Lower Extremity Joint Coupling in Children after Pediatric Anterior Cruciate Ligament Reconstruction

Dissertation

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Abstract

Despite the advent of surgical techniques to respect open growth plates, outcomes following physeal-sparing anterior cruciate ligament reconstruction (pACLR) in children are suboptimal, with high 2nd injury and low return to sport rates. Researchers have applied the Dynamic Systems Theory (DST) to the skeletally mature population following traditional anterior cruciate ligament reconstruction (ACLR) in aims of better understanding lower extremity coordination and movement variability to help elucidate the suboptimal outcomes and inform rehabilitation decision-making in this patient population. This approach has yet to be applied to the pediatric population following pACLR. Thus, the purpose of this work was to examine lower extremity coordination and movement variability in children following pACLR, and to compare that to adolescents following traditional ACLR as well as adolescent healthy controls. We hypothesized that during a single-leg landing task, children following pACLR would demonstrate 1) increased movement variability on their surgical limb as compared to the surgical limb of adolescents following ACLR and to the preferred limb of adolescent healthy controls, and 2) increased movement variability on their non-surgical limb as compared to the non-surgical limb of adolescents following ACLR and to the non-preferred limb of adolescent healthy controls. Participants included 11 skeletally immature children following primary, unilateral pACLR using a hamstring autograft (11.54±1.69 years, 9 male/2 female), 20 adolescents following primary, unilateral, transphyseal ACLR (16.99±0.60 years, 6 male/14 female), and 20 adolescent healthy controls (16.17±0.57 years, 2 males/18 females). Lower extremity kinematics from three trials on each limb of a single-leg landing task from a 31 cm box onto a force plate were captured and the landing phase was analyzed using a 3D motion analysis system. A vector coding technique was utilized to calculate lower extremity joint coupling angles for each trial. Movement variability was quantified using the root mean square of the circular standard deviation of coupling angles across each participant's 3 trials. Lower extremity movement variability for the involved and uninvolved limbs, respectively, was compared between groups with Kruskal-Wallis test, with significance set *a priori* at $p \leq 0.05$. Mann Whitney U post hoc tests were conducted as appropriate, with significance set *a priori* at $p \leq 0.0167$ per the Bonferroni correction method. The pediatric ACLR group demonstrated increased movement variability on the involved limb as compared to the preferred limb of adolescent healthy controls for hip rotation/knee rotation (pediatric ACLR=49.03, 95% CI=17.051-80.98; healthy controls=18.17, 12.75-23.60; $p=0.007$) and for knee abduction/ankle dorsiflexion (pediatric ACLR=8.32, 5.54-11.09; healthy controls=4.45, 3.47-5.42; $p=0.005$). The adolescent ACLR group demonstrated increased variability on the involved (adolescent ACLR=10.99, 7.93-14.05; healthy controls=4.45, 3.47-5.42; $p<0.001$) and uninvolved limbs (adolescent ACLR=6.72, 3.63-9.80; healthy controls=4.99, 2.87-7.10; $p<0.001$) for knee abduction/ankle dorsiflexion as compared to healthy controls. Increased movement variability may be indicative of neuromuscular compromise within the movement system. Further research is warranted to explore how this may relate to increased injury risk. Increased movement variability may impact a child’s ability to develop the motor competence and physical literacy needed for lifelong health and well-being. Further research with a larger sample size and more longitudinal approach is needed to further elucidate these findings.

Dedication

With the deepest gratitude I dedicate this work to my family, for their unending and unwavering support throughout the many twists and turns that led us here.

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Chapter 1. Introduction

Youth participation in organized sports in the United States is commonplace, with over 60 million American youth involved with sports activities.[1,2] However, participation in athletic activities increases risk of sports-related musculoskeletal injuries.[1] Cost estimates of emergency department visits due to sports injuries in youth have been estimated at nearly $100 billion annually, with knee injuries as not only the most common but also the most costly due to often-required surgical intervention and/or organized rehabilitation.[1,3] Of sports-related knee injuries in youth, the incidence of anterior cruciate ligament (ACL) tears is significant, with a recent study reporting that ACL tears comprise 31% of total knee injury claims among skeletally immature athletes across a 5-year span. Given the recent awareness and high incidence of pediatric ACL tears and the associated medical costs, understanding outcomes is imperative for effective medical and rehabilitation management in order to optimize post-injury function in this young patient population.

While a surgical ACL reconstruction (ACLR) procedure is the standard of care for adolescents and adults following an ACL injury, this has not always been the standard for the skeletally immature population.[4] Historically, concerns regarding growth disturbances caused by tunneling through open growth plates (physes)—as would be done during a standard ACLR procedure in adults—led to the common practice of delaying surgery in children until growth plates were closed.[4] However, delaying surgery in children with ACL injury has been shown to cause further issues including instability, activity limitations, and potential for further joint damage.[5] These concerns led to the development of pediatric, physeal-sparing ACLR (pACLR) surgical techniques specific to skeletally immature patients to respect open growth plates.[6] Both intra- and extra-articular approaches have been developed for use in the pediatric population which can be broadly categorized as extraphyseal, partial-transphyseal, and all-epiphyseal techniques.[6–11] Since the development of these specific pACLR techniques, the incidence of pACLR surgeries in the United States has risen dramatically, with recent analysis demonstrating that the incidence of ACLR in the pediatric population increased nearly 300% over a recent 10-year period.[12]

Despite the significant increase in pACLR surgeries performed, evidence regarding outcomes after pACLR is lacking, resulting in debate across the field regarding appropriate management of ACL tears in this unique patient population. To date, research in pediatric ACL injury and reconstruction has focused predominantly on diagnosis, surgical indications and technique, and incidence of growth disturbance.[7] There is a dearth of literature addressing appropriate rehabilitative techniques and decisions in the pediatric population following pACLR, with the generalizability of the current research complicated by the existence of multiple pACLR techniques.[7] Extensive research in the skeletally mature population following ACLR has led to published rehabilitation guidelines that are both temporal and criterion-based, with some institutions having protocols specific to graft choice and/or presence of concomitant procedure performed during a transphyseal ACLR in the adolescent and adult population.[13] The use of both time and objective criteria to guide progression respects known tissue healing timelines as well as functional status of the individual patient during rehabilitation and helps to guide the return-to-sport (RTS) decision.[14] Of the criteria recommended for use in assessing readiness to RTS following ACLR, strength testing of the quadriceps and hamstrings as well as a single leg hop test battery are the most commonly utilized, with ≥90% symmetry between limbs being a typical cutoff.[15] The Delaware-Olso ACL Cohort Study[16] demonstrated that delaying RTS to at least 9 months post-operative and utilizing objective, functional criteria can limit the risk of reinjury by almost 85% in individuals after ACLR.

However, a recent study identified that most academic institutions and major medical centers do not even publish rehabilitation guidelines for children following pACLR.[17]The pACLR rehabilitation guidelines that are available oftentimes rely on a temporal progression rather than objective criteria/milestones, with many patients released to return-to-sport at 6 months post-operative regardless of functional status.[1] Furthermore, there is significant disparity in the timing of the temporal progression recommended in currently published protocols—especially in regards to the timing of returning to sports participation, ranging anywhere from 3-11 months.[1,17] These inconsistencies are indicative of the significant disparity in the management of these patients. Although some protocols were found to incorporate the use of objective criteria for progression, these recommended criteria were established for the skeletally mature population and have yet to be validated in the skeletally immature population, which questions the appropriateness of applying these measures to this patient population.[7] Furthermore, very few protocols distinguish between the many pACLR surgical options and many define “pediatric” as age under 18 regardless of whether a physeal-sparing procedure was performed, which is a significant limitation to the generalizability and utility of these protocols.[1,7,17]

In the existing literature, outcomes in both the skeletally mature and immature have been shown to be suboptimal. In the adolescent and adult populations, recent evidence suggests that less than 50% of individuals return to their prior activity level following ACLR,[18] with up to 30% experiencing a second injury within 2 years of returning to sport.[19,20] Similar outcomes have been demonstrated in children, with 1 in 5 skeletally immature individuals reporting a poor outcome (determined by score on a validated self-reported function questionnaire) and 1 in 4 experiencing a 2nd injury following ACLR.[21] Altered biomechanics are well reported in the skeletally mature following ACLR,[22–25] and have been related to second injury.[26] However, the preponderance of biomechanical research in the ACLR population explores a single joint at a single moment in time. Given the dynamic mechanism of ACL injury and the function of the lower extremity as an interconnected system, researchers have begun to explore the potential association of movement variability and the role of neuromuscular adaptations and lower-extremity coordination as a means to better understand known suboptimal outcomes and increased risk of 2nd injury following ACLR.[22] Recent work has identified that years after ACLR individuals demonstrate differences in joint coordination and increased movement variability on the surgical limb when compared to healthy controls.[22,27–29] The application of dynamic movement theory, which contends that there is a preferred range of coordination variability, may help better understand lower extremity joint coordination and functional adaptations following ACLR.[22,27,28] A better understanding of these functional adaptations may help inform rehabilitative strategies and improve outcomes. However, to date this work has been limited to individuals who have undergone a transphyseal ACLR procedure typically performed in the skeletally mature. Movement variability and measures of coordination have yet to be explored in the skeletally immature population following a physeal-sparing ACLR procedure.

The current work aims to examine lower extremity coordination in children following a pediatric ACLR procedure during a dynamic landing task and compare to adolescents following ACLR as well as adolescent healthy controls. Given that skeletally mature female soccer players following ACLR demonstrated increased lower extremity coordination variability during a high-risk maneuver (a side-step cut),[30] we hypothesized that children following ACLR would demonstrate increased movement variability on their surgical limb as compared to healthy controls. In light of the natural process of motor development, we hypothesized that children would demonstrate increased variability as compared to adolescents following ACLR and adolescent healthy controls.

Chapter 2. Review of Related Literature

Operational Definitions

Pediatric ACLR/physeal-sparing ACLR— For the purposes of this work, pediatric ACLR (pCALR) will refer to an ACL reconstruction procedure that has been adapted to respect the open femoral and/or tibial physes. This is also referred to as physeal-sparing ACLR.

Adolescent— The World Health Organization defines adolescence as “the phase of life between childhood and adulthood, from ages 10 to 19.”[31] For the purposes of this work when discussing outcomes following ACLR, adolescents refer to individuals within this age range (10 to 19 years) who underwent a transphyseal ACLR procedure due to the femoral and tibial growth plates being closed or near-closed. For the analysis included in this work, adolescent participants met the WHO definition of middle adolescence (age 15-17 years), consistent with prior work.[25]

Motor control— Motor control refers to how an individual’s body commands goal-oriented movements.[32] Shumway-Cook[33] defined motor control as “the ability to regulate or direct the mechanisms essential to movement.”

Coordination— Coordination is the mechanism by which different body structures work together to attain motor control of movement by controlling the many redundant degrees of freedom available for task achievement. Lower extremity coordination refers to the movement patterns of the muscles and joints of the lower limb to achieve volitional movement in a controlled manner.[34–36]

Movement variability— Movement variability is the many different manners in which coordinative structures control movement in response to task and environment demands.[34,36,37] Movement variability demonstrates the adaptability of a motor system and provides a balance of flexibility to respond to the environment and stability to protect the body from injury.[34,36]

Neuromuscular adaptations— Neuromuscular adaptations refer to changes that occur within the motor pathway in response to a change in activity or injury. These changes can occur within the brain, the spinal cord, the peripheral nervous system, or the muscles themselves.[38]

Anterior Cruciate Ligament

The anterior cruciate ligament (ACL) is one of two cruciate ligaments of the knee providing joint stability to the tibiofemoral joint.[39,40] Originating at the medial aspect of the lateral femoral condyle and of the tibia on the femur. The ACL is comprised of two bundles named for their insertion points on the tibia: the anteromedial bundle and the posterolateral bundle. The anteromedial bundle is taut throughout flexion of the knee and is preferentially tested in these positions—such as the anterior drawer test. Conversely, the posterolateral bundle is taut in full knee extension to approximately 20 degrees of flexion, and is more preferentially tested with the Lachman test. The anteromedial bundle increases in tension from 20 degrees of flexion through 90 degrees of flexion, whereas the posterolateral bundle increases in tension from 20 degrees of flexion through full extension. Through this double-bundle anatomy with each bundle dominant in different positions, the ACL as a whole is able to resist anterior translation of the tibia through a broader range of knee motion, thus providing greater stability to the tibiofemoral joint than what a single bundle may provide. The ACL also provides secondary restraint to varus and valgus loading at the knee and resists hyperextension and rotational forces, particularly in positions near full extension.[39,40]

ACL injuries are one of the most common sports-related injuries, with more than 200,000 injuries occurring annually in the United States.[40] The mechanism of ACL injuries are more often non-contact (70%) rather than contact (30%), typically by means of a deceleration or acceleration event on a fully or near-fully extended knee with a rotational element—such as cutting or pivoting. Adolescent female athletes have been found to be at higher risk of ACL injury as compared to their male counterparts of a similar age and sport participation, with female athletes demonstrating a 1.5 times higher relative risk for ACL injury as compared to male athletes in the adolescent population.[40,41] Conversely, males appear to be at increased risk as compared to females in the younger populations,[12,42] perhaps due to increased sports participation or tendency toward more risky behaviors than their female counterparts. The recent rise in early sport specialization and year-round participation has resulted in a significant increase in ACL injuries in young athletes of both genders,[43,44] with a recent study finding that ACL tears have risen 2.3% in pediatric patients (ages 6-18 years) over the past 20 years.[45]

Anterior Cruciate Ligament Reconstruction in the Pediatric Patient

While the standard of care for treatment of an ACL injury in the adolescent and adult (skeletally mature) populations in the United States is an ACL reconstruction (ACLR) procedure, there is continued controversy regarding appropriate management of ACL injuries in the skeletally immature.[46] Due to the fear of negatively impacting the open physes in these young patients and potential growth disturbance,[6,43,46] children were historically treated conservatively with bracing, activity modification, and physical therapy prior to surgery when physes were near closure.[4,9] However, delayed surgical interventions has been associated with increased occurrence of meniscal and chondral pathology.[6,43,47] This knowledge along with the development of surgical techniques to respect the open physes has resulted in a dramatic increase in ACLR procedures in the skeletally immature in recent years.[12,44] Indeed, the rate of ACLR procedures performed on pediatric patients (<15 years) reportedly rose over 900% in a recent 20 year period.[44,48,49]

