THE EFFECTS OF A PEDIATRIC ACL INJURY PREVENTION PROGRAM

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ABSTRACT

LINDSAY JORDAN DISTEFANO: The Effects of a Pediatric ACL Injury Prevention Program

(Under the direction of Darin A. Padua)

Implementing an ACL injury prevention program to athletes prior to the ages of highest injury risk may result in reduced ACL injury rates and osteoarthritis development. There is limited knowledge regarding whether this age group can modify lower extremity biomechanics, balance ability, and performance after completing an injury prevention program or if age-specific training is required. The purpose of this investigation was to compare the effects of a traditional and a pediatric-specific ACL injury prevention program on lower extremity biomechanics, balance ability, and jump performance. A total of 65 youth soccer athletes (Males: n=38, mass=34.2±5.4 kg, height=143.1±6.3 cm, age=10±1 years; Females: n=27, mass=33.8±5.4 kg, height=141.0±6.6 cm) volunteered to participate. Teams were cluster-randomized to either a pediatric or traditional injury prevention program, or a control group. Teams performed their respective program as part of their normal warm-up routine. Balance ability, vertical jump performance, and lower extremity biomechanics during anticipated and unanticipated sidestep cutting tasks were assessed before and after an intervention period. Change scores were calculated from the two testing sessions. The pediatric program (Change Mean±SD: Anticipated: 7.73±10.71°; Unanticipated: 7.98±11.93°) reduced the amount of tibial external rotation at initial ground contact during the anticipated ($F_{(2,62)}$=3.79, p=0.03) and the unanticipated ($F_{(2,62)}$=6.92, p=0.002) tasks compared to the control group (Anticipated: -0.35±7.76°;Unanticipated: -3.06±6.18°) after the intervention period. Anterior-posterior time-to-stabilization decreased after the traditional program (Change Mean±SD=-0.92±0.49) compared to the control group (-0.49±0.59) ($F_{(2,60)}$=6.34, p=0.003). The traditional program increased vertical jump height (1.70±2.80) compared to the control group (0.20±0.20)($F_{(2,61)}$=3.45, p=0.04). Youth athletes can improve dynamic balance ability and vertical jump height after completing an injury prevention program with specific exercises targeting balance and vertical jumps. The injury prevention program designed specifically for a preadolescent population modified lower extremity biomechanics, which suggests athletes under 12 years of age can change potential neuromuscular risk factors for injury with specialized training.

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INTRODUCTION

1.1 The Problem of ACL Injuries

Over three million youth are currently registered to take part in organized soccer within the United States and participation grows by approximately 20% every year.(1) Unfortunately, increasing levels of sport participation means that more youth are vulnerable to sport injury. Injuries in youth sports, such as soccer, can be especially problematic because they can decrease children's future involvement in physical activity, which may result in poor long-term health.(2) Nearly 40% of the 6.8 million annual injuries attributed to sport and recreation occur to the lower extremity, with 50% of these injuries being sprains or strains.(3) A common lower extremity sports injury is a sprain or tear of the anterior cruciate ligament (ACL), which occurs approximately 200,000 times in the United States each year with an associated cost of over $3 billion.(4, 5)

ACL injuries are not only associated with high financial costs, but also with short and long-term disability. Osteoarthritis is a common condition that limits daily functioning,(6) and the onset of osteoarthritis at an early age may result in life-long disability.(7) Lohmander *et al.* (2004) indicated that 80% of female soccer players with an ACL injury showed radiographic signs of osteoarthritis development, and over 50% of these players developed radiographic osteoarthritis in the involved knee only 12 years after surgery, regardless of treatment.(7) These consequences demonstrate the immediate need for effective ACL injury prevention, especially in young athletes.

