest Hip EAC in the Hop100 task among all hop tasks, whereas the control group experienced more Hip EAC with Hop50. A within task comparison determined that the range from highest to lowest Hip EAC values was Stance, Gait-2 and Gait-1 for ACLR participants. Control participants had demonstrated Gait-2 as the lowest Hip EAC task of the gait grouping.

Knee EAC (Table 3 & Figure 2b): ACLR participants exhibited the greatest Knee EAC during the SLS task, whereas the Hop100 task was greatest for the control group. However, both groups did share a similar finding with Gait-1 ranking as the task in which the least Knee EAC was displayed. When comparing these tasks between groups, there was a 25.19-unit difference for Gait-1 and SLS in ACLR participants ( $p < .0001$ ) and 39.10-unit difference between Gait-1 and Hop100 in the control group ( $p < .0001$ ). Control participants had greater Knee EAC during all hop tasks than all gait tasks and SLS. This finding had similarities for ACLR participants, with Hop100 and Hop150 having greater Knee EAC than all gait tasks. The exception in the ACLR group was with Hop50, which exhibited less Knee EAC than Stance. Within task comparisons presented similarities for both groups, of which included the findings that both groups demonstrated the greater Knee EAC during Gait-2 and the least with Gait-1. Examination of the hop tasks revealed that both groups demonstrated the least amount of Knee EAC during Hop50. Differences were found between groups for the task with the greatest Knee EAC, which was Hop100 for the control group and Hop150 for the ACLR group.

Ankle EAC (Table 3 & Figure 2c): Both ACLR and control groups demonstrated the greatest amount of Ankle EAC in all gait tasks compared to all hop tasks and SLS. Of all gait

tasks, ACLR participants had the highest Ankle EAC during Gait-1, while control participants demonstrated the most Ankle EAC within the Gait-2 task. Both groups exhibited the least amount of Ankle EAC during Hop100 compared to all other performance tasks. The greatest difference with ACLR participants existed as 32.67 units less Ankle EAC during Hop100 compared to Gait-1 ( $p < .0001$ ). Similarly, control participants exhibited 21.83 units less Ankle EAC during Hop100 compared to Gait-2 ( $p < .0001$ ). A within group comparison of hop time points showed that both groups had the greatest amount of Ankle EAC during the Hop50 task.

Between Group Comparisons (Figure 1 & Figure 2): ACLR and control participants exhibited the greatest between group differences for EA and EAC joint loading outcomes during the Hop100 and Gait-1 tasks. Among all seven performance tasks, Hop100 exhibited the most recurring significant between group differences. ACLR participants displayed greater Hip EA, Ankle EA and Hip EAC than control participants during the Hop100 task. Conversely, control participants had far greater Knee EA and Knee EAC than ACLR subjects during Hop100. Gait-1 exhibited the greatest between group difference for Ankle EAC, with the ACLR group displaying greater EAC than the control group.

## **Discussion**

The purpose of this study was to determine if lower extremity alterations were present in joint loading across physical performance tasks when examining ACLR individuals and subsequently comparing them to healthy matched controls. The primary finding of our study was a significant interaction effect for all EA and EAC joint loading measures. These data support

our hypotheses that ACLR participants would exhibit within differences in joint loading across physical performance tasks and between differences compared to the control participants for joint loading during those same tasks.

As far as we are aware, there are no previous studies that compare EA and EAC joint loading among different functional tasks in ACLR individuals because the literature surrounding measures of joint loading through energy absorption has been heavily focused on healthy participants.<sup>34,35,37-39</sup> However, more recent studies have emerged that examine ACLR participants across different functional tasks<sup>7,10,31-33</sup> but not at time points greater than one year removed from ACL reconstruction. Important joint loading findings from this study relate to the loading patterns at the knee. We compared each task within the two research groups and we compared the ACLR to the healthy matched control group between tasks. ACLR and control participants in the present study both demonstrated the greatest amount of Knee EA during the SLS task compared to all other tasks. When examining Knee EAC, ACLR participants also exhibited the greatest knee contribution during SLS, whereas control participants had the greatest knee contribution at Hop100. When comparing tasks within group, both groups utilized greater Knee EA and EAC during SLS and hop tasks than any gait tasks.

Previously reported literature utilizing squat tasks have assessed ACLR participants during a double-limb squat and have documented differences in Knee EAC on their surgical limb across the continuum of care from the pre-operative time point to return-to-sport (RTS).<sup>7,32,33</sup> Garrison et al<sup>7</sup> measured Knee EAC within the double limb squat in the surgical limb of ACLR patients at preoperative, 12-week post-operative, and return to sport timepoints and reported loading at the knee to be as much as 50% of the total lower extremity contribution at the preoperative time point. The Knee EAC at the two remaining timepoints were 40.98% ± 13.73%

(12-week) and  $47.50\% \pm 12.04\%$  (RTS). By the time of RTS, participants were demonstrating an increase from the 12-week mark, but still not meeting the baseline value from the pre-operative time point. Garrison et al<sup>7</sup> indicated that reduced quadricep strength likely explained some of the variance for Knee EAC at the various time points and that ACLR patients had not restored knee extensor strength even at RTS. In comparison, we measured EAC during a SLS and at one time point (2-9 years post ACLR) and determined that ACLR subjects had close to 60% Knee EAC for the SLS task in our study, which is greater than the reported values from Garrison et al<sup>7</sup>. Our knee EAC values were larger than Garrison et al<sup>7</sup>; however, we used the SLS test, we did not analyze quadriceps strength, and our participants were tested at times further removed from surgery. The larger percentage of contribution of the knee to total energy absorption during the SLS was likely due to a greater restoration in quadriceps strength allowing the subjects to use the knee extensors at a greater capacity within this task.

When examining Knee EA and EAC during more dynamic tasks, ACLR and control participants in the current study utilized less EA and EAC during hop tasks than during the SLS, but exhibited greater EA and EAC during hop tasks compared to gait tasks. Hop100 presented as the hop task with the greatest Knee EA for both ACLR and control participants and Knee EAC for control participants. This time point has been analyzed previously during a double-leg jump landing task in which healthy participants that landed with greater knee extension moments and anterior tibial shear force were suspected to have greater loading on the ACL.<sup>34</sup> We examined an earlier time point of landing at Hop50, where both groups utilized less Knee EA than Hop100 and displayed the lowest knee contribution during this task. When measuring EAC during the initial 50ms during landing from a lateral vertical jump task, previous research has identified less than 10% of the contribution occurring at the surgical knee of the ACLR group and the dominant

limb of the control group.<sup>10</sup> These results suggest different tasks will elicit different landing strategies in the lower extremities and thus need to be accounted for when analyzing movement across several tasks.

Although observations of joint loading at initial contact or shortly thereafter in a landing task is of particular importance to understanding injury risk and reinjury in the ACL literature, examining multiple time points can provide a more beneficial understanding of the overall landing strategy. Previous research<sup>31</sup> using a double-limb vertical drop landing have reported comparable Knee EAC (%) between ACLR and matched control participants at initial contact and at a point of minimum knee flexion as both groups had the greatest overall energy contribution occurring at the knee (~40%) throughout this movement (Figure 2b). As expected ACLR and control participants in the current study produced greater knee EAC values during hop tasks than lower impact tasks, such as gait. By delineating our single leg hop task into three separate time points of 50ms, 100ms and 150ms, we were able to examine these differences across the task and identify how energy is absorbed over time. Both groups increased their knee contribution beyond the Hop50 time point; however, control participants used the greatest amount of Knee EAC at Hop100, followed by a slightly lower value at Hop150. The opposite was observed for ACLR participants, with Knee EAC gradually increasing sequentially from Hop50 to Hop150. These findings suggest that within our observed time points in this hop task, control participants were able to use greater eccentric loading at the knee within a shorter amount of time (Figure 2b) than ACLR participants. ACLR participants also use less knee EAC initially during the landing portion of this task and take longer to reach their maximum EAC (ACLR max at Hop150 vs Control max at Hop100), which implies an altered neuromuscular strategy and eccentric knee extensor involvement (Figure 2b).

Similar to the Decker et al<sup>31</sup> study examining a vertical drop landing, both groups experienced half or nearly half of their total contribution from the knee at the Hop50 time point (Figure 2b). However, unlike the previous study,<sup>31</sup> control participants in the present study utilized a Knee EAC greater than 60% as the task progressed to the Hop100 and Hop150 time points, whereas ACLR participants did not reach the 60% threshold at either time point (Figure 2b). The range in EAC values from the present study to the Decker et al,<sup>31</sup> study reflect the difference in strategy and energy demands between a double-limb and single-limb landing task. Furthermore, these findings demonstrate the ability for both groups to eccentrically dissipate energy at the knee throughout a single leg hop task, even at 2-9 years ( $5.2 \pm 2.5$  years) out from surgery. However, the ACLR group presents with reduced Knee EAC percentages compared to control indicating the ACLR subjects seem to use a different landing strategy to minimize the loading at their surgical knee compared to that of their healthy counterparts.

For both groups, the least amount of Knee EA was present within the gait tasks compared to all other tasks (Figure 1b). This finding was duplicated for Knee EAC, with all three gait tasks using less Knee EAC (Figure 2b) than all other tasks, except for Hop50 in the ACLR group. To our knowledge, we are the first study to assess EA and EAC during gait; therefore, we sought to compare our findings to previous literature using measures of vertical ground reaction force (vGRF), which is a more established method of analyzing joint loading during gait. Existing literature<sup>12,13</sup> of comparable gait analyses at self-selected walking speeds demonstrate that ACLR females several years ( $5.2 \pm 3.2^{12,13}; 4 \pm 3.4$  years<sup>13</sup>) out from reconstruction exhibit greater vGRF than healthy individuals. ACLR participants had significantly greater peak vGRF on their surgical limb immediately following heelstrike and experienced even greater loading rates if they were classified as ‘impulsive loaders’.<sup>13</sup> Biomechanical alterations in gait as measured by greater

peak vGRF, especially at the 6 month time point after ACLR, have been linked to a greater deterioration in medial tibiofemoral joint cartilage at two years removed from the reconstructive surgery.<sup>40</sup> Further comparative results regarding our lower Knee EAC percentages are provided with both Pietrosimone et al<sup>41</sup> and Wellsandt et al<sup>3</sup>. Pietrosimone and colleagues<sup>41</sup> demonstrated that symptomatic participants <12 months unloaded their ACL limb during stance and overloaded the limb at >24 months from ACLR. Despite the conflicting results of overloading and unloading during gait tasks,<sup>41</sup> it is believed that unloading may have a more detrimental effect related to degenerative changes at the tibiofemoral joint following ACL injury by leading to cartilage thinning.<sup>3,42,43</sup> Wellsandt and colleagues<sup>3</sup> reported that ACLR participants with radiographic knee OA had lower moments and contact forces during gait on their involved limbs than subjects without radiographic changes indicating compensatory changes in gait in an effort to possibly avoid knee joint loading. Other research using squatting and hopping tasks<sup>44-46</sup> demonstrated ACLR participants also use lower vGRF during these tasks, which demonstrates unloading. Therefore, even simple changes in gait will likely further influence changes in cartilage composition that could lead to the development of knee OA.<sup>21</sup>

Unlike measures of joint loading utilizing vGRF, which examine the ability of the limb to absorb forces as a whole, energy absorption values broken down by lower extremity joints elude to a pattern or strategy to movement during a functional task and can help to explain why unloading may occur at the knee. To help explain alterations in energy absorption, particularly unloading of the ACL limb during a double-limb squat task, previously reported studies<sup>32,33</sup> have referenced compensations occurring at the hip. Several studies have observed the 12-week time point after ACLR in which these compensations are observed, as measured by EA and EAC.<sup>7,32,33</sup> Unloading of the knee during a double-limb squat task have resulted in an



increase in Hip EAC of the surgical limb.<sup>32</sup> Observations of hip strength were not part of these studies, but could potentially contribute to the greater utilization of hip extensors on the ACL limb as opposed to the knee extensors.

Healthy individuals, typically display a combined effort of the knee extensors and plantar flexors in an attempt to attenuate the ground reaction forces (GRFs) during the impact phase of double-leg landing and then follow this with a collective knee and hip contribution to stabilize the landing.<sup>37</sup> Conversely, an increase in Ankle EAC, compared to contributions at other joints, was reported during a lateral vertical jump task requiring an eccentric loading of a single-limb.<sup>10</sup> During this particular task, the ankle exhibited the greatest EAC, making up 78-87% of the contribution among both ACLR and control participants. The knee was used the least in both groups in this study,<sup>10</sup> but ACLR participants used a greater hip contribution and a lower ankle contribution on their surgical limb compared to that of their control counterparts.<sup>10</sup> On the contrary, the hip and ankle joints were used less during a vertical landing task when compared to the knee in both ACLR and healthy participants.<sup>31</sup> The findings by Decker et al<sup>31</sup> were unique in that the ankle and hip contributions were opposite between the ACLR and control groups. Control subjects completing the vertical drop landing demonstrated greater hip contribution than ankle during this task, whereas ACLR participants exhibited nearly as much ankle EAC as the knee, with the hip offering the lowest contribution.<sup>31</sup>

Ankle EA exhibited the smallest values of all other EA variables studied across all joints and tasks, especially in gait 1 and 2 and the later time points of hop tasks. These findings are supported by other literature that show limited ankle EA and EAC during a stationary task, such as a squat,<sup>32</sup> while other more dynamic tasks, such as a jump, require eccentric plantar flexor engagement upon accepting the load, particularly at initial impact.<sup>10,34,35</sup> We did not classify soft

versus stiff landings, but landing strategy has been shown to influence the loading contributions of each joint, with healthy females utilizing more ankle contribution due to landing in a more erect position (stiff) from a vertical drop landing than their male counterparts.<sup>38</sup> Although not significant, ACLR participants in the present study used greater Ankle EAC during all hop time points compared to control participants, which suggests the need for greater ankle plantar flexor involvement to counter the underloading of the knee extensors. Conversely, when analyzing ankle EAC, the gait tasks used the greatest percent contribution amount across all tasks especially in ACLR participants. These data compare to previous literature<sup>13,41</sup> that identified greater vGRF in the ACL limb at the moment of initial contact or immediately following heelstrike during gait because our ACLR participant findings demonstrate the ankle contributing a significant amount to the energy dissipation.