A traditional ACLR procedure tunnels through both the femoral and tibial physes,[6] increasing the risk of growth disturbance in the skeletally immature.[8,50] Procedures to reduce the risk of physeal disruption and potential growth arrest in patients with active physes have been developed and include both intra- and extra-articular approaches which can be broadly categorized as extraphyseal, partial-transphyseal, and all-epiphyseal techniques.[6–11] Choice of surgical procedure in this young patient population is predicated upon skeletal age, which can be determined through a number of approaches including direct assessment of the physes on knee MRI, via Sanders bone age from wrist/hand radiographs, or via Tanner staging either from patient self-assessment or surgeon assessment on the day of procedure (Figure 1).[9,10] For adolescents with femoral physes near closure, a traditional transphyseal technique may be utilized as the risk of angular deformity due to physeal disruption is limited.[9] A partial-transphyseal technique can also be implemented, where the distal tibial physis is tunneled through while the proximal femoral physis is spared, as most growth disturbances are due to disruption of the femoral physis rather than the tibial.[6,10] For pre-adolescents with substantial epiphyseal bone stock, an all-epiphyseal procedure may be implemented.[4,6,9,46] In this approach, tunnels are confined to the femoral and tibial epiphyses to avoid the physes while aiming to provide a more anatomic footprint to the reconstruction.[6,50] Multiple variations of this technique have been described, dependent upon tunnel placement, graft type, and fixation technique.[6,50] Most common graft choices include patellar tendon autograft, hamstrings tendon autograft, and allograft, with quadriceps tendon autograft becoming a more prevalent choice in recent years.[4,6,7,10,46,49,51] In an all-epiphyseal approach, femoral and tibial tunnels are typically placed parallel to the respective physis using imaging guidance.[11] Despite extreme care not to disrupt the physeal tissue, instances of growth abnormalities (angular deformity and limb-length discrepancies) have been identified with this surgical approach.[11] Due to the risk of growth abnormalities, children with wide open physes (Tanner stage 1 or 2, or skeletal age $\leq$11 for females and $\leq$12 for males) are often treated with an iliotibial band (ITB) autograft reconstruction via the modified MacIntosh procedure,[10,43] described further by Kocher, et al.[8,11] In this combined extra- and intra-articular extraphyseal technique, the ITB graft is harvested from the proximal portion of the central third of the ITB band, with the distal insertion left in place, and is pulled “over-the-top” of the lateral femoral condyle and then through the knee joint and fixated onto the proximal tibia anteriorly (Figure 2).[8]

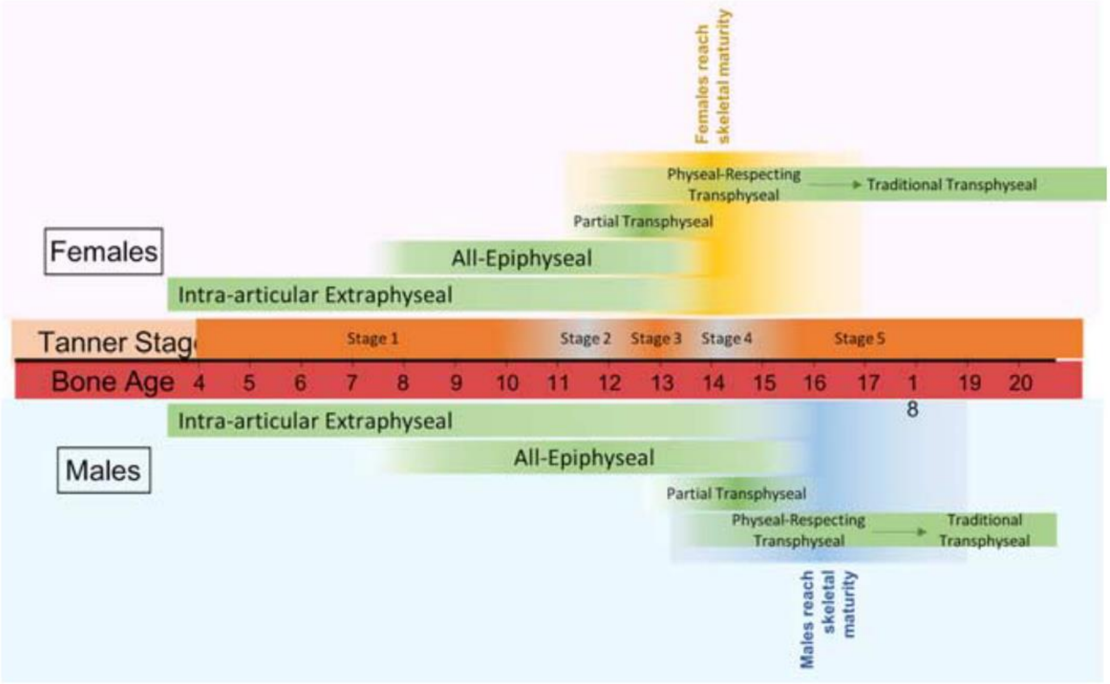


Figure 1. Algorithm for pACLR technique choice. From Joseph, et al[52]

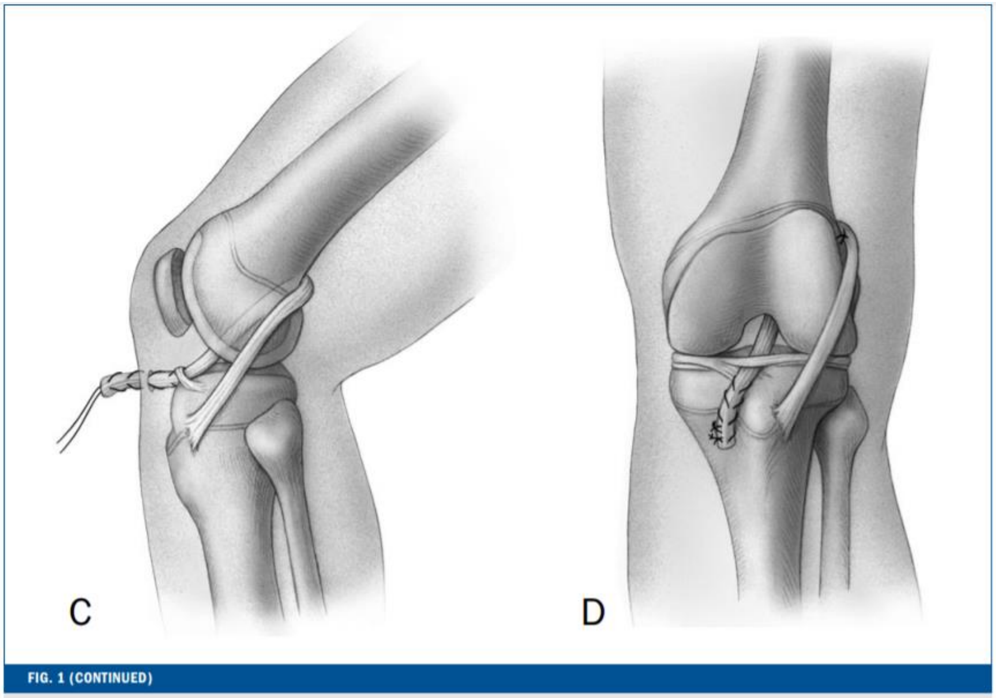


FIG. 1 (CONTINUED)

Physeal sparing, combined intra-articular and extra-articular reconstruction with use of an autogenous iliotibial band for prepubescent patients. *A:* The iliotibial band graft is harvested free proximally and left attached to Gerdy's tubercle distally. *B:* The graft is brought through the knee in the over-the-top position posteriorly. *C:* The graft is brought through the knee and under the intermeniscal ligament anteriorly. *D:* The graft is fixed to the intermuscular septum on the femoral side and to the periosteum of the proximal part of the tibia on the tibial side.

Figure 2. Depiction and description of "over-the-top" physeal-sparing ACLR procedure. From Kocher, et al[8]

Due to the relative newness of these pediatric ACLR (pACLR) procedures, the surgical techniques and approaches continue to be developed and improved, which limits the understanding of outcomes and thus continues the debate regarding which technique is the best choice for this young patient population.[50] The debate is further fueled by the high rate of retear in younger patients following ACLR regardless of surgical procedure, with one study reporting a 37.5% retear rate in patients aged 10-19 years.[53] Wall, et al.[50] reported good functional outcomes in 27 children at least 2 years following an all-epiphyseal pACLR (81% return to sport [RTS] rate, average score of 94% on self-reported functional questionnaire), but their cohort also demonstrated a high rate of complications (48%) and need for further surgical intervention (37%). Demange, et al.[54] reported limited growth disturbances in a small cohort of children who underwent a partial-transphyseal pACLR ("over-the-top" technique to respect the femoral physis with transtibial physeal tunneling), but with a 25% incidence of retear. In another small cohort of children who underwent a modified MacIntosh pACLR procedure with an ITB autograft, Kocher, et al. reported no growth abnormalities, high self-reported functional scores, and a low graft failure rate (4.5%),[8] but biomechanical studies suggest that this non-anatomical technique may increase knee joint strain.[6,8,50]

Overall, outcomes are varied following pACLR, and the many variations to the surgical techniques result in difficulty interpreting these outcomes in the literature due to small sample sizes and continued developed of the physeal-sparing approaches. Thus, in their recent consensus statement regarding management of ACL injuries in youth, the International Olympic Committee recommended and advocated for further high-quality studies specific to each surgical technique to help elucidate outcomes and guide intervention decision-making in this young, at-risk patient population.[7]

Rehabilitation following Pediatric Anterior Cruciate Ligament Reconstruction

Due to the many varied and continually developing surgical techniques as well as the relative newness of commonly performing a pACLR to address ACL injury in the skeletally immature, there is a lack of quality evidence regarding outcomes and to guide rehabilitation decision-making in this young patient population.[17] To date, research in pediatric ACL injury and reconstruction has focused primarily on diagnosis, surgical indications and technique, and incidence of growth disturbance.[7] There is a dearth of literature addressing appropriate rehabilitative techniques and decisions in the pediatric population following pACLR, and even less that delineate between the various surgical approaches.[7,17] Extensive research in the skeletally mature population following ACLR has led to published rehabilitation guidelines that are both temporal and criterion-based, with some institutions having protocols specific to graft choice and/or presence of concomitant procedure performed during a transphyseal ACLR in the adolescent and adult population.[13] The use of both time and objective criteria to guide progression respects known tissue healing timelines as well as functional status of the individual patient during rehabilitation.[14] The Multicenter Orthopaedic Outcomes Network (MOON) Knee Group has published extensive research demonstrating the success of this approach in rehabilitation of adolescents and adults following ACLR over the past 20 years.[14,55] The MOON group is very clear that progression within rehabilitation and return-to-sport (RTS) clearance following ACLR should be based upon the achievement of objective, functional criteria, and that timeframes provided within their guidelines are averages only.[14] Of the criteria recommended for use in assessing readiness to RTS following ACLR, strength testing of the quadriceps and hamstrings as well as a single leg hop test battery (Figure 3) are the most commonly utilized, with $\geq$90% symmetry between limbs being a typical cutoff.[15] Indeed, the Delaware-Olso ACL Cohort Study[16] has demonstrated that delaying RTS to at least 9 months post-operative and utilizing objective, functional criteria can limit the risk of reinjury by almost 85% in individuals after ACLR. This work strongly demonstrates the value of both time-based and criterion-based decision-making during ACLR rehabilitation.

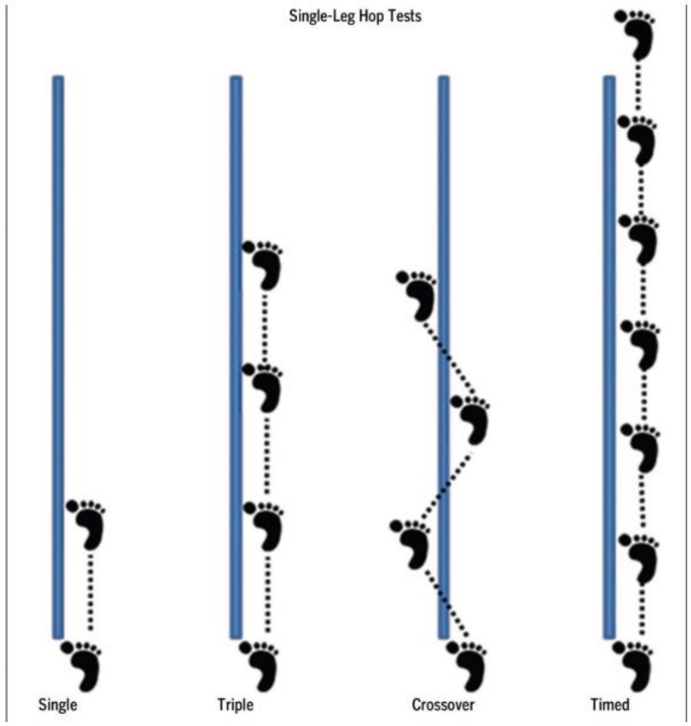


Figure 3. Single Leg Hop Test Battery Commonly Used in Return-to-Sport Decision-making following ACLR. From Schmitt, et al[56]

However, a recent study identified that most academic institutions and major medical centers do not even publish rehabilitation guidelines for children following pACLR.[17] And, of those that are available, many rely on a temporal progression rather than objective criteria/milestones, with many patients released to return-to-sport at 6 months post-operative regardless of functional status.[1] Furthermore, there is significant variability in the timing of the temporal progression recommended in currently published protocols—especially in regards to the timing of returning to sports participation, ranging anywhere from 3-11 months.[1,17] The disagreement in the timing of the return to play decision was further elucidated in a recent survey of the PRiSM (Pediatric Research in Sports Medicine) society, with 43% of providers indicating RTS should occur between 6-8 months post-operatively and 52% preferring 9-12 months post-operative in children following pACLR.[17,57] These time discrepancies are indicative of the significant disparity in the management of these patients. Several protocols reviewed by Yellin, et al.[1] in a recent systematic review did include the achievement of objective physical milestones in rehabilitation progression decision-making, such as symmetric thigh strength and functional performance (based on single-leg hop tests). However, these recommended criteria were established for the skeletally mature population and have yet to be validated in the skeletally immature population, which questions the appropriateness of applying these measures to this patient population.[7] Furthermore, very few protocols distinguish between the many pACLR surgical options and many define "pediatric" as age under 18 regardless of whether a physeal-sparing procedure was performed, which is a significant limitation to the generalizability and utility of these protocols.[1,7,17] Many organizations, such as the International Olympic Committee (IOC), have advocated for research exploring RTS criteria and rehabilitation guidelines in children following physeal-sparing ACLR, with hopes for further delineation by surgical technique.[7]

As the preponderance of evidence in this patient population is focused on surgical technique and surgical outcomes, there is limited understanding of the clinical and biomechanical outcomes of children following pACLR, which could potentially improve rehabilitation decision-making. Greenberg, et al did explore clinical outcomes in pediatric patients following ACLR, finding that very few individuals met commonly recommended return-to-sport criteria utilized in the skeletally mature population (44% did not achieve ≥90% limb-symmetry in quad strength at 7 months post-operative, 62% did not meet ≥90% limb-symmetry on a single leg hop test battery at 12 months post-operative, and only 25% met all typically recommended return-to-sport criteria by 15 months post-operative).[58] However, this study included individuals who underwent either a physeal-sparing or transphyseal surgical technique, again limiting the utility and generalization of these findings. Sugimoto, et al examined 72 skeletally immature patients following ACLR and found that very few (4.2%) met all RTS criteria commonly utilized in the skeletally mature population.[59] This study did stipulate skeletally immaturity and excluded pediatric patients (defined as <18 years of age) with closing or closed physes, but did not delineate by surgical procedure performed.[59] These findings—specifically that such a low percentage of skeletally immature patients meet RTS criteria utilized in the skeletally mature— highlights the need to better understand rehabilitation and return-to-sport criteria in this patient population. Furthermore, there is great variability in which clinical measures are employed to assess children after pACLR, and the measures utilized are typically not validated in the patient population.[60] The significant discrepancies in rehabilitation guidelines as well as clinical measures applied to measure success precludes a good understanding of outcomes following pACLR.[61]

Motor Development, Physical Literacy, and Pediatric ACLR

The lack of evidence specific to children after pACLR may elucidate the suboptimal outcomes that have been demonstrated in this population, specifically high second injury rates and low return to sport rates.[62] An adolescent athlete who returns to a cutting and pivoting sport following an ACLR procedure has been demonstrated to be at a 30-40 times greater risk of sustaining an ACL injury when compared to their uninjured peers.[63] In a recent study, 1 in 6 pediatric patients following ACLR underwent ≥1 repeat procedure within 3 years from initial ACLR.[64] In another study, only 63.5% of ACLR patients with open physes returned to cutting/pivoting sports.[62] Importantly, nearly 20% of children in this study changed their primary sport of interest, with a majority of them citing their knee as the reason.[62] These are young children who are driven to change their primary activity of interest due to their poor knee function. Given the known relationship between activity involvement in youth and lifelong physical activity, as well as the associated health consequences, this is of great concern.