1.2 Current State of ACL Injury Prevention

The majority of ACL injuries occur due to a “non-contact” mechanism with no direct contact made between the individual and another player or object.(4, 8) A non-contact ACL injury usually occurs while an individual is trying to rapidly decelerate during a landing or cutting maneuver.(9-13) Risk factors for a non-contact ACL injury appear to be multifaceted and include a variety of environmental, anatomical, hormonal, and neuromuscular characteristics.(14) Neuromuscular risk factors are a primary area of focus for ACL injury prevention programs because they can be modified through intervention in contrast with the other types of risk factors. These neuromuscular risk factors include balance,(15) lower extremity muscle strength,(16-20) and movement patterns during athletic maneuvers.(21-23) Landing or cutting with limited knee flexion can result in excessive anterior tibial shear force from the quadriceps muscle, which can damage the ACL.(22-28) Combined excessive lower extremity rotation and knee valgus also place the ACL at a high risk for injury.(29, 30) Modifying these risk factors is emphasized in most ACL injury prevention programs and may have great potential for reducing ACL injury rates.

Neuromuscular ACL injury prevention programs focus on minimizing ACL loading by trying to increase knee flexion and decrease knee valgus, tibial rotation, and anterior tibial shear force during events associated with non-contact ACL injury. There is moderate evidence that supports the use of neuromuscular ACL injury prevention programs to change potential risk factors(31-40) and reduce ACL injury rates.(19, 40-45) Observing injury rates is critical for determining if ACL injury prevention is possible, but it is also necessary to understand how these programs work by evaluating potential neuromuscular risk factor improvement. Neuromuscular training programs have successfully modified movement patterns by increasing knee flexion angles,(33, 35, 46) altering hip adduction and rotation angles, and decreasing vertical ground reaction forces.(32, 36, 37, 39, 46-51) ACL injury prevention programs have also been shown to improve balance, muscle activity, and strength in both high school and college athletes.(32, 33, 37, 52-55)

There are limitations with the previous ACL injury prevention program investigations. First, all of the previous studies evaluating the effects of an ACL injury prevention program have compared lower extremity kinematics and kinetics during a landing task. While ACL injuries commonly occur during a landing, this mechanism of injury only accounts for a small percentage of ACL injuries in soccer.(56, 57) The more common mechanism of injury in soccer appears to be due to cutting or changing direction.(58) Cowley et al.(59) demonstrated greater amounts of knee valgus in soccer players during a cutting task compared to a drop vertical jump. A second limitation is that while information about how individuals move during an anticipated cutting task is beneficial, it does not replicate what actually occurs during sport and most likely during an injury.(60-62) Injuries often occur when an individual is knocked off balance or has to make a sharp change of direction.(58) Therefore, evaluating the changes occurring in lower extremity kinematics and kinetics using an unanticipated cutting task, may enhance our ability to understand the potential that an ACL injury prevention program has to reduce injury risk in soccer.

Females are 1.4-4.6 times more likely to sustain an ACL injury compared to males in similar sports.(4) Several studies have observed sex differences in lower extremity kinematics and kinetics during an anticipated sidestep cutting task, which may provide some explanation for the discrepancy in injury rates.(17, 63-65) These findings support the use of a sidestep cutting task to evaluate differences in movement patterns between populations, however, the majority of these studies and previously discussed work that studied landing patterns evaluate tasks that are anticipated, or planned. As a result of these conclusions, several studies have included unanticipated cutting tasks into their laboratory testing protocols. The general consensus is that unanticipated tasks result in greater amounts of neuromuscular risk factors for injury, such as increased knee joint loading, decreased initial knee flexion, increased knee flexion and valgus moments, and increased amounts of knee valgus compared with anticipated movements.(60-62, 66)

The most common way to incorporate unanticipated cutting tasks into a laboratory based testing protocol is to use a light timing system.(60, 62, 65, 66) This requires asking participants to run toward a force plate, and trigger the light system, which causes an arrow or a light to be displayed informing the participant to move in a specific direction. This method does cause reactive movements, but the task is still not realistic to a game scenario.(61) A common maneuver in sports, such as soccer, is to evade or mark an opponent. McLean et al.(61) addressed this limitation by using a stationary skeleton to simulate the presence of a "defensive opponent" while the participants performed the cutting task. The authors concluded that the presence of a simulated opponent resulted in increases in medial ground reaction forces, hip flexion, hip abduction, knee flexion, and knee valgus compared with the sidestep cutting condition with no opponent present. This study was progress in the ability to make laboratory based testing more realistic, however, the "defensive opponent" was stationary and predictable. Using a live model as the opponent to cause the participants to decide which direction to move is a logical progression for simulating real game and injury scenarios.