There are several limitations related to the current study including the collected measurements, the chosen plane of motion for the various tasks, and the subject pool. Although we report differences in EA and EAC between various tasks in both ACLR and control participants, we did not analyze any factors, such as strength measures, that would serve to explain any of the variance in these findings. Previous work has used hip<sup>10</sup> and quadriceps strength<sup>7,32</sup> to explain some of the variance in EAC differences in ACLR individuals between limbs or in comparison to control subjects. Therefore, it is difficult to conclude specific factors that cause the difference in joint loading. The tasks used were all in the sagittal plane, which limits any comparison to frontal, transverse, or multiplanar tasks. Future research is needed to examine the interaction between tasks in various planes of movement. In regards to subject selection, the current ACLR participants were  $5.21 \pm 2.49$  years (range 2-9 years) post-operative. Even though our purpose was to examine joint loading in individuals several years following

reconstruction, we acknowledge that this vast range of time since surgery may influence performance on each task. We also did not control for ACL graft types and the presence of meniscal injury at the time of ACL injury and our participants were recruited from various locations but were only measured during one single time point or visit to one of the labs. We did not have the ability to recruit participants from a single clinic or physician group, so we were unable to account for history of physical therapy or other considerations post injury and reconstruction.

### **Conclusion**

The results of this investigation indicate that ACLR individuals exhibit variations in joint loading throughout the ankle, knee and hip joints within multiple physical performance tasks and when compared to healthy control subjects. Our work shares many of the same trends as previous work describing EA and EAC in ACLR and control subjects.<sup>10,31,34-36</sup> We were able to identify patterns or strategies for loading and can conclude that different tasks present with variations to EAC and do not always demonstrate a consistent relationship between loading across different tasks or planes of movement. Also, the variations in the actual values for joint loading via EA and EAC may identify the use of inconsistent neuromuscular control patterns by ACLR participants that is dependent on the type landing task.

Of particular interest is that control subjects consistently used a much greater amount of Knee EAC than ACLR participants, thereby limiting their contributed amounts of hip and ankle energy absorption on gait deceleration and hopping tasks. For all hop tasks, ACLR participants had a relatively greater overall contribution from both hip and ankle joints than the control

group. These alterations in energy absorption used by ACLR participants provide insight into a modified approach to underload the knee while compensating at the ankle and/or hip to complete various dynamic tasks. As task difficulty increases, such as with a single-legged hop task, ACLR individuals exhibit a greater inability to load the knee initially upon landing and throughout the task when compared to control subjects. Although we did not examine factors to determine the presence or development of knee OA, these findings suggest that ACLR participants several years removed from surgery exhibited joint loading alterations that may negatively impact their knee joint health. Further work is needed to compare energy absorption of the lower extremity among ACLR participants with and without knee osteoarthritis and EAC needs to be measured across various time points within the continuum of care<sup>7</sup> and at several time points greater than two years removed from ACLR. This may allow for the understanding of how joint loading may change over time.

## Figure Legends

**Figure 1a:** Hip energy absorption (EA) (J) (y-axis) for the ACLR and control groups. Physical performance tasks are along x-axis. Larger negative values indicate more energy absorption.

**Figure 1b:** Knee energy absorption (EA) (J) (y-axis) for the ACLR and control groups. Physical performance tasks are along x-axis. Larger negative values indicate more energy absorption.

**Figure 1c:** Ankle energy absorption (EA) (J) (y-axis) for the ACLR and control groups. Physical performance tasks are along x-axis. Larger negative values indicate more energy absorption.

**Figure 2a:** Hip energy absorption contribution (EAC) (%) (y-axis) for the ACLR and control groups. Physical performance tasks are along x-axis. Larger values indicate more contribution to total energy absorption of lower extremity.

**Figure 2b:** Knee energy absorption contribution (EAC) (%) (y-axis) for the ACLR and control groups. Physical performance tasks are along x-axis. Larger values indicate more contribution to total energy absorption of lower extremity.

**Figure 2c:** Ankle energy absorption contribution (EAC) (%) (y-axis) for the ACLR and control groups. Physical performance tasks are along x-axis. Larger values indicate more contribution to total energy absorption of lower extremity.

**Table 1:** Participant Demographics

	<b>ACLR</b>		<b>Control</b>	
	<b>Male (n=9)</b>	<b>Female (n=11)</b>	<b>Male (n=9)</b>	<b>Female (n=11)</b>
Age	23.3 ± 1.7	20.6 ± 1.5	22.9 ± 1.9	21.6 ± 1.7
Height (m)	1.8 ± 0.1	1.7 ± 0.1	1.8 ± 0.1	1.6 ± 0.1
Weight (kg)	84.8 ± 5.9	69.2 ± 13.9	80.3 ± 10.9	65.0 ± 6.9
Tegner	6 ± 1.8	6.1 ± 1.8	5.3 ± 0.9	6 ± 2.1

**Table 2:** EA Outcomes (Hip, Knee, and Ankle) Under 3 Types of Physical Performance Tasks (SLS, Hop, and Gait) Between the ACLR and Control Groups.

Tasks		Hip_EA (J)				Knee_EA (J)				Ankle_EA(J)			
		ACLR		Control		ACLR		Control		ACLR		Control	
		ΔEst.	P	ΔEst.	P	ΔEst.	P	ΔEst.	P	ΔEst.	P	ΔEst.	P
Gait-1	Gait-2	0.08	0.999	-0.34	0.3291	0.51	0.7408	-0.67	0.4293	0.08	0.8818	0.02	0.9999
Gait-1	Hop100	2.52	<.0001	0.49	0.0311	2.72	<.0001	4.30	<.0001	0.12	0.5286	-0.21	0.0333
Gait-1	Hop150	0.12	0.9853	-0.61	0.0022	0.89	0.1220	0.26	0.9873	-1.72	0.1463	-0.15	0.3000
Gait-1	Hop50	1.34	<.0001	0.71	0.0001	1.65	<.0001	2.26	<.0001	0.87	<.0001	0.96	<.0001
Gait-1	Stance	0.60	0.0024	0.54	0.0106	1.04	0.0385	0.75	0.2882	0.63	<.0001	0.44	<.0001
Gait-1	SLS	2.04	<.0001	0.41	0.1312	4.64	<.0001	5.29	<.0001	0.81	<.0001	1.07	<.0001
Gait-2	Hop100	2.44	<.0001	0.82	<.0001	2.21	<.0001	4.97	<.0001	0.04	0.9969	-0.23	0.0130
Gait-2	Hop150	0.05	0.9999	-0.27	0.5911	0.37	0.9248	0.94	0.0868	-0.26	0.0033	-0.17	0.1649
Gait-2	Hop50	1.26	<.0001	1.04	<.0001	1.14	0.0145	2.94	<.0001	0.79	<.0001	0.94	<.0001
Gait-2	Stance	0.53	0.0141	0.88	<.0001	0.52	0.7212	1.43	0.0006	0.54	<.0001	0.42	<.0001
Gait-2	SLS	1.96	<.0001	0.74	<.0001	4.12	<.0001	5.96	<.0001	0.72	<.0001	1.05	<.0001
Hop100	Hop150	-2.39	<.0001	-1.10	<.0001	-1.83	<.0001	-4.04	<.0001	-0.30	0.0003	0.06	0.9725
Hop100	Hop50	-1.18	<.0001	0.22	0.7989	-1.07	0.0296	-2.04	<.0001	0.75	<.0001	1.17	<.0001
Hop100	Stance	-1.91	<.0001	0.05	0.9999	-1.68	<.0001	-3.55	<.0001	0.50	<.0001	0.65	<.0001
Hop100	SLS	-0.48	0.0392	-0.08	0.9984	1.92	<.0001	0.99	0.0556	0.68	<.0001	1.28	<.0001
Hop150	Hop50	1.21	<.0001	1.32	<.0001	0.76	0.2729	0.02	<.0001	1.05	<.0001	1.11	<.0001
Hop150	Stance	0.48	0.0374	1.15	<.0001	0.15	0.9995	0.49	0.7796	0.80	<.0001	0.58	<.0001
Hop150	SLS	1.91	<.0001	1.01	<.0001	3.75	<.0001	5.03	<.0001	0.98	<.0001	1.22	<.0001
Hop50	Stance	-0.73	<.0001	-0.17	0.9354	-0.62	0.5370	-1.51	0.0002	-0.25	0.0048	-0.52	<.0001
Hop50	SLS	0.70	0.0002	-0.30	0.4574	2.98	<.0001	3.40	<.0001	-0.06	0.9529	0.11	0.6306
Stance	SLS	1.44	<.0001	-0.14	0.9781	3.60	<.0001	4.54	<.0001	0.18	0.1090	0.63	<.0001

Energy absorption (EA) of the hip, knee, and ankle was calculated during descending phase of SLS and single-leg hop tasks and stance phase during gait.

Gait-1 is the first 50% of the stance phase; Gait-2 is the second 50% of the stance phase; Stance is the entire stance phase of gait cycle.

Hop was analyzed relative to the time after initial foot contact on the force plate: 50ms (Hop50), 100ms (Hop100), and 150ms (Hop150).

ΔEst.: 100\*Estimate of the difference between two tasks

P: the adjusted p value from the Tukey multiple comparison test

**Table 3:** EAC outcomes (Hip, Knee, and Ankle) Under 3 Types of Physical Performance Tasks (SLS, Hop, and Gait) Between the ACLR and Control Groups.

Tasks		Hip_EAC (%)				Knee_EAC (%)				Ankle_EAC (%)			
		ACLR		Control		ACLR		Control		ACLR		Control	
		ΔEst.	P	ΔEst.	P	ΔEst.	P	ΔEst.	P	ΔEst.	P	ΔEst.	P
Gait-1	Gait-2	-0.67	1.0000	5.39	0.2792	-10.55	0.003	-3.79	0.7109	11.21	<.0001	-1.60	0.9836
Gait-1	Hop100	-16.55	<.0001	18.87	<.0001	-16.12	<.0001	-39.10	<.0001	32.67	<.0001	20.23	<.0001
Gait-1	Hop150	-2.92	0.8907	24.31	<.0001	-21.87	<.0001	-35.03	<.0001	24.79	<.0001	10.72	<.0001
Gait-1	Hop50	-9.23	0.0027	14.52	<.0001	-6.38	0.1218	-15.40	<.0001	15.61	<.0001	0.88	0.9994
Gait-1	Stance	-1.64	0.9936	3.15	0.8497	-8.02	0.0179	-2.79	0.9141	9.67	<.0001	-0.36	1.000
Gait-1	SLS	-1.65	0.9935	24.76	<.0001	-25.19	<.0001	-32.05	<.0001	26.84	<.0001	7.29	0.0043
Gait-2	Hop100	-15.88	<.0001	13.48	<.0001	-5.58	0.2512	-35.31	<.0001	21.46	<.0001	21.83	<.0001
Gait-2	Hop150	-2.25	0.9672	18.92	<.0001	-11.32	<.0001	-31.24	<.0001	13.57	<.0001	12.32	<.0001
Gait-2	Hop50	-8.56	0.0076	9.13	0.0032	4.17	0.6103	-11.61	<.0001	4.39	0.2798	2.48	0.8705
Gait-2	Stance	-0.97	0.9997	-2.24	0.9681	2.52	0.9456	1.00	0.9996	-1.55	0.9863	1.24	0.9959
Gait-2	SLS	-0.98	0.9997	19.36	<.0001	-14.64	<.0001	-28.26	<.0001	15.62	<.0001	8.89	0.0001
Hop100	Hop150	13.63	<.0001	5.43	0.2699	-5.74	0.2189	4.07	0.6356	-7.88	0.0013	-9.51	<.0001
Hop100	Hop50	7.32	0.0404	-4.35	0.5483	9.74	0.0014	23.69	<.0001	-17.06	<.0001	-19.35	<.0001
Hop100	Stance	14.90	<.0001	-15.72	<.0001	8.10	0.0161	36.31	<.0001	-23.00	<.0001	-20.59	<.0001
Hop100	SLS	14.89	<.0001	5.89	0.1849	-9.06	0.0040	7.05	0.0596	-5.84	0.0491	-12.94	<.0001
Hop150	Hop50	-6.31	0.1240	-9.79	0.0011	15.49	<.0001	19.62	<.0001	-9.18	<.0001	-9.84	<.0001
Hop150	Stance	1.28	0.9984	-21.16	<.0001	13.85	<.0001	32.24	<.0001	-15.12	<.0001	-11.08	<.0001
Hop150	SLS	1.27	<.0001	0.45	1.000	-3.32	0.8218	2.98	0.8855	2.05	0.9447	-3.43	0.5888
Hop50	Stance	7.58	0.0291	-11.37	<.0001	-1.64	0.9940	12.61	<.0001	-5.94	0.0419	-1.24	0.9958
Hop50	SLS	7.58	0.0292	10.24	0.0005	-18.81	<.0001	-16.65	<.0001	11.23	<.0001	6.41	<.0001
Stance	SLS	-0.03	1.0000	21.61	<.0001	-17.17	<.0001	-29.26	<.0001	17.17	<.0001	7.65	0.0021

Energy absorption contribution (EAC) of each joint was calculated relative to the total EA (sum of hip, knee, and ankle EA) and is expressed as a percentage or value out of 100.