These traumatic pediatric ACL injuries are occurring with increasing frequency during later childhood.[65] If we consider this timeframe in light of a commonly utilized analogy within motor development of the "motor development mountain," (Figure 4)[66] this occurs during a time when children are progressing from mastering fundamental motor skills[67,68] and are learning more transitional motor skills—such as specific swimming strokes and games like street hockey which involve the use of a tool as well as the inclusion of multiple people.[66,67,69] This timeframe also includes a critical timeframe and concept known as the "proficiency barrier."[70] The notion of a proficiency barrier in motor skill development refers to the level of fundamental motor skill development that is necessary to be able to apply these skills to sports and lifetime activities and remain active throughout life.[68–71] It is unknown how interrupting this natural progression with a traumatic injury right at the time when children should be overcoming the proficiency barrier will impact children's motor development. However, it has been demonstrated that almost 90% of children who fall below the proficiency barrier of motor skill development do not meet recommended moderate-to-vigorous physical activity guidelines.[70] This is particularly concerning as climbing the "motor development mountain" has been associated with long-term health benefits, while not successfully climbing the mountain has been associated with a sedentary lifestyle, increased hypokinetic disease and lifelong health consequences such as an increased risk of heart disease and type II diabetes.[68,71,72]

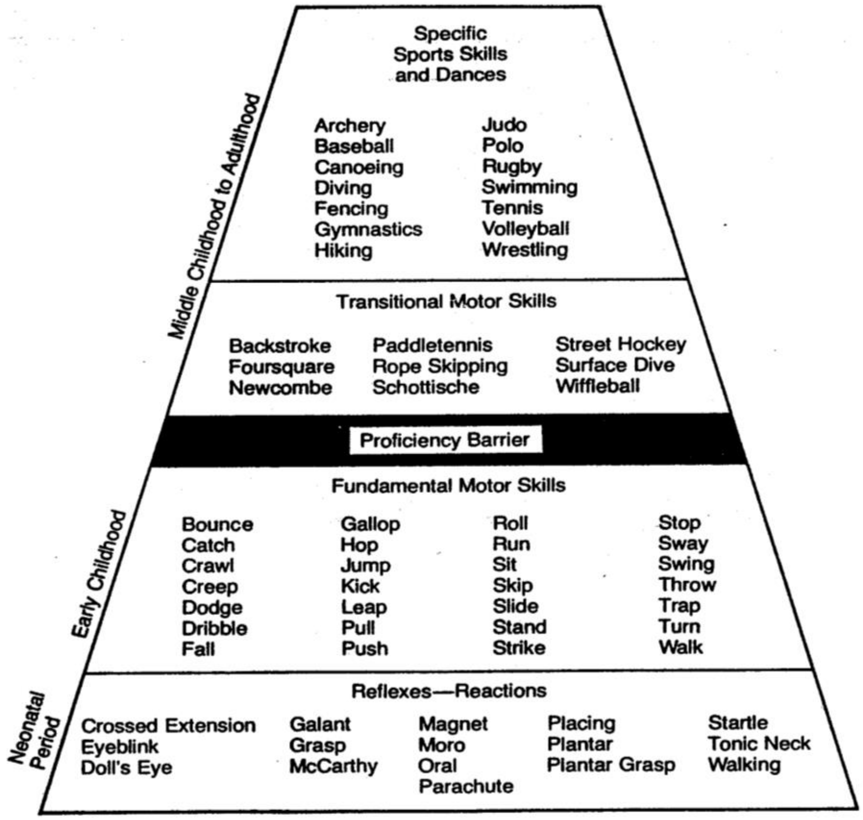
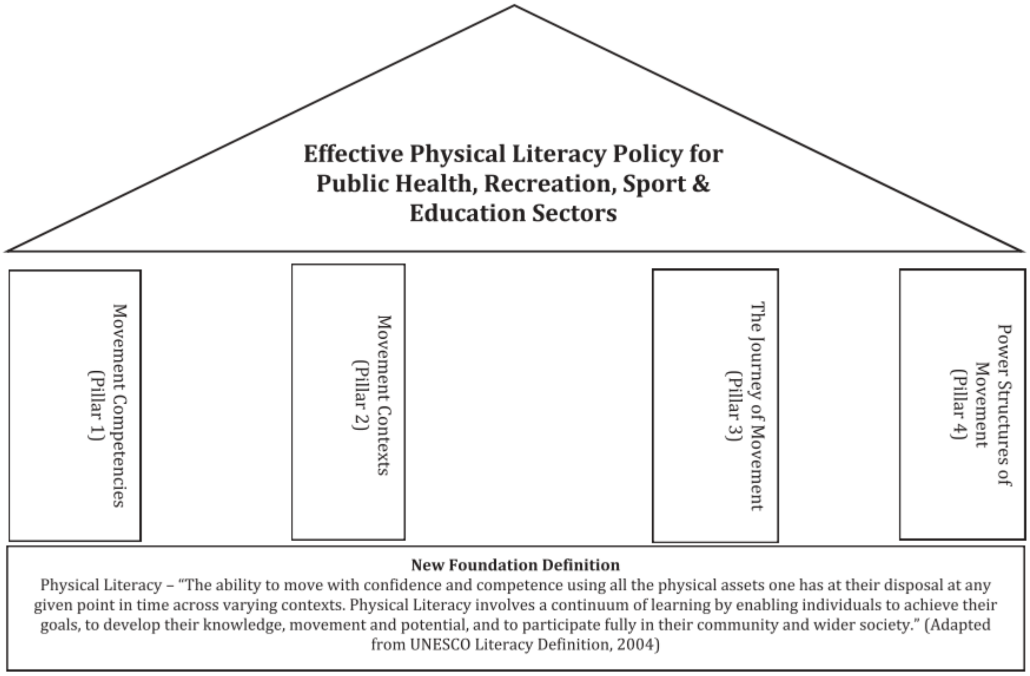


Figure 4. Clark’s Motor Development Mountain[66]

Along with the analogy of the motor development mountain comes the concept of physical literacy—the motivation, confidence, physical competence, knowledge, and understanding to be physically active for life.[73] As previously alluded to, impacting the motor development trajectory during the timeframe of mastering the proficiency barrier may have a negative impact on the physical literacy of these children. Pediatric ACLR could adversely impact two of the four “pillars” of physical literacy (Figure 5)[73] 1.) movement competencies—as previously explored in relation to the motor development mountain, and 2.) the journey of movement—a traumatic event is often defining and could affect an individual’s psychological relationship with activity. The traumatic consequence of pACLR may be a reduced motor competence and a detrimental impact on the journey of movement, propelling a child into a negative spiral of disengagement with activity.[71] The negative spiral of disengagement, as outlined by Stodden et al.’s Model of Motor Competence and Physical Activity (Figure 6),[71] results in an increased risk of obesity for these children and the myriad of poor health consequences that accompany an unhealthy weight.[70,71,74] Indeed, recent work by MacAlpine and colleagues[75] found that children and adolescents experience significant increases in their body mass index (BMI) in the first 2 years after ACLR. Thus, a better understanding of the impact of pACLR on a child’s motor development and physical literacy is imperative to improving long-term health outcomes. From a broader perspective, future longitudinal work is needed that not only looks at the child’s impact of the injury relative to a specific sport or return to sport, but examines the broader consequences of the injury on motor development trajectories across the lifespan.



Physical Literacy – "The ability to move with confidence and competence using all the physical assets one has at their disposal at any given point in time across varying contexts. Physical Literacy involves a continuum of learning by enabling individuals to achieve their goals, to develop their knowledge, movement and potential, and to participate fully in their community and wider society." (Adapted from UNESCO Literacy Definition, 2004)

Figure 5. Dudley's Four Pillars of Physical Literacy[73]

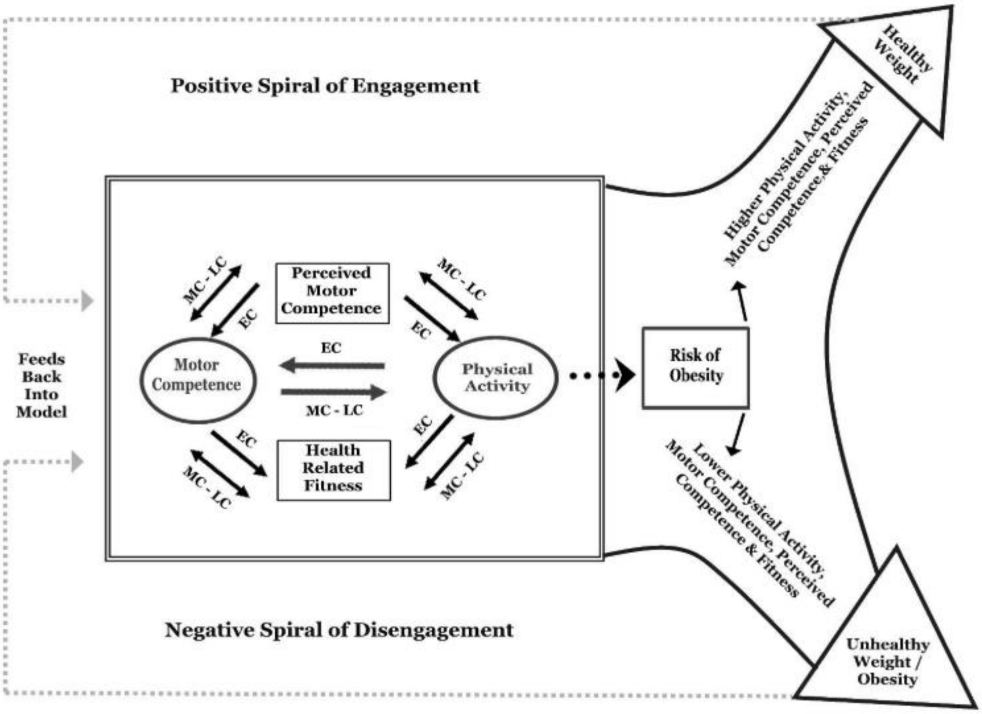


Figure 6. Stodden's Model of Motor Competence and Physical Activity[71]

Neuroplasticity and ACLR

The impact of the globally developing neuromuscular system on rehabilitation in these children is relatively unknown. Central nervous system adaptations after ACLR are known to occur in the skeletally mature, and thought to be compensations due to the loss of knee mechanoreceptors.[76–79] These adaptations include increased frontal and frontoparietal cortex during sensorimotor tasks, as well as increased cortical recruitment for motor planning.[76–79] The presence of these changes in children has yet to be explored. Furthermore, as previously mentioned, these children are still within the emergent, natural process of the development of motor control and motor coordination which begins at birth and continues through adolescence.[66,69] It is not clear how interrupting this developmental trajectory with a traumatic injury and subsequent surgical intervention impacts long-term development of motor control and coordination in these children. Sustained differences in movement strategies between limbs as a result of adaptations to an ACL injury and pACLR are not only related to second injury and long-term physical activity (as previously discussed), but also may increase risk of pathology later in life, such as early onset osteoarthritis.[80] These childhood traumatic injuries and subsequent surgical interventions could predicate the foundation for long-term health consequences. Also, it highlights that the globally developing neuromuscular system in these children must be considered when designing rehabilitation programs. Indeed, applying motor learning strategies to support neuroplasticity has been shown to be more effective than traditional rehabilitation strategies in reducing biomechanical risk factors for ACL injury.[81,82]

Aspects of Motor Control, Coordination, and Variability

It is well-known that altered biomechanics during functional movements have been reported in individuals following ACLR—including decreased knee flexion, increased knee abduction, increased hip adduction and internal rotation, and increased ankle eversion.[22] These adaptations do not fully explain the demonstrated suboptimal outcomes and high rates of 2nd injury, as described previously. Current literature exploring biomechanical changes following ACLR typically explores a single point during a movement (such as initial contact with gait) or are limited to a single joint measure (such as knee flexion).[22] However, given the dynamic mechanism of ACL injury and the function of the lower extremity as an interconnected system, researchers have begun to explore the potential association of movement variability and the role of neuromuscular adaptations and lower-extremity coordination with the known suboptimal outcomes and increased risk of 2nd injury following ACLR.[22]

The application of dynamic systems theory (DST) may help better understand lower extremity joint coordination and functional adaptations following ACLR.[22,27–29] DST (Figure 7) has its foundations in work from Bernstein dating back to 1967.[28,32,37] Bernstein introduced the concept of “redundant degrees of freedom” (DOF) within a movement system, or multiple ways to perform a dynamic task.[22,28] DST contends that human movement is influenced by factors (“constraints”) related to the environment (such as the playing surface or weather), the specific task at hand (such as walking or jumping), and the individual (such as a knee injury).[29] Coordination is the process by which these multiple DOF are controlled by “coordinative structures” to create an organized movement system capable of responding to the demands of the task at hand.[22,28,83] As such, variability in movement is considered a necessary component to a healthy motor system capable of adapting to its environment.[22,27,28,81] It has been proposed that there is an optimal amount of movement variability within a motor system that allows for balance between the need for stability (to ensure movement quality and reduce risk of injury) and flexibility (to respond to the demands of the ever-changing environment).[22,34] High variability in movement may be indicative of impaired neuromuscular control, and may leave an individual at risk of injury due to an inability to control movement when environmental demands are high.[30] Conversely, very low levels of variability is indicative of a "rigid" system, which may leave an individual at risk of injury due to an inability to adapt to changes in the environment.[30]

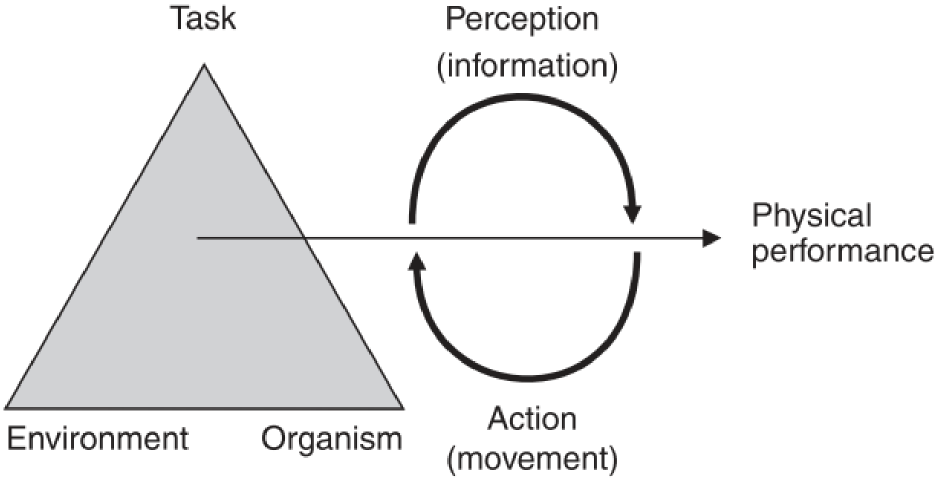


Figure 7. Newell's Depiction of Dynamic Systems Theory[28]

This concept of "optimal movement variability" helps elucidate findings Leporace and colleagues reported in their systematic review examining motor coordination during gait in individuals following ACL injury;[84] Specifically, that patients with ACL deficient knees who had not undergone a surgical reconstruction demonstrated reduced variability during gait indicative of a more rigid system, whereas patients following an ACLR procedure demonstrated increased variability in gait as compared to healthy controls. The authors discussed that this may be due to overall movement system restricting movement in the ACL deficient group secondary to pain or fear as a result of the mechanical instability in the knee, whereas the ACLR group demonstrated increased variability indicative of a less controlled system secondary to neuromuscular compromise and proprioception deficits following the surgical intervention.[84] Both scenarios indicate a movement system with reduced ability to respond to increased demands from the environment secondary to individual constraints to the dynamic system.