Secondly, nearly all of the research investigating the effects of ACL injury prevention training on neuromuscular factors has been performed in high school and college athletes. There is only one study that has tried to modify neuromuscular risk factors in children under 12 years old with an injury prevention program and failed to see positive changes.(38) Thus, it is not clear if the ACL injury prevention training guidelines used in a high school or college population will have a positive effect in a pediatric population.

1.3 Potential for ACL Injury Prevention in Pediatric Athletes

ACL injuries are most common among individuals between the ages of 16-18 years old, but the frequency of ACL injury increases steadily starting in 11 and 12 year olds.(67) Reducing risk factors for ACL injury before children reach the ages at greatest risk for injury may enhance the potential for reducing injuries. Furthermore, while injuries are relatively uncommon at young ages under 12 years old compared with the later years of adolescence, but an ACL injury in this population presents a complicated dilemma for health care professionals because these individuals are skeletally immature. There are mixed opinions on the best treatment choice in this population because conservative treatment may cause further joint damage and decreased physical activity levels.(68, 69) The other option is surgical treatment, but this treatment is technically difficult and may result in iatrogenic growth disturbances due to physeal damage.(68, 70, 71) These findings present further rationale for preventing ACL injuries, especially in a young population.

Previous research demonstrates potential neuromuscular risk factors for ACL injury exist in children as young as 10 years old, but few studies have thoroughly evaluated these factors in this population or between sexes.(72-74) These neuromuscular risk factors are usually evaluated during landing or cutting tasks because these movements are associated with ACL injury. Interestingly, several neuromuscular injury risk factors, such as limited sagittal plane motion, lateral leg movements, and toeing-out during landing and cutting tasks are also considered developmental difficulties during the acquisition of fundamental motor skills.(75, 76) Typically, it is assumed that children will attain mastery of fundamental motor skills, such as landing and cutting, by late childhood (10-12 years old).(75, 76) Late childhood is considered to be a critical period for fundamental motor skill refinement and motor development,(75-77) as children do not master complex motor skills until they reach approximately 10-12 years old.(78) At this age, growth is fairly steady and gradual, resulting in an ideal environment for children to develop coordination and neuromuscular skill.(79) Unfortunately, many children still do not attain mastery of fundamental motor skills, and this failure may be because of common public assumptions that motor skill learning is automatic, and that teaching of these skills is not necessary.(75, 76) If children in this age group do not receive proper motor skill instruction and practice, they may be inhibited from acquiring these skills later in life, leading to reduced participation in sports and other forms of physical activity.(79) Therefore, late childhood may be an ideal time to improve motor skills and correct neuromuscular risk factors for injury.

While it appears intervening with children at a young age is critical, there is a gap in knowledge on whether this age group will respond to an ACL injury prevention program. Prapavessis et al.(51) demonstrated some promise with targeting this age group by using simple verbal instructions during landing, and found success with reducing landing forces. However, Grandstrand *et al(38).* is the only study to evaluate neuromuscular risk factor alterations following a multifaceted injury prevention program in children (ages 9 to 11 years old). This study utilized an intervention program that was based on previous research performed in high school/college aged individuals and reported no improvements following the training program. The authors concluded the inability to modify neuromuscular factors may have been influenced by the fact that the pediatric athletes were unable to perform several of the exercises. These conclusions indicate that traditional injury prevention programs may not be suitable for young children.