Gait-1 is the first 50% of the stance phase; Gait-2 is the second 50% of the stance phase; Stance is the entire stance phase of gait cycle.

Hop was analyzed relative to the time after initial foot contact on the force plate: 50ms (Hop50), 100ms (Hop100), and 150ms (Hop150).

ΔEst.: Estimate of the difference between two tasks

P: the adjusted p value from the Tukey multiple comparison test



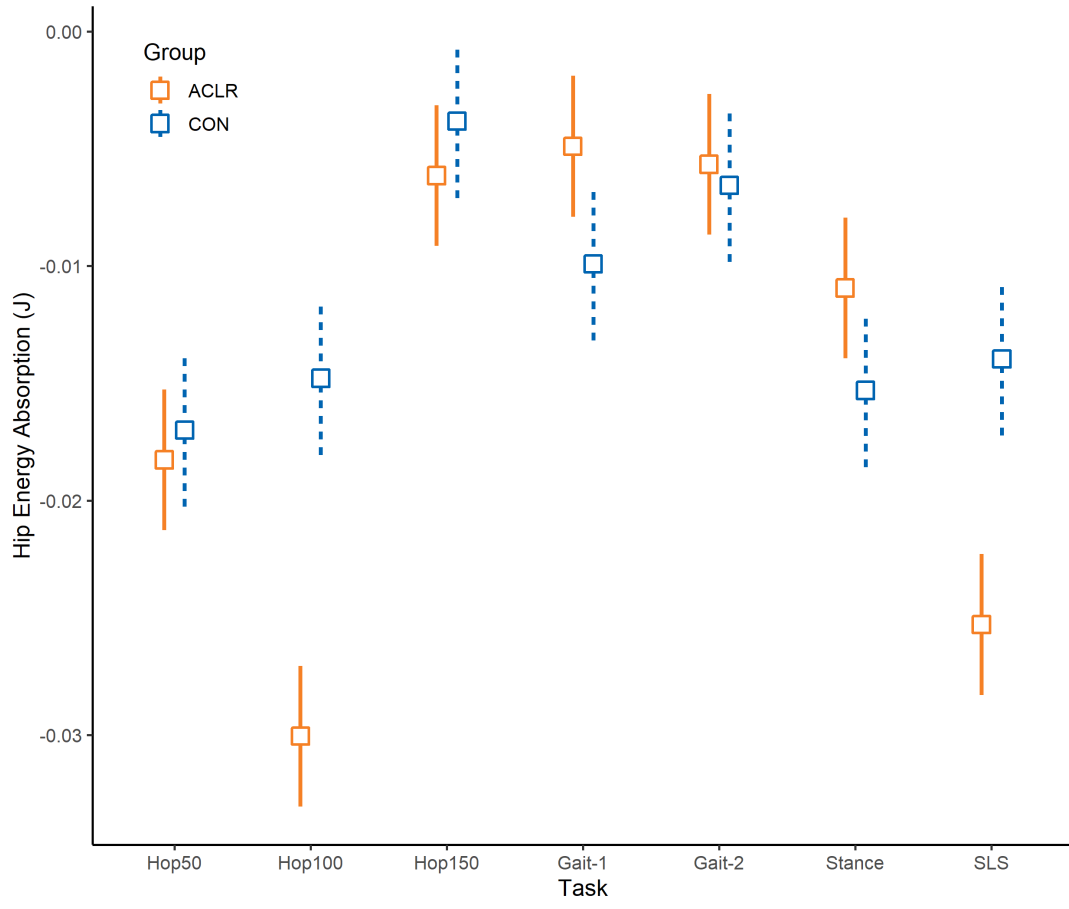


Figure 1a

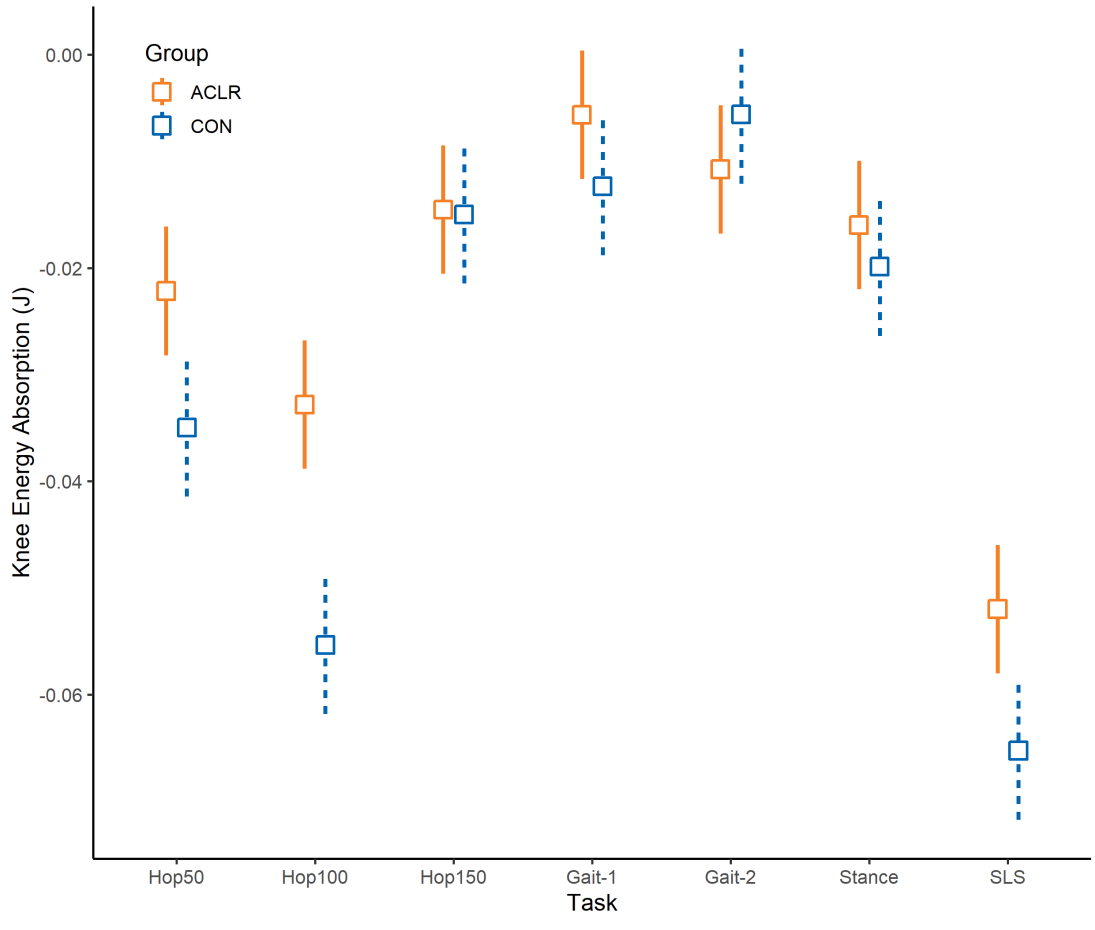


Figure 1b

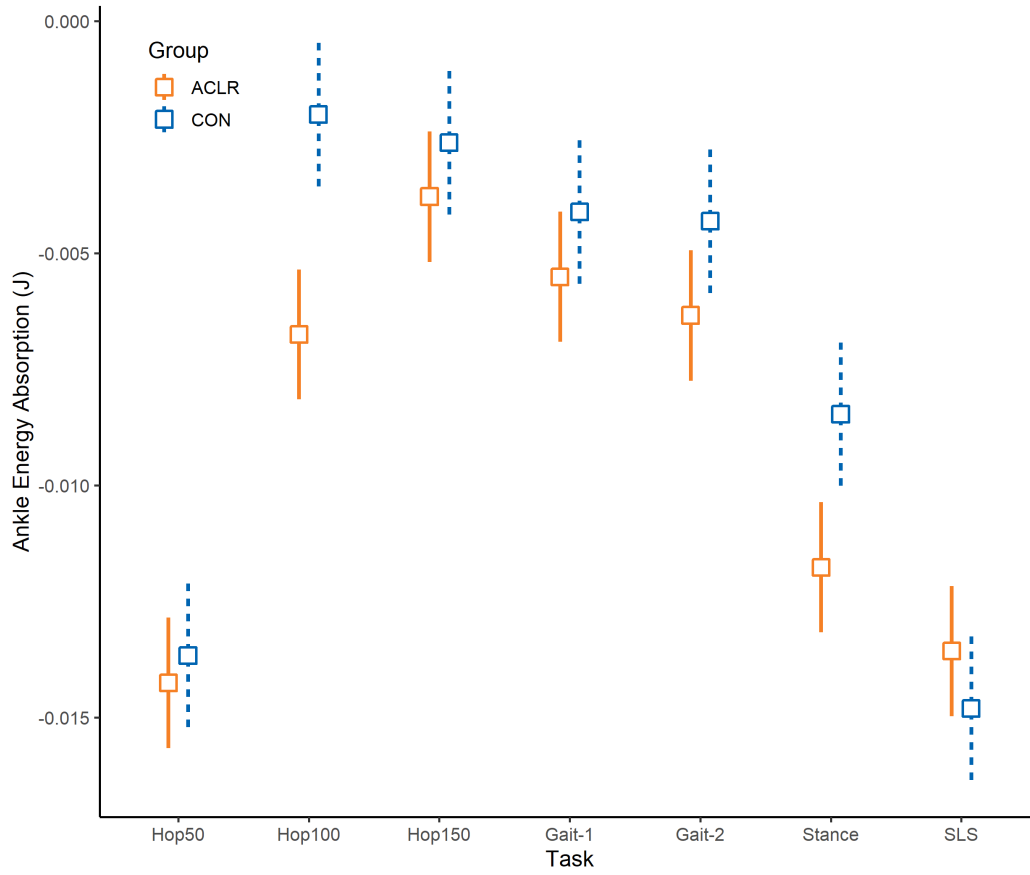


Figure 1c

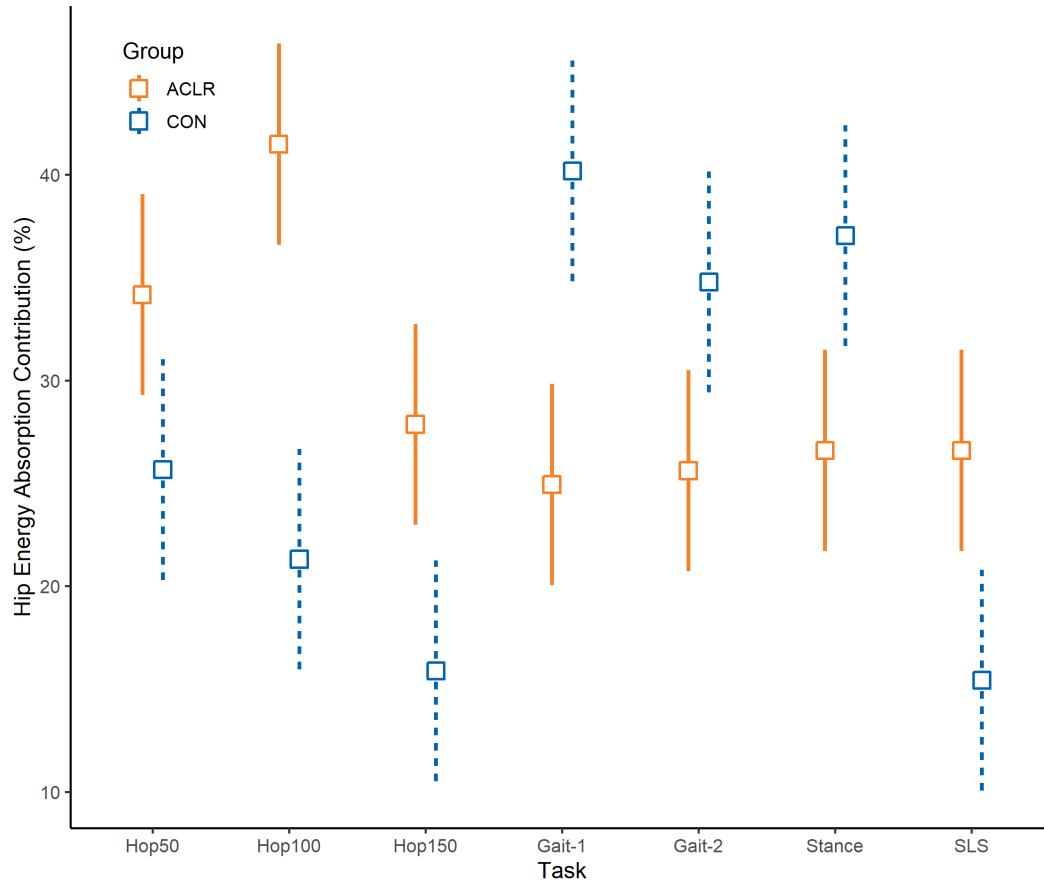


Figure 2a

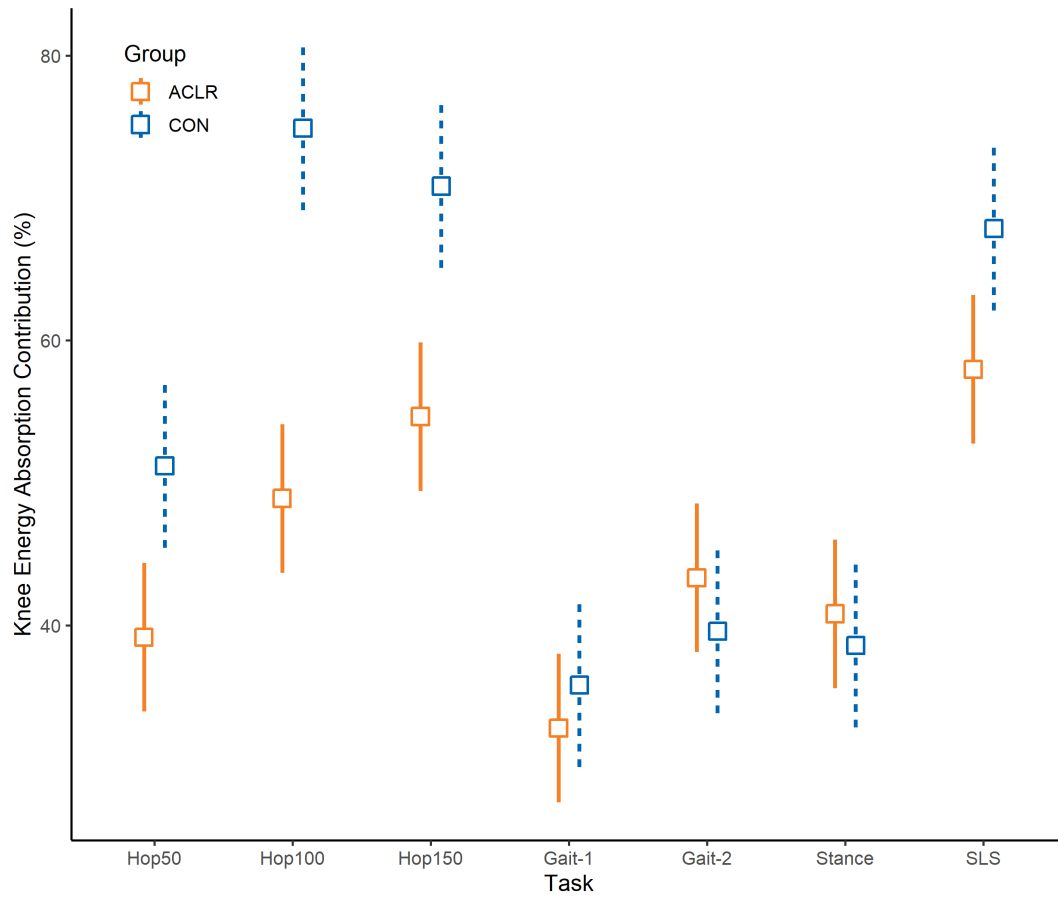


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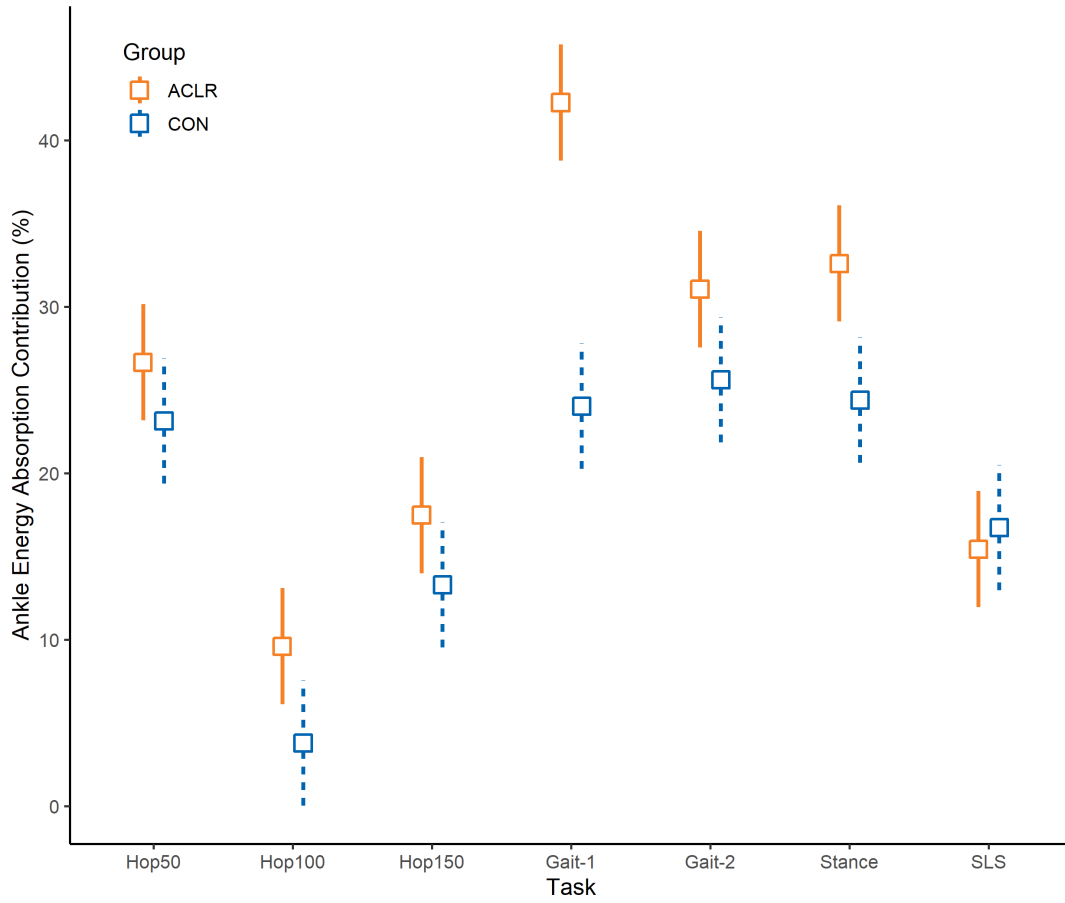


Figure 2c

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## **Chapter 3**

### **The influence of self-reported function on lower extremity energy absorption in ACL reconstructed individuals**

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## Abstract

**Background:** Measurements of self-reported function (SRF) following anterior cruciate ligament reconstruction (ACLR) are useful to understand individuals' perceptions of knee function and their impact on quality of life. Data from SRF has been presented with physical tasks measurement; however, it has not been examined when compared to joint loading using energy absorption (EA) and energy absorption contribution (EAC). The purpose was to determine if energy absorption within a variety of physical performance tasks was influenced by SRF scores both within ACLR subjects and between ACLR and controls. The primary hypothesis was that ACLR subjects with lower SRF would display differences in energy absorption patterns compared to ACLR subjects with high SRF. The secondary hypothesis was that ACLR individuals with similarly classified SRF as control subjects would also have differences in joint loading patterns across all tasks. **Methods:** Twenty ACLR subjects (11 females, 9 males; Age =  $21.9 \pm 2.1$ ; Years since ACLR =  $5.2 \pm 2.5$ ) were compared to 20 age, sex, limb and activity-matched healthy controls (11 females, 9 males; Age =  $22.2 \pm 1.9$ ). Lower extremity biomechanical data was collected during single leg squat (SLS), single leg hop and gait tasks. Energy absorption (EA) and energy absorption contribution (EAC) were calculated at the knee, hip and ankle joints during all tasks. SRF was evaluated using the Knee Injury and Osteoarthritis Outcome Score (KOOS) and International Knee Documentation Committee (IKDC) subjective forms. ACLR and control subjects were classified as either high or low relative to established cut-off scores for each scale. Linear mixed effects models were used to determine an interaction between group, task and self-reported function. **Results:** A significant three-way interaction was found between group, task and SRF for certain EA and EAC joint loading outcomes. Accordingly, a significant difference between ACLR and control was found

across certain tasks and SRF. For example, with a high SRF score, the ACL group showed a lower mean knee EA than the control group for the Hop100 task and Ankle EA outcomes (IKDC:  $\Delta=17.75$ ,  $p=.004$ ; KOOS Stiffness:  $\Delta=1.77$ ,  $p=.002$ ; KOOS Sport & Rec:  $\Delta=1.59$ ,  $p=.01$ ); however, this direction was reversed at a low SRF score (IKDC  $\Delta= -6.39$ ,  $p=.03$ ; KOOS Stiffness:  $\Delta= -1.27$ ,  $p<.001$ ). **Conclusion:** ACLR participants with lower SRF used joint loading strategies that limited knee loading and emphasized hip and ankle compensations. When compared to control groups with similar SRF scores, ACLR participants still consistently demonstrated altered loading strategies with more ankle and/or hip contribution in an effort to underload the knee. **Word Count: 407**

## Introduction

Measures of self-reported function (SRF) are commonly used with individuals after anterior cruciate ligament (ACL) injury and throughout rehabilitation following ACL reconstruction (ACLR). However, more emphasis is often placed on objective outcomes, such as strength and performance during functional tasks, to determine a patient's status or readiness to return to sports (RTS) following ACLR. Whereas patient reported outcome (PRO) scales measure SRF and can provide valuable insight into the individual's perception of the status of their injured knee and their perceived function. Because RTS requires physical, emotional, and mental readiness, it is a combination of objective and subjective factors that should determine RTS following ACLR.

Return to sport after an ACL injury is not always guaranteed even after reconstructive surgery. At 12 months post ACLR, Ardern et al<sup>1</sup> found that 33% of patients had returned to competitive sport, while the return-to-competitive-sport rate was only 46% at 39 months. Another study conducted by this group<sup>2</sup> revealed that 40% of subjects that do not return to a pre-injury level of activity cited poor knee function as a major reason for failure to return. The major deterrents for individuals not returning to full sport status studies can be psychological factors, such as fear of reinjury or a lack of confidence.<sup>3,4</sup> In contrary, ACLR individuals that did return to their pre-injury status had more positive psychological responses, reported better knee function in sport and recreational activities, perceived a higher knee-related quality of life, and were more satisfied with their current knee function.<sup>2</sup>