Individuals after ACLR demonstrate differences in joint coordination and movement variability which can persist for years.[22,30,84] Pollard, et al compared lower extremity coordination patterns by assessing inter-joint movement variability during a side-step cutting maneuver—a movement often associated with non-contact ACL injuries—in female soccer players who had and had not experienced an ACL injury and ACLR procedure.[30] Athletes following ACLR demonstrated significantly greater movement variability when compared to their uninjured counterparts, which the authors concluded was indicative in changes to neuromuscular control and which they conjectured may account for the increased risk of second injury and incidence of joint degradation (osteoarthritis) identified in individuals following primary ACLR.[30] Gribbin, et al[29] examined hip and knee joint coordinative movement during walking and jogging in individuals following ACLR, and found that following ACLR subjects demonstrated increased movement variability indicative of a less controlled system on the surgical limb as compared to the nonsurgical limb. Similarly, Davis, et al[22] reported that individuals following ACLR demonstrated greater variability in hip-knee coordination during gait on both their surgical and non-surgical limbs when compared to uninjured individuals.

Pediatric ACLR and Movement Variability

To our knowledge, the inter-joint movement variability of children following pALCR has yet to be quantified. As mentioned previously, outcomes following pACLR are suboptimal. Changes in neuroplasticity are known to occur in the skeletally mature population following ACLR,[77,85] and, although not directly identified in the skeletally mature population to date, it is reasonable to presume that children may experience a similar consequence following pACLR. Furthermore, children are in the midst of the natural process of motor development which occurs from birth to adolescence.[66,86] Specifically, ACL injuries are occurring with increased frequency during middle childhood,[65] a time period when children are working to overcome the "proficiency barrier" of motor competence and transition from foundational motor skills (such as running, jumping, throwing) to more complex motor skills (such as associated with sports participation).[70] Not successful achieving this "proficiency barrier" of motor competence is related to lower physical activity participation and puts a child at risk for the myriad of health consequences associated with an inactive lifestyle.[70,74] It is not clear how interrupting this natural development with a traumatic injury which can superimpose further neuroplastic changes effects the long-term motor development and coordination in these children. It is clear that improved rehabilitation strategies are critical to address the neuromuscular and motor development needs of children after pACLR to ensure they do not fall into the "negative spiral of disengagement"[71] with physical activity and the associated lifelong poor health consequences.

Although not a direct measure of movement variability or coordination, incorporating a movement assessment within rehabilitative guidelines has been explored within a pediatric population following ACLR.[87] A group out of the Hospital for Special Surgery in New York developed a quality of movement assessment utilizing 2D technology and integrated it into their rehabilitative guidelines. The movement assessment evaluated criteria such as movement strategy, dynamic alignment, symmetry, depth, and control, and could be considered a rudimentary assessment of achieving an optimal level of movement variability to demonstrate a stable yet flexible motor control system. Using this process in a sample of 42 children, 93% of their subjects were able to return to their primary sport of interest, and the rate of second injury was reduced to 7.6%. Furthermore, individuals in their study who went back to sport at greater than 12 months post-operatively had a reduced rate of 2nd injury as compared who returned to sport at less than 12 months.[87] Although still a relatively small sample from which to make widespread conclusions, the importance of a greater understanding of neuromuscular control, coordination, and movement variability in children following pACLR in order to improve rehabilitation and outcomes in this at-risk patient population is abundantly evident.

Quantifying Movement Variability

The preponderance of biomechanical analyses of individuals following ACLR explore a single joint at a single time point during a dynamic movement. As discussed previously, the lower extremity functions as an interconnected system and the mechanism of ACL injury is dynamic. Vector coding techniques to quantify inter-joint coupling angles have been employed as one method to assess lower extremity coordination and movement variability between lower limb joints and across time.[22,29,88–90] This technique involves creating an angle-angle diagram for a particular dynamic movement of the lower extremity where the proximal joint is plotted on the x-axis and the distal joint is plotted on the y-axis (Figure 8). A coupling angle (CA) is calculated as the vector angle connecting two chronologically successive data points relative to the horizontal, per Equation 1 (Figure 9), where "*i*" is the percent of time of the "m^th^" trial of the dynamic movement of interest.[36,88,90] CA can range from 0 to 360 in order to preserve possible lost data if CA were compressed to 0 to 180.[36]

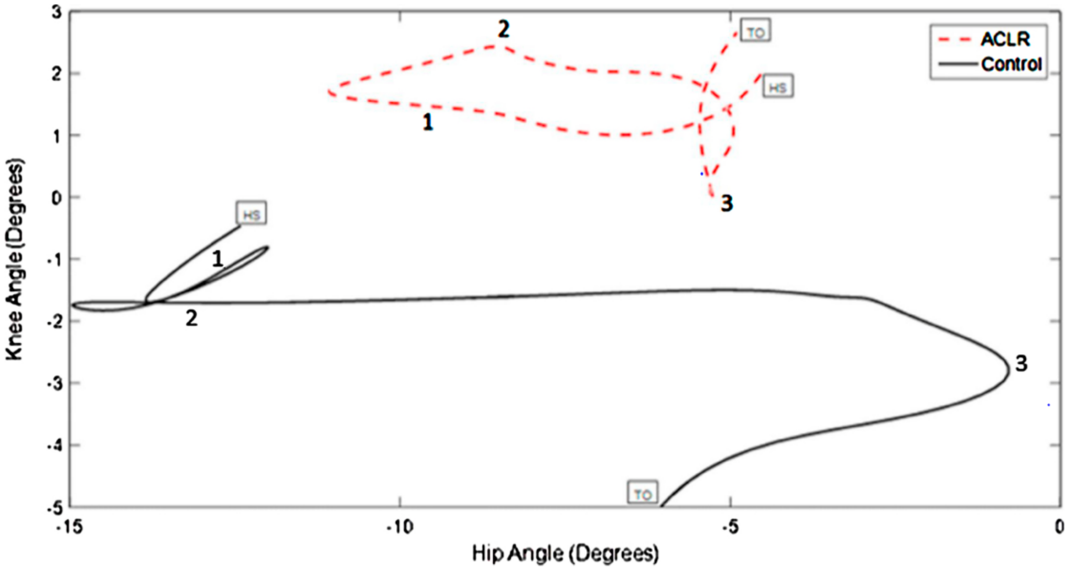


Figure 8. Example of Angle-Angle Diagram. From Davis, et al[36]

$$CA = \tan^{-1}\left(\frac{y_{m,i+1} - y_{m,i}}{x_{m,i+1} - x_{m,i}}\right)$$

Figure 9. Equation 1—Coupling angle calculation[36,88,90]

Angles are directional in nature so mean coupling angles ($\overline{CA}$) are computed using circular statistics from mean vertical ($\bar{y}_i$) and mean horizontal ($\bar{x}_i$) components for each percentage (i) of the dynamic movement (time normalized from 0-100%) of interest across trials (m), per Equations 2-4 (Figures 10-12).[36,88,90] Then, the circular standard deviation of the mean coupling angle is calculated and this is representative of movement variability.[36]

$$\bar{x}_i = \frac{1}{n}\sum \cos CA_{m,i}$$

Figure 10. Equation 2— Calculation of Mean Horizontal Component of Coupling Angle[36,88,90]

$$\bar{y}_i = \frac{1}{n}\sum \sin CA_{m,i}$$

Figure 11. Equation 3— Calculation of Mean Vertical Component of Coupling Angle[36,88,90]

$$\overline{CA} = \begin{cases} \arctan\left(\frac{\bar{y}_i}{\bar{x}_i}\right) & \text{if } \bar{x}_i > 0 \\ \arctan\left(\frac{\bar{y}_i}{\bar{x}_i}\right) & \text{if } \bar{x}_i < 0 \end{cases}$$

Figure 12. Equation 4—Calculation of Mean Coupling Angle[36,88,90]

Chang[90] identified four coordination patterns from analysis of coupling angles between the rearfoot and the forefoot during gait. Coordination patterns fall within 45° “bins” (Figures 13-14) between the vertical, horizontal, and 45° diagonals and represent joint contributions to movement. Davis[36] adapted this scheme more broadly to the lower extremity during gait and defined the four patterns as: (1) in-phase, (2) anti-phase, (3) proximal contribution, and (4) distal contribution (Table 1). An in-phase pattern represented motion in which both joints were rotating in the same direction, whereas in an anti-phase pattern they would be rotating in opposite directions.[36] A proximal contribution pattern represents more motion from the proximal joint (i.e. the hip) as compared to the distal (i.e. the knee), with a distal contribution pattern being the opposite (more contribution from the distal joint as compared to the proximal).[36]

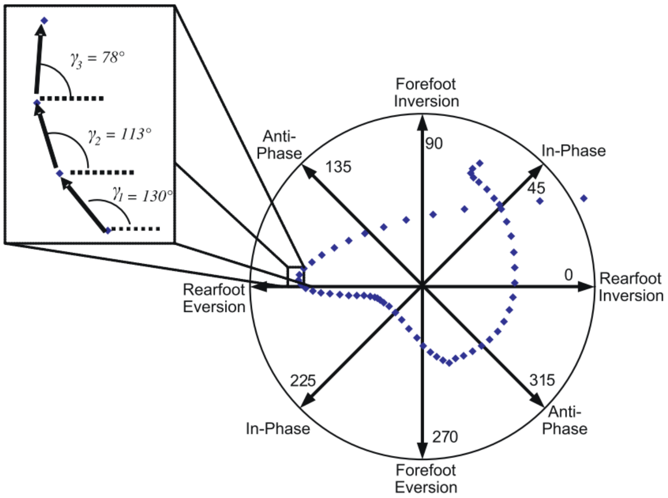


Fig. 1. A frontal plane relative motion plot of rearfoot segment and forefoot segment angles. Segment angles were computed relative to a fixed orthogonal laboratory coordinate system. Data are from one exemplar trial of stance (truncated for viewing purposes). A polar plot is overlaid to illustrate four inter-segmental coordination patterns: in-phase, anti-phase, rearfoot (proximal) phase and forefoot (distal) phase. The inset provides an expanded view of three coupling angles (γ).

Figure 13. Chang's Coordination Patterns of Forefoot and Rearfoot Motion during Gait[90]

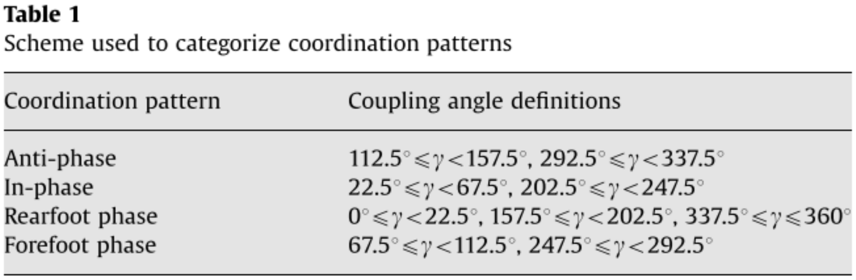


Table 1
Scheme used to categorize coordination patterns

Coordination pattern	Coupling angle definitions
Anti-phase	$112.5° \leqslant \gamma < 157.5°$, $292.5° \leqslant \gamma < 337.5°$
In-phase	$22.5° \leqslant \gamma < 67.5°$, $202.5° \leqslant \gamma < 247.5°$
Rearfoot phase	$0° \leqslant \gamma < 22.5°$, $157.5° \leqslant \gamma < 202.5°$, $337.5° \leqslant \gamma \leqslant 360°$
Forefoot phase	$67.5° \leqslant \gamma < 112.5°$, $247.5° \leqslant \gamma < 292.5°$

Figure 14. Chang's Categorization of Coordination Patterns of Rearfoot and Forefoot Motion during Gait[90]

Coordination Pattern	**Coupling Angle Definition**	**Description of Pattern**
Anti-Phase	$112.5^\circ \leq CA < 157.5^\circ$ $292.5^\circ \leq CA < 337.5^\circ$	Both joints rotating in the same direction
In-Phase	$22.5^\circ \leq CA < 67.5^\circ$ $202.5^\circ \leq CA < 247.5^\circ$	Both joints rotating in the opposite direction
Proximal Contribution	$0^\circ \leq CA < 22.5^\circ$ $157.5^\circ \leq CA < 202.5^\circ$ $337.5^\circ \leq CA \leq 360^\circ$	More motion from proximal joint as compared to distal
Distal Contribution	$67.5^\circ \leq CA < 112.5^\circ$ $247.5^\circ \leq CA < 292.5^\circ$	More motion from distal joint as compared to proximal

Table 1. Joint Coordination Patterns[36]

Quantifying movement variability by utilizing vector coding to determine joint coupling angles is a preferred technique to quantify lower extremity coordination due to its potential clinical utility.[22] Indeed, Herb, et al.[89] explored the effect of rehabilitation with a destabilization device in individuals with chronic ankle instability (CAI) utilizing vector coding to quantify joint-coupling variability. Heiderscheit[88] examined intralimb coordination variability during gait in individuals with and without patellofemoral pain (PFP) using a vector coding technique to evaluate lower extremity joint couplings. Subjects with symptomatic PFP demonstrated reduced variability in the transverse plane during running, which the authors concluded may be secondary to pain.[88] Similarly, individuals with hip acetabular cartilage defects exhibited reduced movement variability during gait which Samaan, et al interpreted as a compensation for reduced stability secondary to the chondral lesion.[91] Joint coupling variability differences have also been identified between limbs during gait in individuals following ACLR.[29] These studies demonstrate that assessing joint coordination via vector coding is a promising method to further understand lower extremity movement in children following pACLR and potentially guide rehabilitation strategies.