There are several reasons to suggest young prepubescent individuals may require specialized training programs in order to modify injury risk factors. While this population is able to achieve strength gains, the mechanism for these gains is different than adults, and is most likely due to neural adaptations rather than muscle hypertrophy.(80, 81) Therefore, children have a reduced need for challenging strengthening programs with heavy resistance. Instead, resistance training programs utilizing high repetitions and low weight have been encouraged.(82) Young or physically immature individuals are at a greater risk for overuse injury compared to older individuals, and this may also need to be a consideration within an injury prevention program.(83, 84) This risk may be due to inexperience, decreased overall fitness level, incomplete physes, or because muscle strength and soft tissue growth appear to occur after bone growth.(83-86) Recovery time for children is essential to avoid these overuse injuries, so reduced frequency of a training program is recommended.(84, 86)

While feedback and instruction are frequently components of ACL injury prevention programs, it appears young pre-pubertal children may require more feedback and instruction than their older peers. Young children have been shown to require more continuous feedback and utilize different forms of attention compared with their older counterparts when learning a task.(87, 88) Task difficulty should match the cognitive ability of the learner when the learner is acquiring a new skill, which is especially true for children.(89) Wulf and Shea

(2002) recommended that difficult tasks should be separated into basic components when taught to children.(90)

Recommendations for pediatric anaerobic and aerobic training programs have been made, but no research has investigated whether a pediatric ACL injury prevention program should be designed to address the differences between adults and children in strength, physical, and motor development, as well as motor learning.(86) Based on these differences, it appears that ACL injury prevention programs for children should be implemented with lower frequency, higher repetitions, basic progressions, more instruction and feedback opportunities, and encourage mature performance of basic fundamental motor skills, such as landing from a jump. Addressing differences between children and adults may enhance the ability to change neuromuscular risk factors and prevent ACL injuries in a young population.

1.4 Limitations of Previous ACL Injury Prevention Programs

The majority of ACL injury prevention programs have been studied in college or high school female athletes. While injury is most common in this population, there is reason to believe males should also be studied. Females are more likely to injure their ACL and demonstrate greater movement and strength injury risk factors compared with their male counterparts.(4) However, males account for a higher absolute number of ACL injuries, but are rarely evaluated with ACL injury prevention programs. Failing to include males in ACL injury prevention programs may preclude an overall reduction in ACL injury rates, as little information is known about how this population may respond to a program. Both sexes need to be incorporated into injury prevention programs in order to prevent ACL injuries on a large scale.

The conclusions of previous investigations on ACL injury prevention programs are further limited by the paucity of randomized controlled trials and insufficient explanation of compliance monitoring, injury definitions, and program execution. In addition, many of these studies utilized programs that require an extensive amount of time to complete.(32, 35, 55, 56) Injury prevention programs need to be easily and efficiently adopted by the general population and not constrained by time, cost, or manpower in order for them to be effective.(91) These findings suggest that the outcomes of ACL injury prevention programs may be enhanced if the programs are evaluated in randomized controlled trials, efficiently implemented to both males and females, as well as to individuals before they reach the age associated with the highest injury risk. Therefore, the purpose of the proposed study is to evaluate whether pediatric (9-10 year old) soccer players are able to change potential neuromuscular injury risk factors after completing an injury prevention program and to compare changes between a pediatric ACL injury prevention program and a traditional program.

1.5 Research Questions

RQ1. Are there significant differences between pediatric soccer players before and after completing a pediatric, a traditional, or a control nine week ACL injury prevention program in the following biomechanical variables during an anticipated sidestep cutting task?

a. At initial ground contact:
   i. Knee flexion angle
   ii. Knee valgus angle
   iii. Tibial rotation angle
   iv. Hip flexion angle
   v. Hip adduction angle
   vi. Hip rotation angle
b. Peak during first 40% of stance phase:

    i. Knee flexion angle
    ii. Knee valgus angle
    iii. Tibial rotation angle
    iv. Hip flexion angle
    v. Hip adduction angle
    vi. Hip rotation angle
    vii. Anterior tibial shear force
    viii. Knee extension moment
    ix. Knee valgus moment
    x. Tibial rotation moment

RQ2. Are there significant differences between pediatric soccer players before and after completing a pediatric, a traditional, or a control nine week ACL injury prevention program in the following biomechanical variables during an unanticipated sidestep cutting task?