PRO scales are also valuable tools to provide qualitative information regarding individuals who have been diagnosed with knee osteoarthritis (OA) or are at increased risk of developing OA. Two common instruments used to identify factors related to knee function and



the development of OA post ACLR are the International Knee Documentation Committee (IKDC) Subjective Knee Evaluation Form and the Knee Injury and Osteoarthritis Score (KOOS).<sup>5</sup> The IKDC provides a scaled score from 0-100 from 18 scored items and the KOOS scale is split into five subscales (pain, other symptoms, function in daily living (ADL), function in sport and recreation (Sport/Rec) and knee related quality of life (QOL)) where each score is scaled from 0-100. For both scales, a score of 100 means no limitation with activities of daily living or sports activities and the absence of symptoms. Whittaker et al<sup>6</sup> reports a moderately high correlation between the KOOS symptoms subscale and quality of life (QOL) subscale, which suggests that knee related symptoms influence knee related quality of life. The inclusion of the QOL subscale in the KOOS questionnaire allows users to gather important general health data, in conjunction with more focused subscales for activity, sport and rec, and symptoms.

In a group of elite handball and football players who had a previous history of an ACL injury 1-6 years prior to the study, ACLR players reported significantly lower subscores in all 5 KOOS domains compared to their healthy counterparts, although none had developed OA within the time point studied.<sup>7</sup> Lohmander et al.<sup>8</sup> reported over 50% of former female soccer players, twelve years post ACLR, were identified as having radiographic knee OA, with over 80% having general radiographic changes. Along with these structural changes, 75% of these subjects reported having symptoms that affected their knee-related quality of life and daily activities.<sup>8</sup> Consistent with the aforementioned studies but using a longer time point post-surgery, Barenius et al<sup>9</sup> examined patients 14 years following ACLR using the KOOS scale and demonstrated that patients with OA in any compartment in any knee had significantly worse scores than patients without OA and Øiestad et al<sup>10</sup> demonstrated that patients 10-15 years removed from ACLR with any radiographic knee OA changes also had significantly worse KOOS symptom scores. In a

group of adults, age 54 years and older with a diagnosis of knee OA, van der Esch et al<sup>11</sup> found that activity limitations and self-reported knee instability were significantly present along with knee pain and a lack of muscular strength. These findings further support that poor self-perceived function is common among ACLR individuals with and without radiographic changes and that they are consistent with adults already diagnosed with OA.

Combining PRO data with objective measures of physical function is of substantial importance to understand the totality of knee function following ACL injury. Joint loading is a common measure of physical function after ACLR and can identify deficits within the surgical knee of ACL individuals.<sup>12-22</sup> The strategy in which an individual loads the joints of lower extremity can be determined with measures of energy absorption (EA) and energy absorption contribution (EAC). These measures are influenced by kinematic and kinetic variables that determine eccentric muscle action of the lower extremity musculature to quantify the amount of energy that each joint accounts for during movement.<sup>23,24</sup> EA is primarily quantified in regards to the hip extensor, knee extensor and plantarflexor muscles of the lower extremity and is based on the integration of the negative portion of the power curve during a functional task.<sup>24</sup> These values are then quantified to determine overall contributions of each joint, totaling a sum of 100, or often represented as 100%, which determines EAC.

Previous studies determining the impact of ACLR on EA and EAC outcomes have identified differences in joint loading in the surgical limb of ACLR individuals.<sup>19,20,25-27</sup> These studies have utilized outcomes related to quadriceps strength,<sup>19,20,25</sup> knee extension range of motion<sup>19</sup> and hip strength<sup>20</sup> along with EA and EAC variables to determine the impact that these factors have on ACLR individuals' ability to load their surgical limb at various time points from preoperative to one year following RTS. While a combination of these findings determines an

altered loading strategy by ACLR participants, there is limited information in the literature on the impact of SRF on EA and EAC variables. Additionally, EA and EAC has not been measured in ACLR participants beyond the one-year time point, which is needed to understand long-term knee joint health related to the development or progression of OA.

The primary purpose of this study was to identify if ACLR participants with lower SRF (IKDC and KOOS scales) had alterations in joint loading during physical performance tasks compared to ACLR participants with high SRF. The secondary purpose of this study was to determine how self-reported function, impacts outcomes on physical performance tasks between ACLR and control groups, based on their level of SRF. It was hypothesized that ACLR participants with lower SRF on the IKDC and KOOS scales would display deficits in performance tasks, compared to ACLR participants with high SRF. Likewise, it was hypothesized that ACLR individuals with similarly classified SRF (low SRF or high SRF) as control participants would have alterations in joint loading across all physical performance tasks.