Chapter 3: Design and Methodology

Participants:

Participants were a subset from the ACL Reconstruction Long-term outcomes in Adolescents and Young adults (ACL-RELAY) study. The ACL-RELAY study is a prospective, ongoing study exploring outcomes in young, active individuals following ACLR. Participants are recruited from orthopedic surgeon practices and physical therapy clinics in the greater Cincinnati, OH region. Enrollment occurs at the time of return to sport (RTS) clearance (determined by the participant's medical team) following completion of a rehabilitation program. Participants must intend to return to high-level athletic participation >50 hours per year, and are excluded if they have a history of back injury or surgery, a previous lower extremity injury, or a concomitant ligament injury along with their ACL injury (excluding grade 1 medial collateral ligament sprain). The initial testing visit occurs within 4 weeks of each participant's RTS clearance. All participants and parents (when applicable) signed informed assent and consent, respectively, approved through the Institutional Review Boards.

Pediatric subjects: Participants in the pediatric group were subjects from the ACL-RELAY study who had underwent a primary, unilateral, physeal-sparing ACLR procedure. The surgical technique utilized in this group was an all-epiphyseal sparing ACLR procedure with a hamstring autograft.

Adolescent ACLR subjects: For this analysis, the adolescent participants consisted of subjects from the ACL-RELAY study who underwent primary, unilateral, transphyseal ACLR and met the World Health Organization and American Academy of Pediatrics definition of middle adolescence: age 15-17 years.[25] Middle adolescence was chosen as opposed to early adolescence (aged 10-14) to avoid potential age overlap with the pediatric group and to capture adolescents who had more likely achieved skeletal maturity.[92] The surgical technique utilized in this group was a transphyseal procedure with either a hamstring autograft, patellar tendon autograft, or allograft.

Adolescent Healthy Controls: Participants in the control group were individuals enrolled in the ACL-RELAY study who had not experienced an ACL injury, were 15-17 years of age (middle adolescence), participated in high-level sports >50 hours per year, had no history of low back pain, and had no lower extremity injury (requiring physician management) or surgery in the year prior to data collection. As this group did not have a surgical limb, we utilized the preferred limb for comparison, consistent with previous work.[93] The preferred limb was defined as the limb that contacted the ground first on the majority of double leg jump trials.[93]

Group size: The target group examined in the current analysis is the pediatric group who underwent a physeal-sparing ACLR procedure. This work is exploratory in nature. For this preliminary analysis, the most recent 20 participants from the ACL-RELAY study that met inclusion criteria for the adolescent ACLR and the adolescent healthy control groups were included as a representative sample of each group, respectively. All participants that met the inclusion criteria for the pediatric ACLR group were included in this analysis.

Hypotheses and variables of interest:

1) Children following pACLR will demonstrate increased movement variability on the surgical limb as compared to the surgical limb of adolescents following ACLR and to the preferred limb of adolescent healthy controls
    a. Independent variable— surgical limb of pediatric ACLR vs surgical limb of adolescent ACLR vs preferred limb of adolescent healthy control
    b. Dependent variable— movement variability of the surgical/involved/preferred limb (circular standard deviation of the mean coupling angles; coupling angles of interest listed in Table 2)
2) Children following pACLR will demonstrate increased movement variability on the non-surgical (uninvolved) limb as compared to the non-surgical (uninvolved) limb of adolescents after ACLR and the non-preferred limb of adolescent healthy controls

a. Independent variable— non-surgical limb of pediatric ACLR vs non-surgical limb of adolescent ACLR vs non-preferred limb of adolescent healthy control

b. Dependent variable— movement variability of the non-surgical/uninvolved/non-preferred limb (circular standard deviation of the mean coupling angles; coupling angles of interest listed in Table 2)

Lower Extremity Coupling Angles of Interest	**Acronym**
Hip Flexion—Knee Flexion	HF-KF
Hip Flexion—Knee Abduction	HF-KA
Hip Flexion—Knee Rotation	HF-KR
Hip Adduction—Knee Flexion	HA-KF
Hip Adduction—Knee Abduction	HA-KA
Hip Adduction—Knee Rotation	HA-KR
Hip Rotation—Knee Flexion	HR-KF
Hip Rotation—Knee Abduction	HR-KA
Hip Rotation—Knee Rotation	HR-KR
Knee Flexion—Ankle Dorsiflexion	KF-AD
Knee Abduction—Ankle Dorsiflexion	KA-AD

Table 2. Lower Extremity Joint Coupling Angles of Interest

Coupling Angles of Interest: The joint coupling angles of interest were chosen due to reported kinematic differences in the existing literature between individuals following ACLR and uninjured individuals.[36,94,95]

Motion Analysis:

Single-Leg Drop Landing Task: A single-leg (SL) landing task was chosen as the dynamic movement examined due to known changes in SL landing mechanics demonstrated by the skeletally mature following ACLR, with these SL landing asymmetries being associated with self-reported function up to 2 years post-operatively.[96] Furthermore, the mechanism of and ACL injury is most typically an acceleration or deceleration event on a single limb,[40,41] such as with a SL land.

Kinematic data for the lower extremity and trunk were calculated using 3-dimensional motion analysis and embedded force platforms during a single-leg (SL) landing task on both the involved and uninvolved limbs, as previously described.[96,97] Motion analysis was performed utilizing a 12-camera three-dimensional motion analysis system (240 Hz, Motion Analysis Corp., Santa Rosa, CA, USA) with 4 embedded force plates (1200 Hz, AMTI, Watertown, MA, USA). The system tracked retroreflective markers attached to specific locations and anatomical landmarks on the upper extremities, lower extremities, and trunk of each subject by trained research personnel to determine joint centers and segment positions during the landing task. To perform the SL landing task, participants stood on a 31-cm box on the testing limb and were instructed to drop off the box and land on the same testing limb on a force plate. The period from initial contact (when the vertical ground reaction force first exceeded 10 N) to lowest center of mass was examined and defined as the landing phase. Three trials on each limb for each participant were recorded and analyzed.

***Data Processing*:** Coupling angles for two adjacent joints of the lower extremity and trunk were calculated using a vector coding technique described by Davis[22] and described in detail above (Figures 8-14, Table 1). Angle-angle curves were created using custom Matlab (Mathworks, MA) script with the proximal limb on the y-axis and the distal limb on the x-axis.

Statistical Analysis:

The average lower extremity movement variability was compared between groups for each joint coupling (Table 2) during the landing phase using vector coding technique, described above.

Group comparisons: The circular standard deviation of the mean coupling angle, representative of movement variability, was compared for each joint coupling of interest for the involved/preferred limb across groups using Kruskal Wallis test. Kruskal Wallis was chosen due to the presence of 3 groups and the non-parametric nature of the data due to non-normal distribution and moderate to high skewness. Significance was set *a priori* at $p<0.05$. For all significant findings, Mann Whitney U post-hoc tests were performed with significance set *a priori* at $p<0.0167$ per the Bonferroni correction method. Statistical analyses were performed using IBM SPSS Statistics (Version 24, Armonk, NY, USA).

Chapter 4: Manuscript

Introduction

Anterior cruciate ligament (ACL) injuries are commonplace among active individuals in the United States, with more than 200,000 injuries and over 100,000 subsequent surgical reconstructions performed annually.[40,48] Given the recent rise of competitive youth sports participation and early sports specialization, the incidence of ACL injuries in pediatric patients is rising.[1,7] While surgical reconstruction is the standard of care in the adolescent and adult populations, ACL injuries in youth were historically treated conservatively prior to skeletal maturity.[4,46] The development of surgical techniques to respect open physeal plates and the evidence that delaying surgery is related to progressing meniscal and chondral pathology has led to an increasing number of ACL reconstruction (ACLR) procedures performed in the skeletally immature.[6,12,43,44,47] However, the preponderance of evidence regarding rehabilitation decision-making and outcomes following ACLR is grossly limited to adolescent and adult populations, and there is an overall dearth of literature to guide and understand the post-operative process in the skeletally immature.[1]

In the existing literature, outcomes in both the skeletally mature and immature have been shown to be suboptimal. In the adolescent and adult populations, recent evidence suggests that less than 50% of individuals return to their prior activity level following ACLR,[18] with up to 30% experiencing a second injury within 2 years of returning to sport.[19,20] Similar outcomes have been demonstrated in children, with 1 in 5 skeletally immature individuals reporting a poor outcome (determined by score on a validated self-reported function questionnaire) and 1 in 4 experiencing a 2nd injury following ACLR.[21] Altered biomechanics are well reported in the skeletally mature following ACLR,[22–25] and have been related to second injury.[26] However, the preponderance of biomechanical research in the ACLR population explores a single joint at a single moment in time. Given the dynamic mechanism of ACL injury and the function of the lower extremity as an interconnected system, researchers have begun to explore the potential association of movement variability and the role of neuromuscular adaptations and lower-extremity coordination as a means to better understand known suboptimal outcomes and increased risk of 2nd injury following ACLR.[22] Recent work has identified that years after ACLR individuals demonstrate differences in joint coordination and movement variability when compared to healthy controls.[22,27–29] The application of dynamic movement theory, which contends that there is a preferred range of coordination variability, may help better understand lower extremity joint coordination and functional adaptations following ACLR.[22,27,28] A better understanding of these functional adaptations may help inform rehabilitative strategies and improve outcomes. However, to date this work has been limited to individuals who have undergone a transphyseal ACLR procedure typically performed in the skeletally mature. Movement variability and measures of coordination have yet to be explored in the skeletally immature population following a physeal-sparing ACLR procedure.

The current work aims to examine lower extremity coordination in children following a pediatric ACLR procedure during a single-leg dynamic landing task and compare to adolescents following ACLR as well as to adolescent healthy controls. We hypothesized that children following pACLR would demonstrate increased movement variability on the surgical limb as compared to the surgical limb of adolescents following ACLR and to the preferred limb of adolescent healthy controls. Furthermore, in light of the process of natural motor development, we hypothesized that children following pACLR will demonstrate increased movement variability on the non-surgical (uninvolved) limb as compared to the non-surgical (uninvolved) limb of adolescents after ACLR and the non-preferred limb of adolescent healthy controls.

Methods

Participants: Participants were a subset from the ACL Reconstruction Long-term outcomes in Adolescents and Young adults (ACL-RELAY) study. The ACL-RELAY study is a prospective, ongoing study exploring outcomes in young, active individuals following ACLR. Participants are recruited from orthopedic surgeon practices and physical therapy clinics in the greater Cincinnati, OH region. Enrollment occurs at the time of return to sport (RTS) clearance (determined by the participant’s medical team) following completion of a rehabilitation program. Participants must intend to return to high-level athletic participation >50 hours per year, and are excluded if they have a history of back injury or surgery, a previous lower extremity injury, or a concomitant ligament injury along with their ACL injury (excluding grade 1 medial collateral ligament sprain). The initial testing visit occurs within 4 weeks of each participant's RTS clearance. All participants and parents (when applicable) signed informed assent and consent, respectively, approved through the Institutional Review Boards.

Pediatric subjects**:** Participants in the pediatric group were subjects from the ACL-RELAY study who had underwent a primary, unilateral, physeal-sparing ACLR procedure. The surgical technique utilized in this group was an all-epiphyseal sparing ACLR procedure with a hamstring autograft. 11 children (age 11.54±1.69, 9 males/2 females, 8.97±2.65 months since surgery, 1.50±0.16 m, 42.62±13.66 kg, BMI 17.63±2.77) met inclusion criteria and were included.

Adolescent ACLR subjects**:** For this analysis, the adolescent participants consisted of subjects from the ACL-RELAY study who underwent primary, unilateral, transphyseal ACLR and met the World Health Organization and American Academy of Pediatrics definition of middle adolescence: age 15-17 years.[25] Middle adolescence was chosen as opposed to early adolescence (aged 10-14) to avoid potential age overlap with the pediatric group and to capture adolescents who had more likely achieved skeletal maturity.[92] The Adolescent ACLR group was comprised of 20 subjects (16.99±0.60 years, 6 males/14 females, 8.67±3.42 months since surgery, 1.69±0.11 m, 67.32±11.92

kg, BMI 23.47±2.43). We did not control for graft type. 13 subjects received a hamstring autograft, 5 received a patellar tendon autograft, and 2 received an allograft.

Adolescent Healthy Controls: Participants in the control group were individuals enrolled in the ACL-RELAY study who had not experienced an ACL injury, were 15-17 years of age (middle adolescence), participated in high-level sports >50 hours per year, had no history of low back pain, and had no lower extremity injury (requiring physician management) or surgery in the year prior to data collection. As this group did not have a surgical limb, we utilized the preferred limb for comparison, consistent with previous work., defined as the limb that contacted the ground first on the majority of double leg jump tasks.[93] 20 subjects were included in this group (16.17±0.57 years, 2 males/18 females, 1.67±0.07 m, 61.09±11.86 kg, BMI 21.71±2.70).

Motion Analysis:

***Single-Leg Drop Landing Task*:** Kinematic data for the lower extremity and trunk were calculated using 3-dimensional motion analysis and embedded force platforms during a single-leg (SL) landing task on both the involved and uninvolved limbs, as previously described.[96,97] Motion analysis was performed utilizing a 12-camera three-dimensional motion analysis system (240 Hz, Motion Analysis Corp., Santa Rosa, CA, USA) with 4 embedded force plates (1200 Hz, AMTI, Watertown, MA, USA). The system tracked retroreflective markers attached to specific locations and anatomical landmarks on the upper extremities, lower extremities, and trunk of each subject by trained research personnel to determine joint centers and segment positions during the landing task. To perform the SL landing task, participants stood on a 31-cm box on the testing limb and were instructed to drop off the box and land on the same testing limb on a force plate. The period from initial contact (when the vertical ground reaction force first exceeded 10 N) to lowest center of mass was examined and defined as the landing phase. Three trials on each limb for each participant were recorded and analyzed.

***Data Processing*:** Coupling angles for two adjacent joints of the lower extremity and trunk were calculated using a vector coding technique described by Davis[22]. Angle-angle plots for the SL landing task were created using custom Matlab (Mathworks, MA, USA) for the lower extremity where the proximal joint was plotted on the y-axis and the distal joint was plotted on the x-axis. The coupling angle (CA) was calculated as the vector angle connecting two chronologically successive data points relative to the horizontal, per Equation 1 (Figure 15), where "*i*" is the percent of time of the "mth" trial of the dynamic movement of interest.[36,88,90] CA can range from 0 to 360 in order to preserve possible lost data if CA were compressed to 0 to 180.[36]

$$CA = \tan^{-1}\left(\frac{y_{m,i+1} - y_{m,i}}{x_{m,i+1} - x_{m,i}}\right)$$

Figure 15. Equation 1—Coupling angle calculation[36,88,90]

Angles are directional in nature so mean coupling angles ($\overline{CA}$) were computed using circular statistics from mean vertical ($\bar{y}_i$) and mean horizontal ($\bar{x}_i$) components for each percentage (i) of the dynamic movement (time normalized from 0-100%) of interest across trials (m), per Equations 2-4 (Figures 16-18).[36,88,90] Then, the circular standard deviation of the mean coupling angle was calculated and this is representative of movement variability.[36]

$$\bar{x}_i = \frac{1}{n}\sum \cos CA_{m,i}$$

Figure 16. Equation 2—Calculation of Mean Horizontal Component of Coupling Angle[36,88,90]

$$\bar{y}_i = \frac{1}{n}\sum \sin CA_{m,i}$$

Figure 17. Equation 3—Calculation of Mean Vertical Component of Coupling Angle[36,88,90]

$$\overline{CA} = \begin{cases} \arctan\left(\frac{\bar{y}_i}{\bar{x}_i}\right) & \text{if } \bar{x}_i > 0 \\ \arctan\left(\frac{\bar{y}_i}{\bar{x}_i}\right) & \text{if } \bar{x}_i < 0 \end{cases}$$

Figure 18. Equation 4—Calculation of Mean Coupling Angle[36,88,90]

Coupling Angles of Interest**:** Lower extremity coupling angles of interest are listed in Table 3.[22] These angles were chosen due to known differences between ACLR populations and uninjured populations cited in the current literature.[36]

Lower Extremity Coupling Angles of Interest	**Acronym**
Hip Flexion—Knee Flexion	HF-KF
Hip Flexion—Knee Abduction	HF-KA
Hip Flexion—Knee Rotation	HF-KR
Hip Adduction—Knee Flexion	HA-KF
Hip Adduction—Knee Abduction	HA-KA
Hip Adduction—Knee Rotation	HA-KR
Hip Rotation—Knee Flexion	HR-KF
Hip Rotation—Knee Abduction	HR-KA
Hip Rotation—Knee Rotation	HR-KR
Knee Flexion—Ankle Dorsiflexion	KF-AD
Knee Abduction—Ankle Dorsiflexion	KA-AD

Table 3. Lower Extremity Joint Coupling Angles of Interest

Statistical Analysis:

Descriptive Statistics: Height (m), weight (kg), body mass index (BMI), and time from surgery to testing (months) were compared between groups with one-way ANOVA with Bonferroni post-hoc comparisons.