a. At initial ground contact:
    i. Knee flexion angle
    ii. Knee valgus angle
    iii. Tibial rotation angle
    iv. Hip flexion angle
    v. Hip adduction angle
    vi. Hip rotation angle
b. Peak during first 40% of stance phase:
    i. Knee flexion angle
    ii. Knee valgus angle
    iii. Tibial rotation angle
    iv. Hip flexion angle
    v. Hip adduction angle
    vi. Hip rotation angle
    vii. Anterior tibial shear force
    viii. Knee extension moment
    ix. Knee valgus moment
    x. Tibial rotation moment

RQ3. Are there significant differences between pediatric soccer players before and after completing a pediatric, a traditional, or a control nine week ACL injury prevention program in the following biomechanical variables during a false cue unanticipated sidestep cutting task?

a. At initial ground contact:
    i. Knee flexion angle
    ii. Knee valgus angle
    iii. Tibial rotation angle
    iv. Hip flexion angle
    v. Hip adduction angle
    vi. Hip rotation angle
b. Peak during first 40% of stance phase:
    i. Knee flexion angle
    ii. Knee valgus angle
    iii. Tibial rotation angle
    iv. Hip flexion angle
    v. Hip adduction angle
    vi. Hip rotation angle
    vii. Anterior tibial shear force
    viii. Knee extension moment
    ix. Knee valgus moment
    x. Tibial rotation moment

RQ4. Are there significant differences between pediatric soccer players before and after completing a pediatric, a traditional, or control nine week ACL injury prevention program in the following performance variables?

a. Dynamic anteroposterior balance as measured through a time to stabilization test
b. Dynamic mediolateral balance as measured through a time to stabilization test
c. Power as measured during a maximal vertical jump test
d. Maximal vertical jump height

RQ5. Are there significant differences present between male and female pediatric soccer players before or after completing a pediatric, traditional, or control nine week ACL injury prevention program as measured by the following variables?

a. Biomechanical variables during anticipated sidestep cutting task
b. Biomechanical variables during unanticipated sidestep cutting task
c. Biomechanical variables during a false cue unanticipated sidestep cutting task

d. Dynamic balance as measured through a time to stabilization test
e. Power as measured during a maximal vertical jump test
f. Maximal vertical jump height

1.6 Research Hypotheses

RH1. There will be significant differences between pediatric soccer players before and after completing a pediatric, a traditional, or a control nine week ACL injury prevention program in the following biomechanical variables during an anticipated sidestep cutting task.

a. Players who complete the pediatric program will demonstrate the following differences compared to participants who complete either the traditional or control programs at initial ground contact:

    i. Increased knee flexion angle
    ii. Decreased knee valgus angle
    iii. Decreased tibial rotation angle
    iv. Increased hip flexion angle
    v. Decreased hip adduction angle
    vi. Decreased hip rotation angle

b. Players who complete the pediatric program will demonstrate the following peak differences during the first 40% of the stance phase compared to participants who complete either the traditional or control programs.

    i. Increased knee flexion angle
    ii. Decreased knee valgus angle
    iii. Decreased tibial rotation angle
    iv. Increased hip flexion angle
    v. Decreased hip adduction angle
    vi. Decreased hip rotation angle
    vii. Decreased anterior tibial shear force
    viii. Decreased knee extension moment
    ix. Decreased knee valgus moment
    x. Decreased tibial rotation moment

RH2. There will be significant differences between pediatric soccer players before and after completing a pediatric, a traditional, or a control nine week ACL injury prevention program in the following biomechanical variables during an unanticipated sidestep cutting task.

a. Players who complete the pediatric program will demonstrate the following differences compared to participants who complete either the traditional or control programs at initial ground contact:

i. Increased knee flexion angle
ii. Decreased knee valgus angle
iii. Decreased tibial rotation angle
iv. Increased hip flexion angle
v. Decreased hip adduction angle
vi. Decreased hip rotation angle

b. Players who complete the pediatric program will demonstrate the following peak differences during the first 40% of the stance phase compared to participants who complete either the traditional or control programs.