## **Methods**

Participants: Forty individuals who met the inclusion criteria were enrolled into this study. Twenty participants had a prior history of an ACLR, and twenty participants were age, sex, limb and activity-matched healthy controls. ACLR participants were an average of  $5.2 \pm 2.5$  years removed from ACL reconstruction (males =  $5.8 \pm 3.0$  and females =  $4.7 \pm 2$ ). The injured limb of the ACLR group was matched to the limb of the control group based upon the side of dominance. Physical activity level was quantified and matched using the Tegner Activity Scale.

Table 1 details participants' demographics. For both groups, participants were considered eligible if they were between the ages of 18 and 25. For the ACL group, eligible participants were enrolled if they had a history of a unilateral ACL reconstruction and were at least 2 years removed from the time of the surgery. Participants were excluded if they had a follow-up procedure to their original ACL limb, suffered a second ACL injury to either the ipsilateral or contralateral limb, or had any lower extremity injury within the last 6 months. For the control group, eligible participants were enrolled if they were not experiencing an active lower extremity orthopedic injury and had not been injured within the last six months.

Following the screening process, if the participants were eligible, they were invited to participate in the study. All participants gave informed consent for the study and the rights of each person were protected. The Institutional Review Board of UT Southwestern (affiliate of Texas Health Resources) and The University of Texas at Arlington approved the research procedures. Following enrollment in the study, each participant completed a demographic information sheet that included injury history and sports participation. Participants also completed IKDC and KOOS questionnaires prior to motion capture testing.

Procedures: A between group, observational case control laboratory-based study was conducted. Data collection took place during a single visit to either the Texas Health Sports Medicine (THSM) Laboratory or the Biomechanics Laboratory at the University of Texas at Arlington (UTA). Participants were prepared for 3D motion capture analysis using reflective markers that were adhered to participants' skin and clothing with double-sided tape. Marker placement consisted of 33 total markers including C7, T12, manubrium, acromion processes, bilateral posterior superior iliac spine, bilateral anterior superior iliac spine, bilateral superior sacral poles, inferior sacrum, bilateral greater trochanters, bilateral mid-thigh, bilateral medial

and lateral femoral condyles, bilateral mid tibia, bilateral medial and lateral malleoli, bilateral first and fifth metatarsal heads, and bilateral calcaneus. Markers at ASISs, medial femoral condyles, and medial malleoli were used only for a static calibration trial. Participants then completed the static trial and three tasks while being recorded using a motion capture system. Single-leg squat (SLS), single-leg hop and gait tasks were performed by each participant, with all trials starting on the participants' non-dominant or non-surgical limb, followed by the dominant or surgical limb.

#### *Single-leg squat (SLS)*

Participants were asked to stand on a single limb on the force plate, with hands on their lower ribs and the contralateral leg raised to 90 degrees of hip and knee flexion during the single leg squat task. Participants performed the single leg squat while keeping their hands on their lower ribs and their feet flat on the floor. A metronome set at 60 bps was used to ensure consistent pace across testing as participants completed five consecutive single limb squats without touching down on each leg. Participants were given a brief practice period to familiarize with the testing position and the metronome before capturing the data.

#### *Single-leg hop*

During the single leg hop task, participants stood on their testing leg at a distance of 50% of their height from the force plate with their hands unrestricted and moving freely. Participants were instructed to take off on one leg and land on same leg, while stabilizing the landing position for 1-2 seconds. A failed attempt was counted if accessory movement is present on landing, the participant fell or was not able to stabilize their landing for 1-2 seconds. Participants were given

unlimited practice trials until they felt comfortable with the task, followed by three captured trials on each leg.

### *Gait*

Gait was the last task completed, where participants were instructed to walk an approximately 10-meter runway at their self-selected speed through the capture space over the embedded force plates. Foot placement on the force plate and identification of an acceptable range of walking speeds were determined during 3-5 practice trials. Speed was monitored for consistency and was accessed based off of the practice trials using 2 infrared photocells (DashR Timing System, Lincoln, Nebraska) placed 2m apart. Gait trials were accepted if the participant maintained a consistent speed, avoided visual targeting of the force plate, and made isolated foot contact without altering the natural gait pattern. These procedures were repeated until three acceptable trials were collected for both limbs.

Data Capture and Reduction: Marker data was captured at 120 Hz using 8 motion-capture cameras at THSM lab (Qualisys AB, Göteborg, Sweden) or 16 motion-capture cameras at the UTA lab (Vicon Motion Systems, Oxford, United Kingdom) surrounding in-ground force plates (Optima Human Performance System, Advanced Mechanical Technology, Inc., Watertown, MA) sampling GRF data at 1200 Hz. After marker identification and labeling, trials were transferred to Visual 3D v6 Professional software (C-Motion, Inc., Germantown, MD) for data processing and reduction.

Energy absorption (EA) of the hip, knee, and ankle was calculated during descending phase of SLS and SLFH tasks and stance phase during gait. Gait trials were analyzed at three specific time points relative to the stance phase of the foot contacting the force plate: (a) the first

50% of the stance phase (Gait-1 in the results and analysis), (b) the second 50% of the stance phase (Gait-2) and (c) the entire stance phase of the gait cycle (Stance). Similarly, the hop trials were analyzed at three specific time points during the landing, relative to the time after initial foot contact on the force plate: 50ms (Hop50 in the results and analysis), 100ms (Hop100), and 150ms (Hop150). The kinematic and kinetic data were used to calculate EA by integrating the negative part of the net power (product of angular velocity and moment; Watts) curve during the entirety of the tasks and normalizing it to the product of height and weight ( $Ht * BW$ ). EA values across all joints and tasks were multiplied by 100 prior to statistical analyses. Energy absorption contribution (EAC) of each joint was calculated relative to the total EA (sum of hip, knee, and ankle EA) and is expressed as a percentage or value out of 100.

Data from the IKDC and KOOS questionnaires were exported and analyzed according to their respective scoring guidelines.<sup>5</sup> The IKDC has 18 items over a variety of topics - 7 items for symptoms, 1 item for sport participation, 9 items for daily activities, and 1 item for current knee function. The response options vary for each item, including yes/no responses, 5-point Likert scales, and 11-point numerical rating scales. The IKDC is scored on each item using an ordinal method, for example a score of a 0 represents the highest level of symptoms or lowest level of function. Scores for each item are summed to give a total score. Participants' total scores were calculated as  $(\text{sum of items})/(\text{maximum possible score}) \times 100$ , to give a total score out of 100. A score of 100 indicates no limitation with daily or sporting activities and the absence of symptoms. The IKDC has a Cronbach's alpha of 0.77-0.91 and an ICC of 0.90-0.95.<sup>5</sup>

The KOOS consists of 5 subscales; pain, other symptoms, function in daily living (ADL), function in sport and recreation (Sport/Rec) and knee related quality of life (QOL).<sup>28</sup> The KOOS has 42 items across the 5 subscales and are measured on a 5-point Likert scale (0-4). Each

subscale was scored separately with a sum of all associated items. While a total score for all subscales combined is not recommended, scores can be transformed to a 0-100 scale, with 0 indicating extreme knee problems and 100 indicating no knee problems. Data was analyzed for each subscale and participants were given total scores out of 100 for all 5 subscales. The KOOS has a range of data for Cronbach's alpha and ICC for each subscale in the instrument.<sup>5</sup>

Low and high cutoff scores were determined for each scale, based on previously reported studies. For the KOOS data, a score of an 85/100 or 85% served as a cutoff between low and high scores for each subscale, as identified by Lynch et al.<sup>29</sup> For the IKDC data, the 15th percentile from the normative data from matched controls was chosen as the cutoff score to ensure that individuals who scored below the cutoff were differentiated from those who scored within the normal variance of IKDC scores, per previously reported data from Lodgerstedt et al.<sup>30</sup> For IKDC analysis, groups were divided into SRF sub-groups based on the calculated cutoff score of 84.5.

Statistical Analysis: A 3-way interaction between group (ACLR and healthy control), task (SLS, Single leg hop, and Gait) and dichotomized self-reported function using the IKDC and KOOS subscales (low and high) was examined using a linear mixed effects analysis using SAS version 9.4 (SAS Institute, Cary NC). The dependent variables were EA and EAC. If the interaction was found to be statistically significant, the Tukey test was followed up to compare the two groups given the high and low cutoff scores of self-reported function for each scale. Alpha levels were set at 0.05.



## Results

Between group mean PRO scores for all SRF scales are represented in Figure 1. Significant interactions were found for group, task and SRF scales for all joint loading variables except for Ankle EAC. Gait-2 was the only task that did not have a significant interaction with group and SRF scales. Additionally, the KOOS ADL scale was not included in the post-hoc comparisons since neither the ACLR group nor the control group had participants score below the 85-point threshold to be classified as having low SRF for that particular scale.

Ankle EA (Table 2): A 3-way interaction was significant for IKDC ( $F = 5.56$ ,  $p = <.0001$ ) and KOOS Stiffness ( $F = 5.17$ ,  $p < .0001$ ) scales. When comparing ACLR participants with high and low SRF during the Hop50 task, ACLR participants with low SRF on both the IKDC and KOOS Stiffness scale exhibited greater ankle EA ( $p < .0001$ ). ACLR participants with low SRF on the KOOS Stiffness scale also exhibited greater ankle EA during Hop100 ( $p < .0001$ ) and SLS task ( $p = 0.005$ ) than ACLR participants with high SRF. ACLR participants with high SRF on the KOOS Stiffness scale used less ankle EA during SLS than their control counterparts with high SRF ( $p = 0.036$ ). ACLR participants with high SRF also displayed less ankle EA on the Hop50 task compared to control participants with high SRF on both the IKDC ( $p = 0.003$ ) and KOOS Stiffness ( $p = 0.012$ ) scales. Conversely, ACLR participants with high SRF experienced greater ankle EA during Hop100 compared to control participants with high SRF on the IKDC ( $p = 0.007$ ) and KOOS Stiffness ( $p = 0.033$ ). This same finding was true for Stance ( $p = 0.014$ ) using the KOOS Stiffness scale. When comparing ACLR participants with low SRF to control participants with low SRF, ACLR subjects exhibited greater ankle EA on Hop50 (IKDC,  $p = 0.018$ ; KOOS Stiffness,  $p = 0.009$ ), Hop100 (IKDC,  $p = 0.025$ ; KOOS Stiffness,  $p = 0.0004$ ), and SLS (KOOS Stiffness,  $p = 0.006$ ).

Knee EA (Table 3): A significant 3-way interaction was present for IKDC ( $F = 5.86$ ,  $p < .0001$ ), KOOS Stiffness ( $F = 3.26$ ,  $p = 0.004$ ), and KOOS Sport & Rec ( $F = 2.61$ ,  $p = 0.017$ ) scales. Further post-hoc comparisons showed a significant interaction for knee EA and the Gait-1, Stance, Hop100 and SLS tasks. Specifically, for SLS, the energy absorbed by the knee of the ACLR group with high IKDC was greater than that of the ACLR group with low IKDC ( $p = 0.019$ ), which was consistent when comparing these groups with the KOOS Sport & Rec scale ( $p = 0.013$ ) during SLS. The SLS task was also significant between high control subjects and high ACLR participants with control participants demonstrating greater knee EA than ACLR participants ( $p = 0.019$ ).

Hop100 was significant across both scales for both the high ACLR/high control and the low ACLR/low control comparisons. The high IKDC ACLR group absorbed 17.75 units less energy at the knee than did the control group with a high IKDC ( $p = 0.004$ ), which was consistent with both the KOOS Stiffness ( $p = 0.002$ ) and KOOS Sport & Rec ( $p = 0.009$ ) scales. When comparing participants with low SRF from both the ACLR and control groups, the low IKDC ACLR group absorbed 36.25 units less energy at the knee during Hop100 than did the control group with a low IKDC ( $p = 0.004$ ). Similar findings of more knee eccentric action in the control group were exhibited with the KOOS Stiffness ( $p = 0.014$ ) and KOOS Sport & Rec ( $p = 0.007$ ) scales. Gait tasks were only significant when comparing the low ACLR group and low control group for the IKDC, with control participants with low SRF demonstrating greater knee EA during Gait-1 ( $p < .0001$ ) and Stance ( $p < .0001$ ).

Hip EA (Table 4): A 3-way interaction was significant for KOOS Symptoms ( $F = 2.58$ ,  $p = 0.018$ ) and KOOS Stiffness ( $F = 5.42$ ,  $p < .0001$ ), but not IKDC. Hop100, Hop50 and SLS were tasks with significant interactions among the aforementioned SRF scales across all sub-group

comparisons. The Hop100 was significant for high ACLR participants compared to low ACLR participants using the KOOS Stiffness scale as the participants with low SRF experienced more hip eccentric action ( $p < .0001$ ). Hop100 was also significant when comparing high ACLR participants to high control participants using the KOOS Stiffness scale, with ACLR participants using more hip eccentric action ( $p = 0.017$ ). ACLR participants with low SRF also used more hip eccentric action during Hop100 tasks compared to control participants with low SRF on both the KOOS Symptoms and KOOS Stiffness scales ( $p < .0001$ ). This finding between low SRF subgroups was consistent in the Hop50 task when comparing KOOS Stiffness scores among ACLR and control groups ( $p = 0.027$ ).

The SLS task exhibited significant interactions between high ACLR/high control groups and low ACLR/low control groups. Hip EA was greater for ACLR participants with high SRF compared to control participants with high SRF on both the KOOS Symptoms scale ( $p = 0.002$ ) and KOOS Stiffness scale ( $p < .0001$ ). Similarly, ACLR participants with low SRF demonstrated more hip eccentric action than control participants with low SRF during SLS when comparing the KOOS Symptoms scale ( $p < .0001$ ) and KOOS Stiffness scale ( $p < .0001$ ).