Coupling Angles: The circular standard deviation of the mean coupling angle, representative of movement variability, was compared for each joint coupling of interest (Table 3) for the involved/preferred limb across groups using Kruskal Wallis test. Kruskal Wallis was chosen due to the presence of 3 groups and the non-parametric nature of the data. Significance was set *a priori* at $p<0.05$. For all significant findings, Mann Whitney U post-hoc tests were performed with significance set *a priori* at $p<0.0167$ per the Bonferroni correction method. Statistical analyses were performed using IBM SPSS Statistics (Armonk, NY, USA).

Results

No statistically significant difference between surgical groups (pACLR or Adolescent ACLR) was identified for time since surgery to testing. There was a statistical significance between the Pediatric ACLR and both the Adolescent ACLR and Healthy Control groups for age, height, weight, and BMI (all ≤ 0.001). However, there was no statistically significant difference between the Healthy Control and Adolescent ACLR groups for height, weight, or BMI (Table 4).

Group	**Pediatric ACLR**	**Adolescent ACLR**	**Healthy Controls**
n	11	20	20
Age (years)	11.54±1.69	16.99±0.60	16.17±0.57
Sex (M/F)	9/2	6/14	2/18
Graft Type	hamstring autograft	13- hamstring autograft 5- patellar tendon autograft 2- allograft	n/a
Time since surgery (months)	8.97±2.65	8.67±3.42	n/a
Height* (m)	1.50±0.16	1.69±0.11	1.67±0.07
Weight* (kg)	42.62±13.66	67.32±11.92	61.09±11.86
BMI*	17.63±2.77	23.47±2.43	21.71±2.70

Table 4. Participant Demographics

Group joint coordination variability results are outlined in Table 5 for the involved/preferred limb and Table 6 for the uninvolved/non-preferred limb. For the involved/preferred limb, between group differences were demonstrated for HF-KF (p=0.043), HR-KR (p=0.033), and KA-AD (p<0.001). For the uninvolved/non-preferred limb, between group differences were demonstrated for KA-AD only (p=0.002).

Coordination Variability	**Pediatric ACLR**	**Adolescent ACLR**	**Healthy Controls**	**p-value (Kruskal-Wallis)**
HF-KF	12.18 (6.76-17.71)	8.24 (6.10-10.39)	6.92 (2.76-11.08)	**0.043***
HF-KA	13.98 (1.27-26.70)	12.99 (8.74-17.23)	20.41 (13.97-26.86)	0.071
HF-KR	13.77 (7.28-20.26)	13.75 (9.61-17.88)	20.01 (10.36-29.66)	0.941
HA-KF	13.14 (8.25-18.02)	7.93 (5.82-10.03)	9.19 (4.89-13.49)	0.059
HA-KA	20.53 (7.21-33.85)	23.56 (15.16-31.97)	25.24 (15.76-34.72)	0.635
HA-KR	27.99 (16.83-39.16)	23.50 (16.65-30.35)	21.11 (13.00-29.23)	0.394
HR-KF	7.18 (3.79-10.56)	9.65 (7.5-11.80)	8.03 (4.91-11.15)	0.208
HR-KA	47.42 (19.15-75.69)	34.29 (18.41-50.17)	34.83 (17.05-52.61)	0.406
HR-KR	49.03 (17.05-80.98)	45.59 (21.56-69.62)	18.17 (12.75-23.60)	**0.033***
KF-AD	7.30 (5.27-9.32)	8.34 (5.14-11.54)	6.02 (4.34-7.71)	0.480
KA-AD	8.32 (5.54-11.09)	10.99 (7.93-14.05)	4.45 (3.47-5.42)	**<0.001***

Expressed as mean (95% Confidence Interval). P-value <0.05 considered significant.

Table 5. Joint Coordination Variability—Involved/Preferred Limb

Coordination Variability	**Pediatric ACLR**	**Adolescent ACLR**	**Healthy Controls**	**p-value (Kruskal-Wallis)**
HF-KF	7.46 (4.04-10.88)	7.15 (5.21-9.09)	4.94 (3.61-6.27)	p=0.128
HF-KA	15.96 (4.87-27.05)	14.45 (9.50-19.40)	13.05 (9.11-19.99)	p=0.857
HF-KR	16.62 (10.65-22.60)	15.29 (9.17-21.41)	17.34 (12.36-22.33)	p=0.558
HA-KF	10.68 (7.75-13.61)	11.19 (8.99-13.39)	8.87 (6.31-11.42)	p=0.129
HA-KA	20.08 (8.09-32.08)	27.95 (19.55-36.35)	19.52 (10.23-28.8)	p=0.173
HA-KR	23.68 (13.71-33.64)	36.23 (20.28-52.19)	19.39 (13.25-25.54)	p=0.228
HR-KF	9.55 (7.40-11.69)	8.07 (5.91-10.23)	7.80 (5.70-9.89)	p=0.251
HR-KA	93.54 (45.76-141.32)	40.77 (21.66-59.88)	37.87 (26.11-49.63)	p=0.061
HR-KR	58.16 (23.51-92.81)	37.72 (19.61-55.83)	30.51 (15.84-45.18)	p=0.304
KF-AD	6.88 (3.33-10.45)	8.14 (5.49-10.80)	6.71 (4.19-9.22)	p=0.750
KA-AD	6.72 (3.63-9.80)	9.14 (6.99-11.30)	4.99 (2.87-7.10)	**p=0.002***

Expressed as mean (95% Confidence Interval). P-value <0.05 considered significant.

Table 6. Joint Coordination Variability—Uninvolved/Non-preferred Limb

Results of Mann-Whitney U post-hoc tests for statistically significant findings are outlined in Table 7 and visualized in Figure 19. Significance set at p=0.0167 per the Bonferroni correction. For the involved/preferred limb, the Pediatric ACLR group differed from the Healthy Controls group in HR-KR (p=0.007) and KA-AD (p=0.005). The Adolescent ACLR group differed from the Healthy Controls group in KA-AD (p<0.001) on the involved/preferred limb. However, the Pediatric ACLR group and the

Adolescent ACLR group did not demonstrate any significant differences in the post-hoc variables assessed on the involved limb. On the uninvolved limb for KA-AD, the Adolescent ACLR group differed from the Healthy Controls (p<0.001), but no statistically significant differences were found between the Pediatric ACLR group and either the Adolescent ACLR group (p=0.095) or the Healthy Controls group (p=0.183).

Significant Coordination Variability	**Pediatric ACLR-Adolescent ACLR**	**Pediatric ACLR-Healthy Controls**	**Adolescent ACLR-Healthy Controls**
Inv HF-KF	p=0.338	p=0.032	p=0.056
Inv HR-KR	p=0.338	**p=0.007***	p=0.121
Inv KA-AD	p=0.298	**p=0.005***	**p<0.001***
Uninv KA-AD	p=0.095	p=0.183	**p<0.001***

Inv=Involved/preferred limb. Uninv=Uninvolved/non-preferred limb.

Table 7. Results of Mann-Whitney U Post Hoc Tests

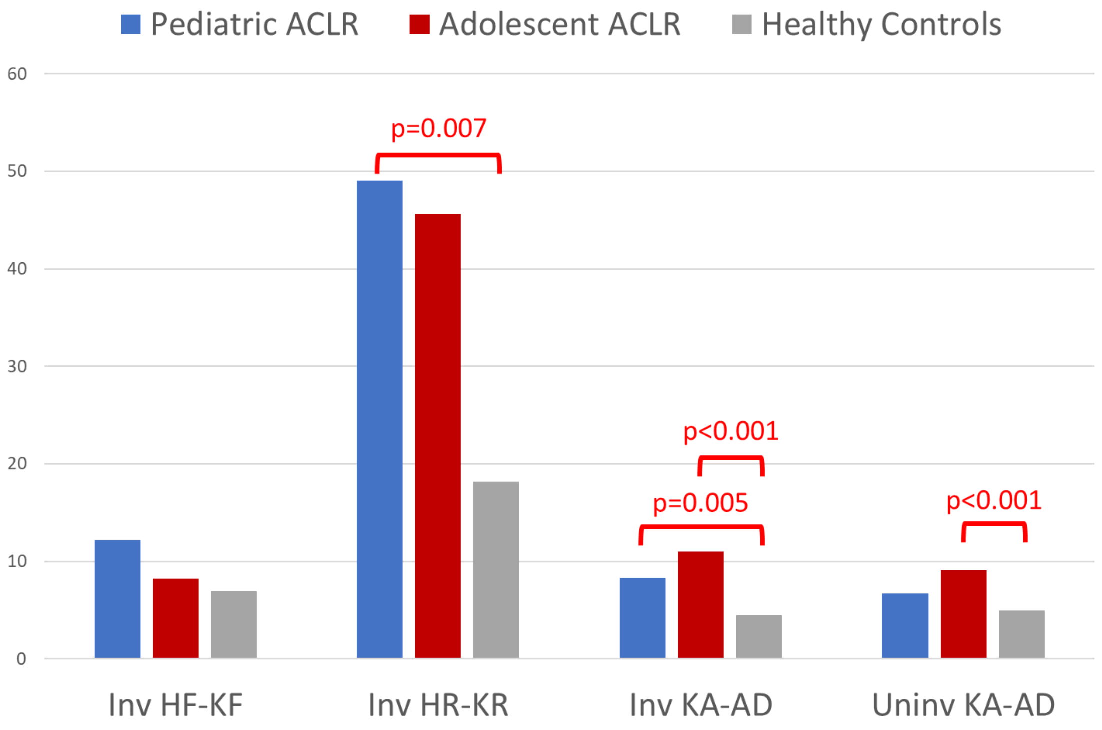


Figure 19. Results of Post Hoc Tests

Discussion

The purpose of the current work was to examine the lower extremity coordination of children following physeal-sparing ACL reconstruction during a dynamic single-limb task by analyzing lower extremity movement variability. We hypothesized that children following pACLR would demonstrate increased movement variability on the involved and uninvolved limbs as compared to the involved/preferred and uninvolved/non-preferred limbs of adolescents following ACLR and to adolescent healthy controls, respectively. A single-leg (SL) landing task was chosen as the dynamic movement examined due to known changes in SL landing mechanics demonstrated by the skeletally mature following ACLR, with these SL landing asymmetries being associated with self-reported function up to 2 years post-operatively.[96] Furthermore, the mechanism of an ACL injury is most typically an acceleration or deceleration event on a single limb,[40,41] such as with a SL land. Our hypothesis was partially supported: children following pACLR demonstrated increased movement variability as compared to adolescent healthy controls on the involved limb, specifically HR-KR and KA-AD, during the SL landing task. However, contrary to our hypothesis, lower extremity movement variability did not differ between the Pediatric ACLR and the Adolescent ACLR for any of the variables examined on either the involved or the uninvolved limbs. Interestingly, although we did not hypothesize regarding the Adolescent ACLR compared to the Healthy Controls, we found that the Adolescent ACLR group differed from the Adolescent Healthy Controls group for KA-AD on both limbs during the SL landing task.

According to the dynamical systems theory (DST), coordination is the process by which the redundant degrees of freedom, or multiple ways to perform a dynamic task, are controlled by “coordinative structures” to create an organized movement system capable of responding to the demands of the task at hand.[22,28,83] As such, variability in movement is considered a necessary component to a healthy motor system capable of adapting to its environment.[22,27,28,81] It has been proposed that there is an optimal amount of movement variability within a motor system that allows for balance between the need for stability (to ensure movement quality and reduce risk of injury) and flexibility (to respond to the demands of the ever-changing environment).[22,34] High variability in movement may be indicative of impaired neuromuscular control, and it has been speculated may leave an individual at risk of injury due to an inability to control movement when environmental demands are high.[30] Conversely, very low levels of variability is indicative of a "rigid" system, which has been proposed may leave an individual at risk of injury due to an inability to adapt to changes in the environment.[30]

This concept of "optimal movement variability" helps elucidate Leporace[84] and colleagues' findings that patients following an ACLR procedure demonstrated increased variability in gait as compared to healthy controls, indicative of a less controlled system likely due to neuromuscular compromise and proprioception deficits following surgical intervention. Conversely, subjects with ACL deficient knees who had not undergone a surgical reconstruction demonstrated reduced variability during gait indicative of a more rigid system, which could be due to the system restricting movement secondary to pain or fear due to mechanical instability in the knee.[84] Both scenarios indicate a movement system with reduced ability to respond to increased demands from the environment secondary to individual constraints to the dynamic system. Similarly, in the current study, both ACLR groups (pediatric and adolescent) demonstrated increased movement variability on the involved limb as compared to healthy controls, which may be indicative of neuromuscular compromise secondary to surgery. Specifically, the Pediatric ACLR group demonstrated increased HR-KR and KA-AD variability, while the Adolescent ACLR group demonstrated increased KA-AD variability.

Our findings—that children and adolescents demonstrate increased movement variability on the involved limb following ACLR procedures— are consistent with other previous work that has identified that individuals after ACLR demonstrate differences in joint coordination and movement variability that can persist for years.[22,30,84] Pollard, et al[30] reported that female soccer players following ACLR demonstrated significantly greater movement variability when compared to their uninjured counterparts during a side-step maneuver, suggestive of deficits in neuromuscular control during this dynamic movement often associated with ACL injury. Previous work had described how increased variability impacted the motor system's ability to perform consistent, dependable movements.[98] Thus, the authors of this study contended that increased variability of the ACLR limb during movement patterns consistent with known ACL injury may account for the increased risk of second injury identified in individuals following primary ACLR.[30] Gribbin, et al[29] examined hip and knee joint coordinative movement during walking and jogging in individuals following ACLR, and found that following ACLR subjects demonstrated increased movement variability indicative of a less controlled system on the surgical limb as compared to the nonsurgical limb. Similarly, Davis, et al[22] reported that individuals following ACLR demonstrated greater variability in hip-knee coordination during gait on both their surgical and non-surgical limbs when compared to uninjured individuals.[22]

Our findings are also consistent with previous work that examined lower extremity coupling variability during a single leg jump landing, a similar task to that performed in the current study. Blache, et al[99] identified that individuals following ACLR demonstrated increased coupling variability on the surgical limb between the hip and knee and between the knee and ankle compared to their contralateral knee and compared to healthy controls. Similarly, the Pediatric ACLR group in the current study demonstrated greater hip/knee and knee/ankle variability on the involved limb as compared to healthy controls, suggestive of a less stable coordination pattern on the ACLR limb. However, the Adolescent ACLR group demonstrated greater knee/ankle variability on the involved limb as compared to healthy controls, but no differences were found for hip/knee variability. Interestingly, the Adolescent ACLR group also demonstrated increased knee/ankle variability on the uninvolved limb as compared to healthy controls. It is unknown whether this is a bilateral adaptation/consequence of ACLR or if this existed prior to ACL injury and may represent a coordination pattern that increases risk of ACL injury. Future research should further explore this.