i. Increased knee flexion angle
ii. Decreased knee valgus angle
iii. Decreased tibial rotation angle
iv. Increased hip flexion angle
v. Decreased hip adduction angle
vi. Decreased hip rotation angle
vii. Decreased anterior tibial shear force
viii. Decreased knee extension moment
ix. Decreased knee valgus moment
x. Decreased tibial rotation moment

RH3. There will be significant differences between pediatric soccer players before and after completing a pediatric, a traditional, or a control nine week ACL injury prevention program in the following biomechanical variables during a false cue unanticipated sidestep cutting task.

a. Players who complete the pediatric program will demonstrate the following differences compared to participants who complete either the traditional or control programs at initial ground contact:

  i. Increased knee flexion angle
  ii. Decreased knee valgus angle
  iii. Decreased tibial rotation angle
  iv. Increased hip flexion angle
  v. Decreased hip adduction angle
  vi. Decreased hip rotation angle

b. Players who complete the pediatric program will demonstrate the following peak differences during the first 40% of the stance phase compared to participants who complete either the traditional or control programs.

  i. Increased knee flexion angle
  ii. Decreased knee valgus angle
  iii. Decreased tibial rotation angle
  iv. Increased hip flexion angle
  v. Decreased hip adduction angle
  vi. Decreased hip rotation angle
  vii. Decreased anterior tibial shear force
  viii. Decreased knee extension moment
  ix. Decreased knee valgus moment
  x. Decreased tibial rotation moment

RH4. There will be significant differences between pediatric soccer players before and after completing a pediatric, a traditional, or control nine week ACL injury prevention program in the following performance variables?

a. Participants who complete the pediatric program will demonstrate greater dynamic anteroposterior balance as measured through a time to stabilization test than participants who complete either the traditional or control programs.

b. Participants who complete the pediatric program will demonstrate greater dynamic mediolateral balance as measured through a time to stabilization test than participants who complete either the traditional or control programs.
c. Participants who complete the pediatric program will demonstrate greater improvements in power as measured during a maximal vertical jump test than participants who complete either the traditional or control programs.
d. Participants who complete the pediatric program will demonstrate greater improvements in maximal vertical jump height as measured during a maximal vertical jump test than participants who complete either the traditional or control programs.

RH5. There will not be significant differences present between male and female pediatric soccer players before and after completing the pediatric, traditional, or control nine week ACL injury prevention program in the following variables.

a. Biomechanical variables during anticipated sidestep cutting task
b. Biomechanical variables during unanticipated sidestep cutting task
c. Biomechanical variables during a false cue unanticipated sidestep cutting task
d. Dynamic balance as measured through a time to stabilization test
e. Power as measured during a maximal vertical jump test
f. Maximal vertical jump height

1.7 Operational Definitions

Pediatric: 9-10 year old child

Initial ground contact: The instant the foot makes contact with the ground represented by the moment the vertical ground reaction force exceeds 10 N.

Toe-off: The instant the foot leaves the ground represented by the moment the vertical ground reaction force drops below 10 N.

Stance phase: The time period between initial ground contact and toe-off.

Limb dominance: The lower extremity limb used to kick a ball for maximal distance.

Anticipated sidestep cutting task: Participants begin standing on a 30 cm high box, a distance of half of their body height away from the force plate, and jump forward off the box with both legs toward the force plate. Participants land with their dominant foot in the center of the force plate and make a 50-70 degree change of direction toward his/her non-dominant side and run 2-3 m.

Unanticipated sidestep cutting task: A model is 3m away from the far end of the force plate (relative to the participant), facing the participant, and jumps from a 30 cm high box and lands on their dominant leg. Immediately upon landing, the model cuts either towards his/her left or right at a 50-70 degree angle. Participants begin standing on a 30 cm high box, a distance of half of their body height away from the force plate, and jump forward off of both legs towards the force plate. Participants land with their dominant foot in the center of the force plate and make a 50-70 degree change of direction towards the direction the model moved. Participants jump from the box immediately after they see the model jump and "chase" the model upon landing.