Knee EAC (Table 5): Post-hoc comparisons revealed a significant 3-way interaction for KOOS Symptoms ( $F = 2.89, p = 0.009$ ), KOOS Stiffness ( $F = 9.30, p < .0001$ ), and KOOS QOL ( $F = 3.51, p = 0.002$ ). Of the seven performance tasks analyzed, Hop50, Hop100 and Hop150 were the only significant tasks upon comparison to group and SRF scale. ACLR participants with high SRF on the KOOS Stiffness scale experienced greater knee energy contribution (EAC) than ACLR participants with low SRF during Hop50 ( $p = 0.002$ ), Hop100 ( $p < .0001$ ) and Hop150 ( $p < .0001$ ). These findings were also consistent in this subgroup for Hop150 when analyzing the KOOS QOL scale ( $p = 0.001$ ).

Control participants with high SRF displayed 17.49 and 19.89 units of greater knee EAC during Hop100 than ACLR participants with high SRF on the KOOS Stiffness scale ( $p = 0.0001$ ) and KOOS QOL scale ( $p = 0.001$ ), respectively. Greater knee EAC was also demonstrated during Hop100 in control participants with low SRF compared to ACLR participants with low SRF on the KOOS Symptoms ( $p < .0001$ ), KOOS Stiffness ( $p < .0001$ ) and KOOS QOL ( $p = 0.025$ ) scales. The findings in this subgroup was also present during Hop150 when comparing low SRF groups using KOOS Stiffness ( $p = 0.0001$ ) and KOOS QOL ( $p = 0.029$ ).

Hip EAC (Table 6): A post-hoc comparison was significant for the IKDC ( $F = 2.37$ ,  $p = 0.028$ ) and KOOS Stiffness ( $F = 6.10$ ,  $p < .0001$ ) scales. Participants in the ACLR group experienced differing findings when comparing participants with low SRF and high SRF. ACLR participants with high SRF on the IKDC experienced greater hip energy contribution (EAC) during Hop50 than their counterparts with low SRF ( $p = 0.022$ ). When examining this sub-group using the KOOS Stiffness scale, ACLR participants with low SRF displayed greater hip EAC than participants with high SRF during the Hop100 ( $p = 0.0001$ ) and Hop150 tasks ( $p < .0001$ ). The Hop100 and Hop150 tasks were also significant when compared to SRF and group, examining low SRF between ACLR and control participants. ACLR participants with low SRF on KOOS Stiffness and IKDC scales exhibited greater hip EAC during Hop100 and Hop150 compared to control participants with low SRF.

ACLR participants with high SRF exhibited a pattern of greater hip EAC on more functional tasks, such as Hop50, Hop100 and SLS. When compared to control participants with high SRF on the IKDC, these participants used greater hip EAC during Hop50 ( $p = 0.012$ ). ACLR participants with high SRF used 13.48 and 18.27 units more of hip EAC during the Hop100 task compared to controls participants with high SRF on the KOOS Stiffness scale ( $p =$

0.005) and IKDC scale ( $p = 0.0003$ ), respectively. This sub-group displayed similar findings during SLS compared to KOOS Stiffness ( $p = 0.033$ ) and IKDC ( $p = 0.046$ ). Alternatively, when compared to ACLR participants with high SRF, control participants with a high SRF on the IKDC used 17.73 more units of hip EAC during Gait-1 ( $p = 0.0005$ ). This finding was also reported when comparing these participants during Gait-1 using the KOOS Stiffness scale ( $p = 0.005$ ).

## **Discussion**

The purpose of this study was to determine if self-reported function (SRF), as categorized by low or high function, impacted performance, as measured by EA and EAC, on functional tasks among ACLR participants compared to control participants. Our primary findings that low SRF ACLR participants displayed alterations in EA and EAC during functional tasks compared high SRF ACLR participants was in line with the initial hypothesis. Our secondary findings, which supported our additional hypothesis, revealed significant interaction effects during the same functional tasks, with ACLR participants demonstrating joint loading alterations compared to control participants with similar SRF function. The combination of these findings suggests that ACLR participants alter joint loading during functional movements despite level of SRF; however, individuals who report lower levels of SRF demonstrate even greater energy absorption and distribution alterations during these tasks, which can have significant implications on overall joint health and function. To the best of our knowledge the impact of SRF on lower extremity joint loading, by measurement of EA and EAC, has not been examined before which makes our study very unique. While our findings may be novel to these specific measurements of joint loading, there is robust literature on the impacts of ACLR and self-reported function, especially

in our target population several years removed from reconstruction. But our study takes ACLR participants at an average of  $5.2 \pm 2.5$  years post-surgery and uses a combination of physical measures and subjective function scales. Several comparison studies<sup>17,31,32</sup> identify decreasing SRF over time after ACLR and these are often explained by biomechanical factors. We have now linked the two and provide evidence that the two exist together and ACLR patients may not be aware of their reduced function as they are likely not focusing on these measures in their daily life.

Patient reported outcomes (PROs) are used regularly with ACLR individuals and have been a successful tool at tracking patients' perspectives on knee function beyond rehabilitation and return to sport (RTS). Due to a lack of consensus on threshold scores for PROs that would indicate a successful outcome following ACLR, the Delaware-Oslo ACL Cohort Research Group sought to establish this criteria at 1 and 2 years post ACLR.<sup>29</sup> A median score of a 90% on the IKDC and an 85% on the KOOS scales were identified as the threshold in which to determine a successful outcome following ACL injury and reconstruction.<sup>29</sup> Despite the lack of an established threshold value beyond the 2-year time point, the data from this research group can still be utilized to compare median scores at later time points. Control participants in the present study exceeded the threshold values for the IKDC and all KOOS subscales, except for KOOS Symptoms, which was reported as a median score of 81.25. On the contrary, ACLR participants had median scores below the established thresholds for the IKDC (82.64), KOOS Symptoms (66.78), Sport/Rec (82) and QOL scales (74.88) despite being an average of 5 years post-surgery. The IKDC scores among the current ACLR participants were lower than the threshold score, which was not much greater than a group of ACLR participants 13.5 years postoperatively that recorded a mean subjective score of 78.4.<sup>33</sup> These findings, combined with our results, indicate a

deterioration in SRF over time, as measured by the IKDC, which may warrant an re-examination of a threshold for participants at these later time points.

Of the PRO scales used in the present study, KOOS ADL was the only scale not analyzed due to the lack of participants in either group below our cutoff score indicating low SRF. Several studies have also recorded the highest values of SRF in the ADL scale of all KOOS subscales,<sup>7,9</sup> even in participants that were reported as having OA.<sup>9</sup> Similarly Chen et al,<sup>21</sup> reported the highest KOOS scores in the ADL scale compared to all other subscales across both symptomatic and asymptomatic ACLR participants. Although the average age of their participants (mean 20.7 years) was slightly lower than our sample ACLR population ( $21.9 \pm 2.1$  years), both groups are likely not at an age in which ADLs would be significantly impacted by knee function.

When examining ACLR individuals with or without OA, PRO scales have been useful to determine if SRF can identify the possible presence of OA. Participants at an average point of 7 years from reconstructive surgery were more likely to have lower satisfaction and SRF with their operated knee if they also presented with radiographic knee OA compared to participants who did not have OA.<sup>34</sup> These findings are also true when utilizing the KOOS scale in individuals with OA between 10-15 years following ACLR.<sup>9,10</sup> Although the presence of OA was not determined in the current study, there are implications that lower impressions of knee function as measured by PROs could potentially indicate the possibility for the development or manifestation of OA, especially in a sample of individuals several years following reconstruction.

Previous literature has utilized physical measurement variables such as quadriceps strength,<sup>19,20,25</sup> knee extension range of motion<sup>19</sup> and hip strength<sup>20</sup> to explain EA and EAC within ACLR participants at various time points from preoperative to one year following RTS.

In the present study, the only significant interaction related to knee EA during gait tasks was at Gait-1 and Stance between ACLR and control participants with low SRF on the IKDC scale. In both instances, control participants had exhibited greater knee EA than ACLR participants, which indicates an unloading strategy by ACLR participants with low SRF during and just after initial contact, as well as across the entire stance phase. A previous study<sup>17</sup> analyzing gait biomechanics at 6 months post ACLR surgery measured vertical ground reaction force (vGRF) and found that ACLR participants with lower vGRF or less loading at initial contact had worse subjective outcomes on the KOOS Pain, ADL, Sport/Rec, and QOL scales during a 12-month follow-up exam. Another study<sup>31</sup> using kinetic analysis during gait displayed increased knee flexion moment, adduction moment, and internal rotation moment in ACLR individuals 2 years post-operatively, which was also significantly associated with negative changes in KOOS outcomes at an 8-year follow-up. Titchenal et al<sup>32</sup> identified an increase in lateral shift in the center of rotation and greater translation occurring at the medial compartment of the tibiofemoral joint during gait when utilizing a kinematic analysis of knee center of rotation in ACLR participants 2 years removed from reconstruction. Several participants in the same study<sup>32</sup> also reported clinically important worse scores on KOOS Symptoms, Pain and QOL when assessed 8 years following reconstruction. These combined findings across studies show that biomechanical differences during gait, even at earlier time points, may predict a decrease in patient-reported outcomes over time. The present study shows that ACLR participants at later time points continue to have biomechanical alterations at the knee during gait that also coincide with lower perception of knee function.

In the present study, we were also able to identify concurrent hip and ankle joint loading differences and subjective outcomes using the KOOS scale during gait tasks. Control participants



with high SRF on both the KOOS Stiffness scale and IKDC utilized greater hip EAC during Gait-1 than ACLR participants categorized with similar SRF. Alternatively, ACLR participants with low SRF using the KOOS Stiffness scale demonstrated greater ankle EA during Stance than their control counterparts. These strategies could potentially supplement their lack of knee loading during gait. Throughout a period of 2-years following ACLR, participants in a previous study<sup>35</sup> who went on to develop OA also demonstrated lower knee adduction moment impulses, peak knee flexion moments and contact forces through their involved limb during gait analyses. Although the comparative studies did not examine joint function beyond the knee, our findings demonstrate the impact of SRF on gait tasks, with ACLR participants utilizing a more distal-to-proximal approach to joint loading, especially when they have lower SRF. These altered strategies compared to control participants could be an indication of an attempt to alleviate feelings of stiffness in the knee, which may or may not be accompanied by OA.

Hop tasks in the current study presented with the most recurrent interaction effects. Although participants in the study were moderately active as measured by the Tegner Activity Scale, the single-legged hop, which was the most dynamic activity tested provided several meaningful findings across all parameters of joint loading. In the present study, ACLR participants with high SRF on the KOOS Stiffness and QOL scales utilized greater knee EAC at all hop time points during the single leg hop than ACLR participants with low SRF. This finding suggests that ACLR individuals with a greater perception of good knee function have a greater ability to use a landing strategy with more eccentric contribution from the knee extensors. Alternatively, ACLR participants with lower ratings of function tend to avoid eccentric loading on their surgical knee during a hop task. The concurrent measurement of SRF along with physical performance tasks provides an explanation for knee loading strategies among subjects in

the current study at our single time point. These combined measures provide a better picture of the meaning and relationship between subjective and objective function among this population.

Low perception of function seems to impact changes in landing strategy as our ACLR participants with lower scores on the KOOS Symptoms and Stiffness scales used less knee EAC than control participants during Hop100 and Hop150 tasks and our control participants with high or low SRF on the KOOS QOL used greater knee EAC during Hop100 and Hop150 when compared to ACLR participants at the same level of SRF. These findings are supported by two studies<sup>21 36</sup> as they also report neuromuscular limitations and asymmetries during single leg landing within hop tasks. Chen et al<sup>21</sup> measured ACLR patients 8 months from surgery with symptoms and lower KOOS SRF scores and determined they had biomechanical differences at the knee during a single-leg hop. In particular, subjects with worse KOOS Pain scores also had larger knee extension moments at initial contact of the landing task indicating poor neuromuscular control. Ithurnburn et al<sup>36</sup> reported that ACLR patients with a mean score 13 points lower on the KOOS QOL at a 2-year post time point had experienced landing asymmetries during a single leg task at the time of RTS.

Changes in knee function during physical tasks have often been accompanied by compensations occurring proximally at the hip joint.<sup>20,21,25,37,38</sup> The findings in this study continue to support this notion among ACLR individuals. During a SLS task, ACLR participants used greater hip EA and hip EAC than control participants in both high and low SRF subgroups, as measured by the IKDC, KOOS Stiffness, and KOOS Symptoms scales. Similar findings were also observed among the same PRO scales for all hop tasks. Although testing by Chen et al<sup>21</sup> was done less than one year from ACLR surgery, ACLR participants used greater hip flexion angles during a single leg hop task and these kinematic findings correlated with worse scores on the

KOOS Pain and Sport/Rec scales. Kinetic changes were also impacted as ACLR subjects had larger hip flexion moments that correlated with worse KOOS Pain, Sport and Symptoms outcomes. Subjects are more likely to increase loading at the hip when they have worse subjective outcomes and an altered strategy at the knee. Therefore, findings from both studies indicate that the presence of ACLR may influence the use of accessory hip contribution during different movements and these are also accompanied a self-reported lower function assessment.