The current study is unique in that the target group is pediatric and underwent a surgical procedure to respect open physeal plates. When considering the skeletally immature population following ACLR, as in the current study, findings related to coordination and movement must be situated within the motor development and physical literacy literature given the ability of an injury to alter the lifelong motor trajectory of the child. These traumatic pediatric ACL injuries are occurring with increasing frequency during later childhood.[65] If we consider this timeframe in light of a commonly utilized analogy within motor development of the "motor development mountain," (Figure 20)[66] this occurs during a time when children are progressing from mastering fundamental motor skills[67,68] and are learning more transitional motor skills.[66,67,69] This timeframe also includes a critical timeframe and concept known as the "proficiency barrier,"[70] which refers to the level of fundamental motor skill development that is necessary to be able to apply these skills to sports and lifetime activities and remain active throughout life.[68–71] It is unknown how interrupting this natural progression with a traumatic injury—such as an ACL injury— right at the time when children should be overcoming the proficiency barrier will impact children's motor development. However, it has been demonstrated that almost 90% of children who fall below the proficiency barrier of motor skill development do not meet recommended moderate-to-vigorous physical activity guidelines.[70] This is particularly concerning as climbing the "motor development mountain" has been associated with long-term health benefits, while not successfully climbing the mountain has been associated with a sedentary lifestyle, increased hypokinetic disease and lifelong health consequences such as an increased risk of heart disease and type II diabetes.[68,71,72] In the current study, the Pediatric ACLR group demonstrated increased movement variability as compared to the Healthy Controls group but not as compared to the Adolescent ACLR group, and these differences were demonstrated on the involved limb only. These findings suggest impaired neuromuscular control on the involved limb secondary to surgical insult. However, from the current study design it is unclear how this may impact long-term motor development and lifelong health. Future work with a more longitudinal design or long-term follow up is recommended to elucidate this.

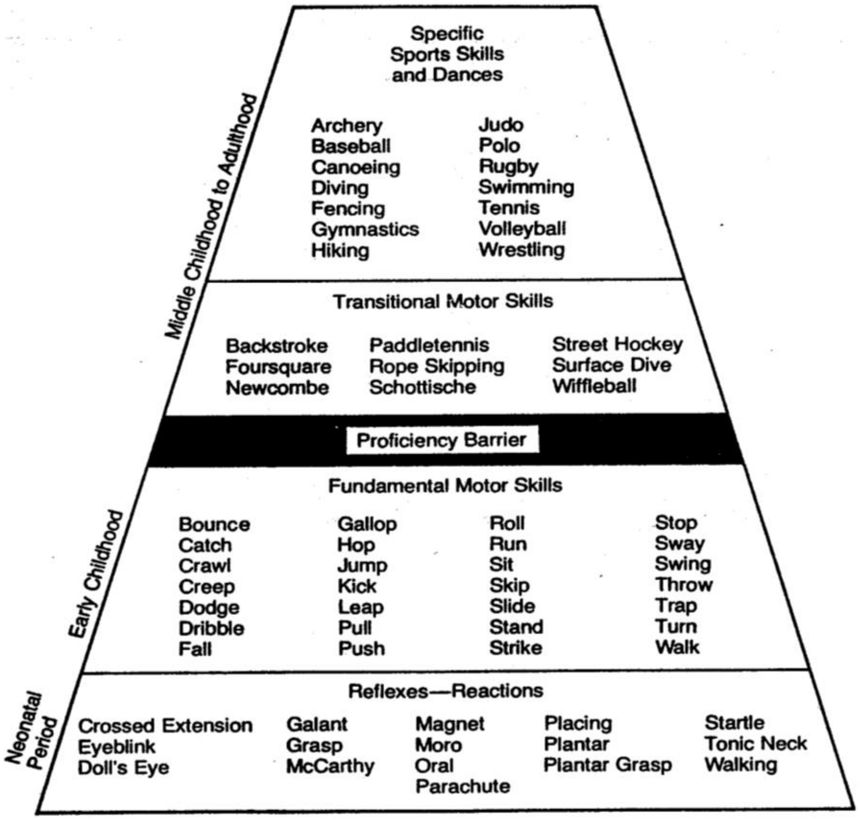


Figure 20. Clark’s Motor Development Mountain[66]

Along with the analogy of the motor development mountain comes the concept of physical literacy—the motivation, confidence, physical competence, knowledge, and understanding to be physically active for life.[73] The traumatic consequence of pACLR may be a reduced motor competence and a detrimental impact on the journey of movement—2 of the 4 pillars of physical literacy—which could propel a child into a negative spiral of disengagement with activity.[71,73] The negative spiral of disengagement, as outlined by Stodden et al.'s Model of Motor Competence and Physical Activity, (Figure 21)[71] results in an increased risk of obesity for these children and the myriad of poor health consequences that accompany an unhealthy weight.[70,71,74] Indeed, recent work by MacAlpine and colleagues[75] found that children and adolescents experience significant increases in their body mass index (BMI) in the first 2 years after ACLR. Thus, a better understanding of the impact of pACLR on a child's motor development and physical literacy is imperative to improving long-term health outcomes. From a broader perspective, future longitudinal work is needed that not only looks at the child's impact of the injury relative to a specific sport or return to sport, but examines the broader consequences of the injury on motor development trajectories across the lifespan. The current work, which demonstrated that ACLR procedures impact lower extremity coordination in children and adolescents, is a first-step in this critical work.

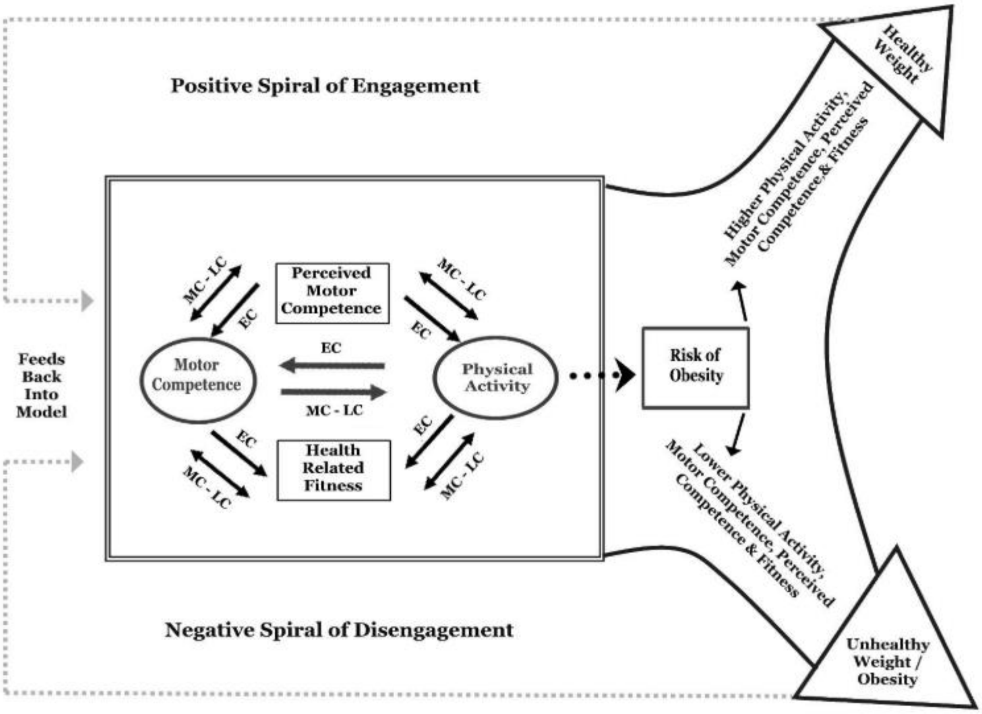


Figure 21. Stodden's Model of Motor Competence and Physical Activity[71]

Although not a direct measure of movement variability or coordination, incorporating a movement assessment within rehabilitative guidelines has been explored within a pediatric population following ACLR.[87] A group out of the Hospital for Special Surgery in New York developed a quality of movement assessment utilizing 2D technology and integrated it into their rehabilitative guidelines. The movement assessment evaluated criteria such as movement strategy, dynamic alignment, symmetry, depth, and control, and could be considered a rudimentary assessment of achieving an optimal level of movement variability to demonstrate a stable yet flexible motor control system. Using this process in a sample of 42 children, 93% of their subjects were able to return to their primary sport of interest, and the rate of second injury was reduced to 7.6%.[87] Furthermore, individuals in their study who went back to sport at greater than 12 months post-operatively had a reduced rate of 2nd injury as compared to those who returned to sport at less than 12 months.[87] Although still a relatively small sample from which to make widespread conclusions, the importance of a greater understanding of neuromuscular control, coordination, and movement variability in children following pACLR in order to improve rehabilitation and outcomes in this at-risk patient population is abundantly evident.

To our knowledge, this is the first study to examine the inter-joint movement variability of children following pALCR. As mentioned previously, outcomes following pACLR are suboptimal. Recent findings have led to a shift in rehabilitation recommendations to increase focus on movement quality. Despite symmetry between limbs on strength and performance measures (typically single leg [SL] hop tests) being a commonly recognized criteria for the clearance to return to sports participation following ACLR, recent work has identified that SL hop distance symmetry is not an adequate measure of knee function or readiness to return-to-sport in adolescents after ACLR.[100] Indeed, the overall message of the International Olympic Committee's (IOC) recent Consensus Statement regarding the management of pediatric ACL injuries recommends a "focus on evaluating the quality of movements during single leg hop testing, instead of the leg symmetry index measures" commonly utilized with the skeletally mature population.[7] Our current findings support this recommendation. Children after ACLR were able to successfully complete a SL landing task on their involved limb. However, they did so with increased inter-joint movement variability as compared to the preferred limb of healthy controls, indicative of persistent neuromuscular compromise which may put the movement system at risk of further injury. These neuromuscular deficits must be addressed within rehabilitation to ensure the child is able to successfully climb the motor development mountain and attain the physical literacy necessary for lifelong health and well-being.

Limitations

The current work is not without limitations. The pediatric ACLR group is a relatively small sample size, and overall this work would benefit from further analysis with a larger group and more robust statistical comparisons to improve generalizability of findings. Also, only 3 trials on each limb for each participant were included due to most subjects only having 3 acceptable trials with clear camera view of markers and an acceptable, controlled landing on a single force plate. The Adolescent ACLR and Healthy Controls group each included 20 participants, for which 3 trials has been demonstrated to be adequate to compare within-person variability between groups with a large effect size (0.8).[36,101] However, the Pediatric ACLR group was comprised of only 11 participants, and thus more trials or participants would be advised.

Two vector coding methods have been proposed to calculate variability, and, as outlined by Davis, et al,[36] each method seems to have inherent limitations and each has the potential to be affected by statistical artifacts when circular statistics are applied. Due to this, it is unknown at present which method is ideal.

The current work also only examined variability between groups on the surgical/preferred limb or the non-surgical/non-preferred limb, respectively. A further analysis of inter-joint movement that examines joint excursion and classifies coordination patterns[36,90] would provide a more complete understanding of coordination adaptations in these populations. Including inter-limb comparisons within participant groups would further enhance our comprehension. Furthermore, the inclusion of a pediatric healthy control group would allow for a greater understanding of any deviations from age-normative or typical movement variability within the pediatric ACLR group.

A longitudinal study design or long-term follow up would be recommended to clarify how movement variability changes over time and how it relates to motor development and 2nd injury risk. This would also allow for a better understanding of the long-term impact of changes in movement variability on motor development.

Conclusions

Children after pediatric ACLR and adolescents after ACLR demonstrate increased movement variability on the involved limb as compared to the preferred limb of adolescent healthy controls during a SL dynamic landing task. Increased movement variability may be indicative of neuromuscular compromise within the movement system secondary to the surgical procedure, and this could potentially increase risk of injury. This may also impact a child's ability to develop the motor competence and physical literacy needed for lifelong health and well-being. Further research with a larger sample size and more longitudinal approach is needed to further elucidate these findings.

Chapter 5. Results and Discussion

Results

No statistically significant difference between surgical groups (pACLR or Adolescent ACLR) was identified for time since surgery to testing ($p>0.05$). There was a statistical significance between the Pediatric ACLR and both the Adolescent ACLR and Healthy Control groups for height, weight, and BMI (all ≤ 0.001). However, there was no statistically significant difference between the Healthy Control and Adolescent ACLR groups for height, weight, or BMI (all $p>0.05$) (Table 8).

Group	**Pediatric ACLR**	**Adolescent ACLR**	**Healthy Controls**
n	11	20	20
Age (years)	11.54±1.69	16.99±0.60	16.17±0.57
Sex (M/F)	9/2	6/14	2/18
Time since surgery (months)	8.97±2.65	8.67±3.42	n/a
Height* (m)	1.50±0.16	1.69±0.11	1.67±0.07
Weight* (kg)	42.62±13.66	67.32±11.92	61.09±11.86
BMI*	17.63±2.77	23.47±2.43	21.71±2.70

Table 8. Participant Demographics

Group joint coordination variability results are outlined in Table 9 for the involved/preferred limb and Table 10 for the uninvolved/non-preferred limb. For the involved/preferred limb, between group differences were demonstrated for HF-KF (p=0.043), HR-KR (p=0.033), and KA-AD (p<0.001). For the uninvolved/non-preferred limb, between group differences were demonstrated for KA-AD only (p=0.002).

Coordination Variability	**Pediatric ACLR**	**Adolescent ACLR**	**Healthy Controls**	**p-value (Kruskal-Wallis)**
HF-KF	12.18 (6.76-17.71)	8.24 (6.10-10.39)	6.92 (2.76-11.08)	**0.043***
HF-KA	13.98 (1.27-26.70)	12.99 (8.74-17.23)	20.41 (13.97-26.86)	0.071
HF-KR	13.77 (7.28-20.26)	13.75 (9.61-17.88)	20.01 (10.36-29.66)	0.941
HA-KF	13.14 (8.25-18.02)	7.93 (5.82-10.03)	9.19 (4.89-13.49)	0.059
HA-KA	20.53 (7.21-33.85)	23.56 (15.16-31.97)	25.24 (15.76-34.72)	0.635
HA-KR	27.99 (16.83-39.16)	23.50 (16.65-30.35)	21.11 (13.00-29.23)	0.394
HR-KF	7.18 (3.79-10.56)	9.65 (7.5-11.80)	8.03 (4.91-11.15)	0.208
HR-KA	47.42 (19.15-75.69)	34.29 (18.41-50.17)	34.83 (17.05-52.61)	0.406
HR-KR	49.03 (17.05-80.98)	45.59 (21.56-69.62)	18.17 (12.75-23.60)	**0.033***
KF-AD	7.30 (5.27-9.32)	8.34 (5.14-11.54)	6.02 (4.34-7.71)	0.480
KA-AD	8.32 (5.54-11.09)	10.99 (7.93-14.05)	4.45 (3.47-5.42)	**<0.001***

Expressed as mean (95% Confidence Interval). P-value <0.05 considered significant.