Unfortunately, for an ACLR, compensations are not solely taken up by the hip. We documented differences in ankle EA between all subgroups across hop tasks and SLS when we compared subjective outcomes on the IKDC and KOOS Stiffness scales. ACLR participants with lower SRF consistently used greater ankle EA during Hop50, Hop100 and SLS tasks than ACLR participants with high SRF and control participants with comparable SRF. Findings among hop tasks were split between ACLR and control participants with high SRF on both scales. Control participants utilized greater ankle EA at the initial time point of Hop50, while ACLR participants had greater ankle EA later at the Hop100 time point. As far as we are aware, ankle biomechanics in the sagittal plane have not previously been assessed as it relates to an interaction with self-reported function beyond the work of this study. In contrast to our sagittal plane findings, previous work by Boo et al<sup>20</sup> observed greater ankle EAC during a lateral vertical jump task in both ACLR and control participants and they noted a significantly greater contribution in control participants. The overall increase in ankle contribution is likely due to the nature of the task; however, their differences between group could potentially be due to a decrease in ACLR participants' self-perception of limb function although SRF was not measured.<sup>20</sup>

Self-reported function has also been studied as it relates to performance-based outcomes on functional tasks at several time points following ACLR. When comparing performance on

multiple hop tests, 53% of ACLR participants with normal IKDC scores at 6 months post reconstruction were able to pass all tests with a 90% or greater limb symmetry score.<sup>30</sup> Although the number of participants to accomplish this increased to 78% at 12 months post ACLR, there was still a significant inability for participants to reach those ideal limb symmetry measures.<sup>30</sup> During a similar examination of multiple hop tasks, Reinke et al<sup>39</sup> found significant correlations between single hop and triple hop ratios with the IKDC, KOOS Sport/Rec and KOOS QOL scales in ACLR individuals 2 years post reconstruction. Elite handball players 1-6 years out from ACLR did not demonstrate any differences during a dynamic balance task, but did report lower self-reported function on all KOOS subscales other than ADL.<sup>7</sup> In individuals that are able to physically perform tasks without any functional limitations, the inclusion of PROs are important to understand how a lower perception of knee function may impact current and future function. While our study did not specifically look at those performance-based measures related to SRF outcomes, these findings may complement our results by showing that both movement strategy and overall success of a movement is altered in the ACLR population and likely influenced by perception of surgical limb function.

While the current study provides new and relevant evidence to demonstrate an interaction between SRF and joint loading via EA and EAC even an average of  $5.2 \pm 2.5$  years post surgery, there are limitations that can influence future research. A sample size closer in time from ACLR would be more advantageous when comparing SRF between participants. Additionally, along with the notion of previous studies, longitudinal data should be gathered to identify changes in SRF over time related to EA and EAC measures. The IKDC and KOOS scales were used to determine SRF and identify sub-groups of SRF, which created disproportionate subgroups for function in both ACLR and control participants. Additionally, the KOOS scale is a subjective

measurement relative to the development or progression of knee OA,<sup>40</sup> neither of which were measured in this study. Further research should include diagnostic measures of OA, in conjunction with subjective outcomes, to determine the presence and influence of OA on EA and EAC. Additional scales, such as the Tampa Scale (TSK-11), may also be warranted to determine the presence of additional subjective information, especially when measuring subjects' abilities to perform more dynamic tasks as it allows patients to express their views to their condition via a Likert scale of agreement on a variety of statements related to pain and fear.

### **Conclusion**

The present study identifies the impact of low or high self-reported function, using the IKDC and KOOS scales, on energy absorption joint loading measures during several physical performance tasks in both ACLR and control subjects. Overall, across tasks, ACLR subjects with lower SRF used joint loading strategies that limited knee loading and emphasized hip and ankle compensations, which supports the notion that a lower perception of function will lead to lower performance by way of energy absorption. When comparing to control subjects, ACLR subjects with comparable SRF in either low or high sub-groups consistently demonstrated altered loading strategies with more ankle and/or hip contribution in an effort to underload the knee. ACLR subjects several years removed from surgery exhibited differences in joint loading, which are even more pronounced when accompanied by lower self-perception of surgical knee function. These findings, while not directly associated with the presence of knee OA in this study, have implications that deficits in functional movement and self-reported function at this stage following ACLR may negatively impact present and future knee joint health. Future work should

identify SRF in subjects with and without knee OA and the interactions across other dynamic tasks.

## Figure Legends

**Figure 1:** Graphical representation of between group mean PRO scores (y-axis) of self-reported function across multiple PRO scales (x-axis). *PRO* patient-rated outcome, *KOOS* Knee injury and Osteoarthritis Outcome Score, *ADL* activities of daily living, *Rec* recreation, *QOL* quality of life, *IKDC* International Knee Documentation Committee.

**Figure 2:** Graphical representation of the interaction between low and high SRF ACLR (ACL) and control (CON) sub-groups' KOOS Stiffness scores (x-axis) on Knee and Hip EAC (y-axis) during Hop50, Hop100, and Hop150 tasks. *SRF* self-reported function, *KOOS* Knee injury and Osteoarthritis Outcome Score.

**Table 1:** Participant Demographics

	<b>ACLR</b>		<b>Control</b>	
	<b>Male (n=9)</b>	<b>Female (n=11)</b>	<b>Male (n=9)</b>	<b>Female (n=11)</b>
Age	23.3 ± 1.7	20.6 ± 1.5	22.9 ± 1.9	21.6 ± 1.7
Height (m)	1.8 ± 0.1	1.7 ± 0.1	1.8 ± 0.1	1.6 ± 0.1
Weight (kg)	84.8 ± 5.9	69.2 ± 13.9	80.3 ± 10.9	65.0 ± 6.9
Tegner	6 ± 1.8	6.1 ± 1.8	5.3 ± 0.9	6 ± 2.1



**Table 2:** Changes in EA Outcomes (post-hoc comparison of group\*task\*SRF scale)

Ankle EA			
High ACL vs. Low ACL		ΔEst.	P
<b>IKDC</b>	Hop50	10.25	<.0001
<b>KOOS Stiffness</b>	Hop50	1.33	<.0001
	Hop100	0.73	<.0001
	SLS	0.45	0.0049
High ACL vs. High Control			
<b>IKDC</b>	Hop50	4.32	0.0032
	Hop100	-4.03	0.0073
<b>KOOS Stiffness</b>	Hop50	0.31	0.0119
	Hop100	-0.27	0.0332
	SLS	0.27	0.0364
	Stance	-0.30	0.0146
Low ACL vs. Low Control			
<b>IKDC</b>	Hop50	-6.63	0.0188
	Hop100	-6.39	0.0255
<b>KOOS Stiffness</b>	Hop50	-0.99	0.0095
	Hop100	-1.27	0.0004
	SLS	-1.04	0.0061

Knee EA			
High ACL vs. Low ACL		ΔEst.	P
<b>IKDC</b>	SLS	-17.35	0.0188
<b>KOOS Sport &amp; Rec</b>	SLS	-1.92	0.0132
High ACL vs. High Control			
<b>IKDC</b>	Hop100	17.75	0.0040
<b>KOOS Stiffness</b>	Hop100	1.77	0.0022
	SLS	1.45	0.0192
<b>KOOS Sport &amp; Rec</b>	Hop100	1.59	0.0089
Low ACL vs. Low Control			
<b>IKDC</b>	Gait-1	47.14	<.0001
	Hop100	36.25	0.0006
	Stance	45.10	<.0001
<b>KOOS Stiffness</b>	Hop100	4.76	0.0137
<b>KOOS Sport &amp; Rec</b>	Hop100	4.97	0.0068

Hip EA			
High ACL vs. Low ACL		ΔEst.	P
<b>KOOS Stiffness</b>	Hop100	2.91	<.0001
High ACL vs. High Control			
<b>KOOS Symptoms</b>	SLS	-2.68	0.0016
<b>KOOS Stiffness</b>	Hop100	-0.68	0.0168
	SLS	-1.09	<.0001
Low ACL vs. Low Control			
<b>KOOS Symptoms</b>	SLS	-1.33	<.0001
	Hop100	-1.57	<.0001
<b>KOOS Stiffness</b>	SLS	-2.29	0.0093
	Hop100	-4.12	<.0001
	Hop50	-2.05	0.0265

ΔEst.: 1000\*Estimate of the difference between two groups  
P: the adjusted p value from the Tukey multiple comparison test

**Table 3:** Changes in EAC Outcomes (post-hoc comparison of group\*task\*SRF scale)

<b>Knee EAC</b>				<b>Hip EAC</b>			
<b>High ACL vs. Low ACL</b>		<b>ΔEst.</b>	<b>P</b>	<b>High ACL vs. Low ACL</b>		<b>ΔEst.</b>	<b>P</b>
<b>KOOS Stiffness</b>	Hop50	19.78	0.0016	<b>IKDC</b>	Hop50	14.62	0.0219
	Hop100	29.01	<.0001	<b>KOOS Stiffness</b>	Hop100	-22.67	0.0001
	Hop150	35.53	<.0001		Hop150	-27.78	<.0001
<b>KOOS QOL</b>	Hop150	21.46	0.0014	<b>High ACL vs. High Control</b>			
<b>High ACL vs. High Control</b>				<b>IKDC</b>	Gait-1	-17.73	0.0005
<b>KOOS Stiffness</b>	Hop100	-17.49	0.0001		Hop50	13.73	0.0117
<b>KOOS QOL</b>	Hop100	-19.89	0.0014		Hop100	18.27	0.0003
<b>Low ACL vs. Low Control</b>					SLS	11.65	0.0456
<b>KOOS Stiffness</b>	Hop100	-56.51	<.0001	<b>KOOS Stiffness</b>	Gait-1	-13.41	0.0047
	Hop150	-56.19	<.0001		Hop100	13.48	0.0045
<b>KOOS QOL</b>	Hop100	-38.12	0.0250		SLS	10.95	0.0325
	Hop150	-37.49	0.0285	<b>Low ACL vs. Low Control</b>			
<b>KOOS Symptoms</b>	Hop100	-25.91	<.0001	<b>IKDC</b>	Hop100	24.89	0.0115
					Hop150	31.17	0.0007
				<b>KOOS Stiffness</b>	Hop100	44.02	0.0033
					Hop150	43.71	0.0036

ΔEst.: Estimate of the difference between two groups  
P: the adjusted p value from the Tukey multiple comparison test

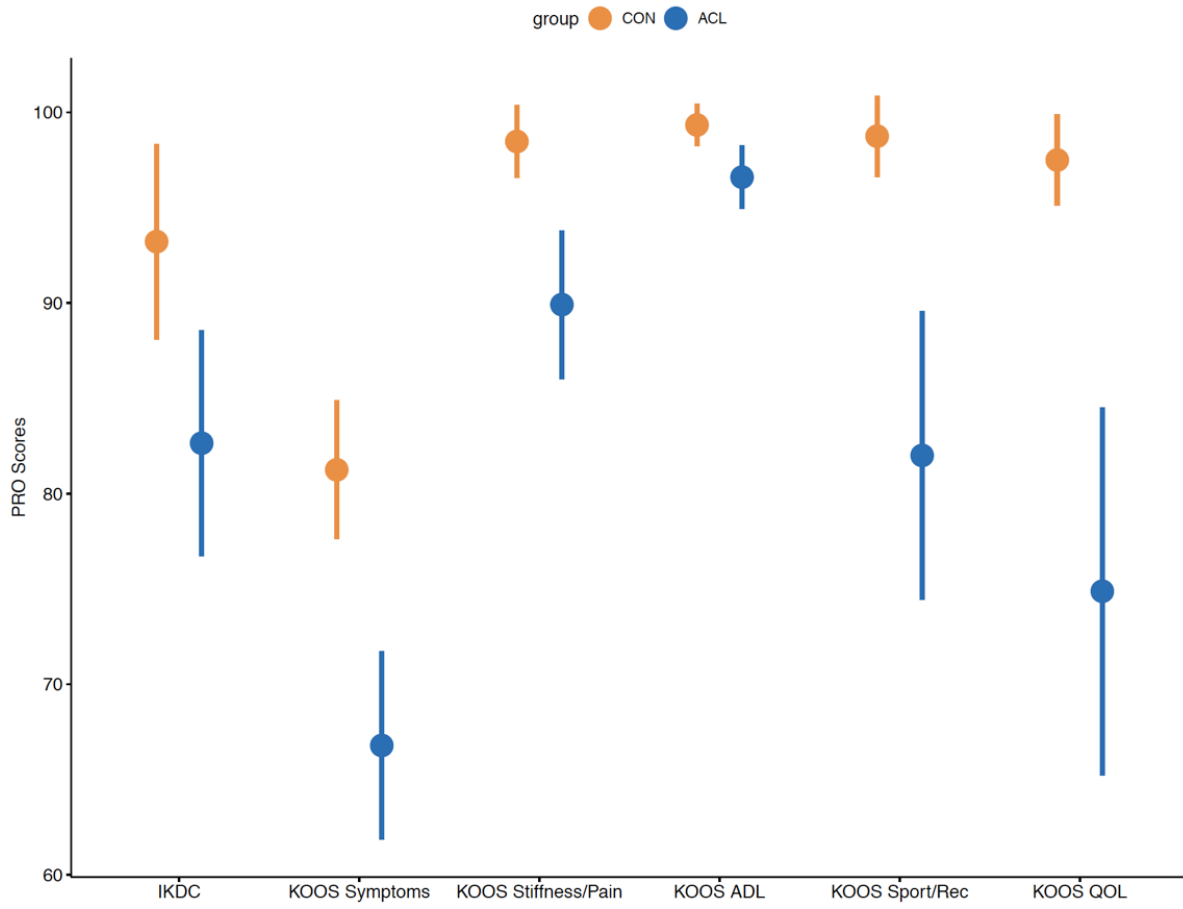
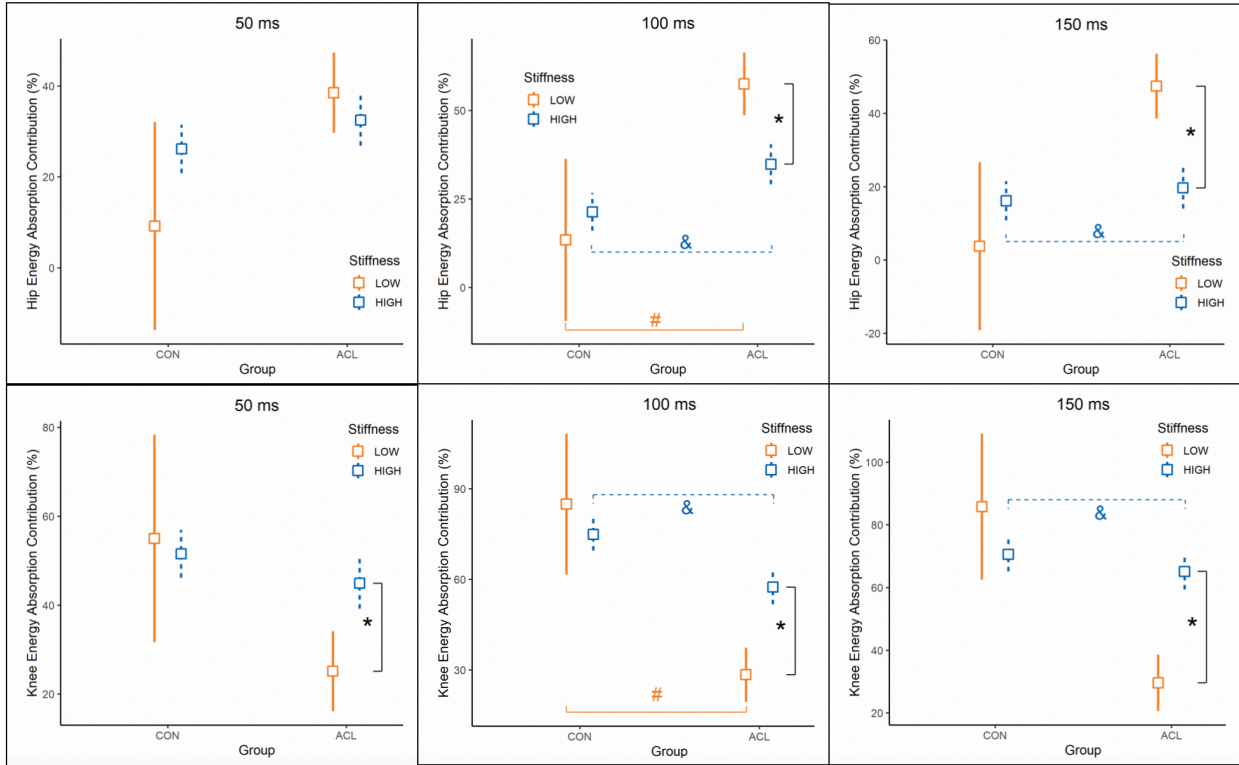


Figure 1



Statistically significant difference ( $p < 0.05$ ) between High ACL vs. Low ACL groups\*, High ACL vs. High Control&, and Low ACL vs. Low Control#

Figure 2

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## **Chapter 5**

### **Future Directions**

Osteoarthritis (OA) of the knee is a progressively debilitating condition, not only in the individuals it affects, but also through community and economic burdens. Risk factors related to the development of knee OA and subsequent worse outcomes and treatment options span from individual factors to community and health insurance elements. Many risk factors have been linked to the prevalence of both radiographic and symptomatic knee OA, which have clear trends in the literature suggesting that the development of knee osteoarthritis is much more likely to occur. Several of those variables at the individual level have been confirmed in multiple studies, such as a history of traumatic knee injury,<sup>1,2</sup> having a higher BMI,<sup>3,4</sup> and old age.<sup>3</sup> Sex differences exist as an additional risk factor for knee OA, with females more at risk to develop knee OA and OA in general than their male counterparts.<sup>3-5</sup> Along with having a greater likelihood of developing knee OA, women are more likely to have severe cases of OA compared to males, most likely due to the role of hormones in the development and outcomes related to OA.<sup>6</sup> There is no conclusive evidence that exists to explain the reason for this trend towards women experiencing knee OA more often and on a more severe level; however, we can use this data to be mindful of an additional risk factor when treating female patients.

Specifically, as it relates to individuals with a history of traumatic knee injury, such as anterior cruciate ligament (ACL) injury, those individuals are over 3 times more likely to develop knee OA than those without previous knee injuries.<sup>7</sup> Not only does risk of developing post-traumatic osteoarthritis (PTOA) increase after ACL injury and ACL reconstruction (ACLR), but there is also the likelihood that these joint changes associated with PTOA are present several years earlier than in individuals who experience non-traumatic OA onset.<sup>8</sup>

Knee OA, as a health problem, has affected individuals for decades with roughly more than 10% of U.S. adults recorded with this condition in 2005.<sup>8</sup> One of the hallmark consequences

of knee OA is the resulting loss of function and disability that develops over time. From 1990 to 2010, the number of years lived with knee or hip disability increased by 64% in the United States.<sup>9</sup> Those individuals affected with knee OA have direct and indirect costs associated with treatment, surgical procedures, and hospitalizations that range from roughly \$500 to \$10,000 per patient, per year.<sup>10</sup> Examining the costs individually using the Osteoarthritis Policy Model, Losina et al<sup>11</sup> found that per-person lifetime costs of knee OA-related care in the United States account for 10% of lifetime direct medical costs, which estimate to roughly \$12,000.

Despite the costs associated with treatment and management of knee OA, some of the biggest challenges individuals with knee OA face are the physical limitations created by this disabling disease. In a group of adults, age 54 years and older with a diagnosis of knee OA, activity limitations and self-reported knee instability were significantly present in addition to knee pain and a lack of muscular strength.<sup>12</sup> These numbers are consistent with reports that roughly a quarter of people with knee OA have difficulty walking and doing activities of daily living, especially as age increases.<sup>13</sup>

With a significant portion of the roughly 250,000 ACL injuries per year<sup>14</sup> occurring in younger participants in cutting and pivoting sports,<sup>15,16</sup> the incidence for OA in this population is likely to occur at a much earlier age than those without a history of joint injury. In this population, especially younger active individuals, the primary focus following ACLR is to return to a pre-injury level of sport or activity. At this point in the timeline following ACLR, direct management of the ACL injured knee through formal rehabilitation has often ended, although joint deficits may continue to persist. A successful return to sport (RTS) status cannot be the trajectory in which we cease care for the ACLR patient. Palmieri-Smith et al<sup>17</sup> noted for many patients an ACL injury is the starting point for a cascade of progressive pathologic joint changes

(e.g., PTOA) that can lead to loss of function and chronic pain thereby causing limitations that affect both activities of daily living and sport or other physical performance.

The Athletic Trainers' Osteoarthritis Consortium (ATOAC) released a consensus statement<sup>17</sup> in 2017, identifying the role of the athletic training community in primary, secondary, and tertiary prevention of PTOA in physically active populations. This statement aligns with the intentions of the current study to have a role in secondary and tertiary prevention of this population. Secondary prevention is related to the recognition or identification an injury or disease early on, so that prompt and appropriate management including restoration of function can be implemented to prevent the secondary effects of the injury or disease.<sup>17</sup> Tertiary prevention involves care focused on reducing or minimizing the long-term consequences of an injury or disease by eliminating or delaying the onset of complications, morbidity, and disability due to the injury or disease.<sup>17</sup>

The main focus of the ATOAC statement,<sup>17</sup> which adopted recommendations from the Chronic Osteoarthritis Management Initiative (COAMI) of the US Bone and Joint Initiative,<sup>18</sup> was to develop a chronic management model in order to detect and modify risk factors for OA at early stages prior to the develop or worsening of knee-related symptoms. The first recommendation by the COAMI<sup>18</sup> was to provide individuals at risk for developing PTOA with strategies to mitigate the onset or worsening of the disease through self-management education and exercise programs. Additionally, annual assessments of ACLR individuals was recommended with the intention of monitoring joint pain and symptoms, as well as identifying decreases in function that may indicate the onset of PTOA.

The work from these two studies falls in line with the suggestions and initiatives of both groups' recommendations, specifically to include assessments of joint loading and self-reported

function annually following RTS from ACLR. Previous work examining EA and EAC following ACLR determined joint loading differences at the surgical knee at 3-month<sup>19-21</sup> and 1-year time points.<sup>22</sup> Our study was the first to examine EA and EAC variables at further time points (5.2±2.5 years) following surgery. This gap in data between 1 and an average of 5 years following ACLR would be better suited for annual assessments of knee function in this ACLR population. In a strong study by Garrison et al<sup>20</sup> a longitudinal examination of knee EAC during the continuum of care from preoperative time points to 12-weeks following ACLR and eventually to the point of RTS was evaluated. But as indicated by Palmieri-Smith,<sup>17</sup> direct patient care need not end at the point of RTS and we should create opportunities for regular re-assessments of critical variables, such as EA, EAC, and self-reported function, after RTS in an effort to understand joint health.

By assessing EA and EAC during functional tasks, we have the potential to identify patterns of normal or deficient joint loading. When examining ACLR participants within the continuum of care, Garrison et al<sup>20</sup> was able to identify that participants demonstrated increases in knee EAC during a double-limb squat task from 12-weeks to time of RTS, which was still lower than values at pre-operative measurement. As part of annual or regular assessments of these measures of joint loading, future work has the possibility of identifying if knee EAC continues to increase over time, whether or not there is a point of plateau, and at which point there is a steady decline in the ability to load the surgical knee. Our study also serves to support the inclusion of hip and ankle EA and EAC variables to understand the total picture of joint loading across the lower extremity. Previous studies<sup>21,22</sup> have identified joint loading at these distal and proximal joints may identify compensations by ACLR individuals during various

functional tasks. Further assessment of each lower extremity joint across multiple time points is warranted within functional tasks that have been previously studied.

The findings in Study 1 support further examination of various functional tasks to identify how joint loading strategies may change across tasks. Our study was the first to identify interactions in EA and EAC between different functional tasks and different time points within the functional tasks. This approach may be better suited to understand ACLR individuals because it provided a multi-dimensional assessment in their physical activity including daily tasks like gait and single leg squatting, but also included more hopping. When examining knee EAC, ACLR participants exhibited the greatest contribution during SLS, whereas control subjects had the greatest contribution during Hop100. Both groups demonstrated the lowest values of knee EAC during gait tasks, which suggests that lower impact movements may use less of a knee contribution to dissipate force. However, the understanding of loading across tasks of various levels of difficulty are imperative to get a full picture of participants who may engage in a range of activities. ACLR participants in the current study were an average  $21.9 \pm 2.1$  years of age, with an average score of a 6 on the Tegner Activity Scale, which implies that they may still be participating in strenuous or competitive activity that could place greater stressors on their surgical limb.

One unique finding of Study 1 was the identification of the landing strategy between ACLR and control subjects across single leg hop time points of 50ms, 100ms and 150ms. Control subjects were able to utilize greater eccentric loading at the knee within a shorter amount of time than ACLR subjects, which may suggest an increased risk of injury upon initial landing in ACLR participants. Conversely, ACLR participants use less knee EAC initially during the landing portion of this task and take longer to reach their maximum EAC, which implies they



may be implementing an altered neuromuscular strategy along with delayed eccentric knee extensor involvement. Analysis of specific time points within a task are critical to understand that if altered loading is present at a certain point within a task, an ACLR individual may be at increased risk for re-injury or negative joint trauma each time this movement occurs. With the implementation of an annual assessment, the research initiatives in Study 1 can set out to observe movement strategies and joint loading patterns in ACLR individuals over time. In order to fulfill the suggestions for secondary prevention of PTOA, these findings could help researchers and clinicians identify an individual with decreasing function that would benefit from a referral to determine the possible presence of knee OA.

In addition to determining declining physical function, via EA and EAC joint loading measures, it is also important to include measures of self-reported function (SRF), as utilized in Study 2. Previous research<sup>23</sup> has identified a threshold score on the International Knee Documentation Committee (IKDC) Subjective Knee Evaluation Form and the Knee Injury and Osteoarthritis Score (KOOS) forms at 1 and 2 years following ACLR. Not only should these thresholds be monitored for patients during assessments at these time points, but our study identified the need for potentially new thresholds beyond the 2-year mark, which would likely be below the 90 and 85 score threshold on the IKDC and KOOS, respectively.<sup>23</sup> ACLR participants in the current study were below the established threshold for the IKDC scale and 3 out of 5 KOOS scales (Symptoms, Sport & Recreation & Quality of Life (QOL)). If these subjects are analyzed annually following RTS, longitudinal data surrounding SRF could inform decisions based on the treatment of care for ACLR individuals.

A meaningful takeaway from Study 2 is the need to obtain both subjective and objective data to holistically understand the ACLR individuals we encounter and to make the soundest

decisions on the appropriate care beyond RTS time points. For example, in the gait task, control participants with low IKDC scores exhibited greater knee EA than ACLR participants with low SRF, which indicates an unloading strategy by low SRF ACLR participants during and just after initial contact as well as across the entire stance phase. When observing a more demanding task, such as the single leg hop, it was determined that ACLR individuals with a higher self-reported knee function have a greater ability to utilize a landing strategy with more eccentric contribution from the knee extensors. Alternatively, ACLR participants with lower subjective function will avoid eccentrically loading their surgical knee during a hop task. These findings, along with other outcomes from Study 2, identify the influence that SRF has on physical function via joint loading. Determining joint loading deficits or lower SRF in regular assessments can help guide treatment and referral of ACLR patients as these alterations may indicate an increased likelihood of developing PTOA.

The findings of the current studies, along with evidence-based guidance<sup>17,18</sup> for preventing and managing PTOA, identify the need for continued, longitudinal, annual assessments of ACLR individuals to detect and modify risk factors related to the development and progression of OA. The focus of this work among athletic training researchers is essential since our profession is well-equipped to understand the distinctive challenges of physically active individuals.

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