Table 9. Joint Coordination Variability—Involved/Preferred Limb

Coordination Variability	**Pediatric ACLR**	**Adolescent ACLR**	**Healthy Controls**	**p-value (Kruskal-Wallis)**
HF-KF	7.46 (4.04-10.88)	7.15 (5.21-9.09)	4.94 (3.61-6.27)	p=0.128
HF-KA	15.96 (4.87-27.05)	14.45 (9.50-19.40)	13.05 (9.11-19.99)	p=0.857
HF-KR	16.62 (10.65-22.60)	15.29 (9.17-21.41)	17.34 (12.36-22.33)	p=0.558
HA-KF	10.68 (7.75-13.61)	11.19 (8.99-13.39)	8.87 (6.31-11.42)	p=0.129
HA-KA	20.08 (8.09-32.08)	27.95 (19.55-36.35)	19.52 (10.23-28.8)	p=0.173
HA-KR	23.68 (13.71-33.64)	36.23 (20.28-52.19)	19.39 (13.25-25.54)	p=0.228
HR-KF	9.55 (7.40-11.69)	8.07 (5.91-10.23)	7.80 (5.70-9.89)	p=0.251
HR-KA	93.54 (45.76-141.32)	40.77 (21.66-59.88)	37.87 (26.11-49.63)	p=0.061
HR-KR	58.16 (23.51-92.81)	37.72 (19.61-55.83)	30.51 (15.84-45.18)	p=0.304
KF-AD	6.88 (3.33-10.45)	8.14 (5.49-10.80)	6.71 (4.19-9.22)	p=0.750
KA-AD	6.72 (3.63-9.80)	9.14 (6.99-11.30)	4.99 (2.87-7.10)	**p=0.002***

. Expressed as mean (95% Confidence Interval). P-value <0.05 considered significant.

Table 10. Joint Coordination Variability—Uninvolved/Non-preferred Limb

Results of Mann-Whitney U post-hoc tests for statistically significant findings are outlined in Table 11. Significance set at p=0.0167 per the Bonferroni correction. For the involved/preferred limb, the Pediatric ACLR group differed from the Healthy Controls group in HR-KR (p=0.007) and KA-AD (p=0.005). The Adolescent ACLR group differed from the Healthy Controls group in KA-AD (p<0.001) on the involved/preferred limb. However, the Pediatric ACLR group and the Adolescent ACLR group did not demonstrate any significant differences in the post-hoc variables assessed on the involved limb. On the uninvolved limb for KA-AD, the Adolescent ACLR group differed from the Healthy Controls (p<0.001), but no statistically significant differences were found between the Pediatric ACLR group and either the Adolescent ACLR group (p=0.095) or the Healthy Controls group (p=0.183).

Significant Coordination Variability	**Pediatric ACLR-Adolescent ACLR**	**Pediatric ACLR-Healthy Controls**	**Adolescent ACLR-Healthy Controls**
Inv HF-KF	p=0.338	p=0.032	p=0.056
Inv HR-KR	p=0.338	**p=0.007***	p=0.121
Inv KA-AD	p=0.298	**p=0.005***	**p<0.001***
Uninv KA-AD	p=0.095	p=0.183	**p<0.001***

Inv=Involved/preferred limb. Uninv=Uninvolved/non-preferred limb.

Table 11. Results of Mann-Whitney U Post-hoc Tests

Discussion

The purpose of the current work was to examine the lower extremity coordination of children following physeal-sparing ACL reconstruction during a dynamic single-limb task by analyzing lower extremity movement variability. We hypothesized that children following pACLR would demonstrate increased movement variability on the involved and uninvolved limbs as compared to the involved/preferred and uninvolved/non-preferred limbs of adolescents following ACLR and to adolescent healthy controls, respectively. A single-leg (SL) landing task was chosen as the dynamic movement examined due to known changes in SL landing mechanics demonstrated by the skeletally mature following ACLR, with these SL landing asymmetries being associated with self-reported function up to 2 years post-operatively.[96] Furthermore, the mechanism of an ACL injury is most typically an acceleration or deceleration event on a single limb,[40,41] such as with a SL land. Our hypothesis was partially supported: children following pACLR demonstrated increased movement variability as compared to adolescent healthy controls on the involved limb, specifically HR-KR and KA-AD, during the SL landing task. However, contrary to our hypothesis, lower extremity movement variability did not differ between the Pediatric ACLR and the Adolescent ACLR for any of the variables examined on either the involved or the uninvolved limbs. Interestingly, although we did not hypothesize regarding the Adolescent ACLR compared to the Healthy Controls, we found that the Adolescent ACLR group differed from the Adolescent Healthy Controls group for KA-AD on both limbs during the SL landing task.

Dynamical systems theory (DST) provides a framework to investigate the coordination and movement variability between lower extremity joints and may improve our understanding of the discrete biomechanical factors identified and related to ACL injury and poor outcomes following ACLR.[22] DST has its foundations in work from Bernstein dating back to 1967.[28,32,37] Bernstein introduced the concept of “redundant degrees of freedom” (DOF) within a movement system, or multiple ways to perform a dynamic task.[22,28] Coordination is the process by which these multiple DOF are controlled by “coordinative structures” to create an organized movement system capable of responding to the demands of the task at hand.[22,28,83] As such, variability in movement is considered a necessary component to a healthy motor system capable of adapting to its environment.[22,27,28,81] It has been proposed that there is an optimal amount of movement variability within a motor system that allows for balance between the need for stability (to ensure movement quality and reduce risk of injury) and flexibility (to respond to the demands of the ever-changing environment).[22,34] High variability in movement may be indicative of impaired neuromuscular control, and may leave an individual at risk of injury due to an inability to control movement when environmental demands are high.[30] Conversely, very low levels of variability is indicative of a “rigid” system, which may leave an individual at risk of injury due to an inability to adapt to changes in the environment.[30]

This concept of “optimal movement variability” helps elucidate Leporace and colleagues’ findings that patients with ACL deficient knees who had not undergone a surgical reconstruction demonstrated reduced variability during gait indicative of a more rigid system, whereas patients following an ACLR procedure demonstrated increased variability in gait as compared to healthy controls.[84] The authors discussed that this may be due to overall movement system restricting movement in the ACL deficient group secondary to pain or fear as a result of the mechanical instability in the knee, whereas the ACLR group demonstrated increased variability indicative of a less controlled system secondary to neuromuscular compromise and proprioception deficits following the surgical intervention.[84] Both scenarios indicate a movement system with reduced ability to respond to increased demands from the environment secondary to individual constraints to the dynamic system. Similarly, in the current study, both ACLR groups (pediatric and adolescent) demonstrated increased movement variability on the involved limb as compared to healthy controls, which may be indicative of neuromuscular compromise secondary to surgery. Specifically, the Pediatric ACLR group demonstrated increased HR-KR and KA-AD variability, while the Adolescent ACLR group demonstrated increased KA-AD variability.

Our findings—that children and adolescents demonstrate increased movement variability on the involved limb following ACLR procedures— are consistent with previous work that has identified that individuals after ACLR demonstrate differences in joint coordination and movement variability that can persist for years.[22,30,84] Pollard, et al compared lower extremity coordination patterns by assessing inter-joint movement variability during a side-step cutting maneuver—a movement often associated with non-contact ACL injuries—in female soccer players who had and had not experienced an ACL injury and ACLR procedure.[30] Athletes following ACLR demonstrated significantly greater movement variability when compared to their uninjured counterparts, which the authors concluded was indicative in changes to neuromuscular control and which they postulated may account for the increased risk of second injury and incidence of joint degradation (osteoarthritis) identified in individuals following primary ACLR.[30] Gribbin,[29] et al examined hip and knee joint coordinative movement during walking and jogging in individuals following ACLR, and found that following ACLR subjects demonstrated increased movement variability indicative of a less controlled system on the surgical limb as compared to the nonsurgical limb. Similarly, Davis, et al[22] reported that individuals following ACLR demonstrated greater variability in hip-knee coordination during gait on both their surgical and non-surgical limbs when compared to uninjured individuals.[22]

Our findings are also consistent with previous work that examined lower extremity coupling variability during a single leg jump landing, a similar task to that performed in the current study. Blache, et al[99] identified that individuals following ACLR demonstrated increased coupling variability on the surgical limb between the hip and knee and between the knee and ankle compared to their contralateral knee and compared to healthy controls. Similarly, the Pediatric ACLR group demonstrated greater hip/knee and knee/ankle variability on the involved limb as compared to healthy controls, suggestive of a less stable coordination pattern on the ACLR limb. However, the Adolescent ACLR group demonstrated greater knee/ankle variability on the involved limb as compared to healthy controls, but no differences were found for hip/knee variability. Interestingly, the Adolescent ACLR group also demonstrated increased knee/ankle variability on the uninvolved limb as compared to healthy controls. It is unknown whether this is a bilateral adaptation/consequence of ACLR or if this existed prior to ACL injury and may represent a coordination pattern that increases risk of ACL injury. Future research should further explore this.

The current study is unique in that the target group is pediatric and underwent a surgical procedure to respect open physeal plates. When considering the skeletally immature population following ACLR, as in the current study, findings related to coordination and movement must be situated within the motor development and physical literacy literature given the ability of an injury to alter the lifelong motor trajectory of the child. These traumatic pediatric ACL injuries are occurring with increasing frequency during later childhood.[65] If we consider this timeframe in light of a commonly utilized analogy within motor development of the “motor development mountain,”[66] this occurs during a time when children are progressing from mastering fundamental motor skills[67,68] and are learning more transitional motor skills.[66,67,69] This timeframe also includes a critical timeframe and concept known as the “proficiency barrier,”[70] which refers to the level of fundamental motor skill development that is necessary to be able to apply these skills to sports and lifetime activities and remain active throughout life.[68–71] It is unknown how interrupting this natural progression with a traumatic injury—such as an ACL injury— right at the time when children should be overcoming the proficiency barrier will impact children’s motor development. However, it has been demonstrated that almost 90% of children who fall below the proficiency barrier of motor skill development do not meet recommended moderate-to-vigorous physical activity guidelines.[70] This is particularly concerning as climbing the “motor development mountain” has been associated with long-term health benefits, while not successfully climbing the mountain has been associated with a sedentary lifestyle, increased hypokinetic disease and lifelong health consequences such as an increased risk of heart disease and type II diabetes.[68,71,72] In the current study, the Pediatric ACLR group demonstrated increased movement variability as compared to the Healthy Controls group but not as compared to the Adolescent ACLR group, and these differences were demonstrated on the involved limb only. These findings suggest impaired neuromuscular control on the involved limb secondary to surgical insult. However, from the current study design it is unclear how this may impact long-term motor development and lifelong health. Future work with a more longitudinal design or long-term follow up is recommended to elucidate this.

Along with the analogy of the motor development mountain comes the concept of physical literacy—the motivation, confidence, physical competence, knowledge, and understanding to be physically active for life.[73] Pediatric ACLR could adversely impact two of the four “pillars” of physical literacy[73] 1.) movement competencies—as previously explored in relation to the motor development mountain, and 2.) the journey of movement—a traumatic event is often defining and could affect an individual’s psychological relationship with activity. The traumatic consequence of pACLR may be a reduced motor competence and a detrimental impact on the journey of movement, propelling a child into a negative spiral of disengagement with activity.[71] The negative spiral of disengagement, as outlined by Stodden et al.’s Model of Motor Competence and Physical Activity,[71] results in an increased risk of obesity for these children and the myriad of poor health consequences that accompany an unhealthy weight.[70,71,74] Indeed, recent work by MacAlpine and colleagues[75] found that children and adolescents experience significant increases in their body mass index (BMI) in the first 2 years after ACLR. Thus, a better understanding of the impact of pACLR on a child’s motor development and physical literacy is imperative to improving long-term health outcomes. From a broader perspective, future longitudinal work is needed that not only looks at the child’s impact of the injury relative to a specific sport or return to sport, but examines the broader consequences of the injury on motor development trajectories across the lifespan.

The current work, which demonstrated that ACLR procedures impact lower extremity coordination in children and adolescents, is a first-step in this critical work.

Although not a direct measure of movement variability or coordination, incorporating a movement assessment within rehabilitative guidelines has been explored within a pediatric population following ACLR.[87] A group out of the Hospital for Special Surgery in New York developed a quality of movement assessment utilizing 2D technology and integrated it into their rehabilitative guidelines. The movement assessment evaluated criteria such as movement strategy, dynamic alignment, symmetry, depth, and control, and could be considered a rudimentary assessment of achieving an optimal level of movement variability to demonstrate a stable yet flexible motor control system. Using this process in a sample of 42 children, 93% of their subjects were able to return to their primary sport of interest, and the rate of second injury was reduced to 7.6%. Furthermore, individuals in their study who went back to sport at greater than 12 months post-operatively had a reduced rate of 2nd injury as compared who returned to sport at less than 12 months.[87] Although still a relatively small sample from which to make widespread conclusions, the importance of a greater understanding of neuromuscular control, coordination, and movement variability in children following pACLR in order to improve rehabilitation and outcomes in this at-risk patient population is abundantly evident.

To our knowledge, this is the first study to examine the inter-joint movement variability of children following pALCR. As mentioned previously, outcomes following pACLR are suboptimal. Recent findings have led to a shift in rehabilitation recommendations to increase focus on movement quality. Despite symmetry between limbs on strength and performance measures (typically single leg [SL] hop tests) being a commonly recognized criteria for the clearance to return to sports participation following ACLR, recent work has identified that SL hop distance symmetry is not an adequate measure of knee function or readiness to return-to-sport in adolescents after ACLR.[100] Indeed, the overall message of the International Olympic Committee's (IOC) recent Consensus Statement regarding the management of pediatric ACL injuries recommends a "focus on evaluating the quality of movements during single leg hop testing, instead of the leg symmetry index measures" commonly utilized with the skeletally mature population.[7] Our current findings support this recommendation. Children after ACLR were able to successfully complete a SL landing task on their involved limb. However, they did so with increased inter-joint movement variability as compared to the preferred limb of healthy controls, indicative of persistent neuromuscular compromise which may increase risk of future injury. These neuromuscular deficits must be addressed within rehabilitation to ensure the child is able to successfully climb the motor development mountain and attain the physical literacy for lifelong health and well-being.

Conclusions

Children after pediatric ACLR and adolescents after ACLR demonstrate increased movement variability on the involved limb as compared to the preferred limb of adolescent healthy controls during a SL dynamic landing task. Increased movement variability may be indicative of neuromuscular compromise within the movement system secondary to the surgical procedure and may increase risk of future injury. This may impact a child’s ability to develop the motor competence and physical literacy needed for lifelong health and well-being. Further research with a larger sample size and more longitudinal approach is needed to further elucidate these findings.

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