False cue unanticipated sidestep cutting task: A model is 1m away from the far end of the force plate (relative to the participant), facing the participant, and jumps from a 30 cm high box and lands on his/her dominant leg. Immediately upon landing, the model shifts their trunk either left or right (false cue or "fake") and then changes direction to cut at a 50-70 degree angle. Participants begin standing on a 30 cm high box, a distance of half of their body height away from the force plate, and jump forward off of both legs towards the force plate. Participants land with their dominant foot in the center of the force plate and make a 50-70 degree change of direction towards the direction the model moved. Participants jump from the box immediately after they see the model jump and "chase" the model upon landing.

Model: The same research assistant used for all testing sessions.

Power: Vertical jump power computed using the following equation: Power (W) = 61.9 x jump height (cm) + 36.0 x mass (Kg) – 1822.(92)

Maximum vertical jump height: Measured during the maximum vertical jump test and calculated from the time the participants are in the air. Time in the air is between toe-off and initial ground contact and height is calculated from: Height = $0.5(g)(t/2)^2$.(93)

Maximum vertical jump test: Double leg countermovement maximal vertical jump. Participants begin with their hands on their hips and their feet shoulder width apart while standing on a force plate. An overhead goal, in the form of Vertec measuring device, is used to encourage maximal performance.(94) Participants jump for vertical height and try to touch the measuring device.

Time to Stabilization Test: Participants stand on a 30 cm high box a distance of half of their body height away from the force plate. Participants jump forward from the box and land with their dominant foot in the center of the force plate while maintaining their hands on their hips and their non-dominant foot off of the ground. Participants balance on one leg as quickly as possible without putting their non-dominant foot down.

Traditional ACL injury prevention program: This program is based on previously studied ACL injury prevention programs.

Pediatric ACL injury prevention program: This program is similar to the traditional program with the same types of exercises but includes the following differences:

1.) More exercise variety
2.) Reduced initial frequency of program implementation. (First phase is performed 2 times per week; second and third phase performed 3 times per week; Traditional program: always 3 times per week)
3.) First week of each phase has fewer repetitions and more time spent on technique instruction
4.) More gradual progressions of exercises (Example: Squat jumps are preceded by proper double leg squat performance)
5.) Dynamic flexibility exercises
6.) Feedback cues are directed towards internal focus of attention ("Bend your knees" versus "Land soft as a feather")

Control ACL injury prevention program: Teams assigned to this program do not complete any assigned program, but instead perform a warm-up designated by their coach.

Intervention period: Nine week period of time during which participants complete either the Pediatric, Traditional, or Control ACL injury prevention program (August – October 2009).

1.8 Assumptions/Limitations

The following assumptions and limitations were made for this study:

1. To avoid exclusion with the participants' teammates, all participants were included in this study regardless of their precise pubertal status. It was assumed that all participants were pre-pubescent.

2. All participants gave their best effort in performing the test protocols.

3. All participants were honest regarding their current injury status.

4. There were no injuries, training effects, or learning during either of the two testing sessions or intervention period.

5. All participants were honest about their physical activity during the nine week intervention period.

6. The data collection equipment collected accurate data during both testing sessions.

7. All participants had no prior experience with any type of jump landing training or ACL injury prevention.

1.9 Delimitations

The following delimitations were made in this study.

1. All participants were under ten years old as of July 1, 2009.

2. All training sessions were supervised by at least one research assistant.

3. All participants were from the same area soccer league.

4. The members of seven soccer teams were recruited for this study.

5. All kinematic and kinetic data were collected from the same motion analysis system.

6. All power data were collected from the same force plate.

7. All participants were free from any injury that prevented them from performing the testing protocol.

8. All participants attended at least 80% of all training sessions during the intervention period.

1.10 Independent Variables

Two independent variables were used in this study.

1. ACL injury prevention program group
    a. Pediatric
    b. Traditional
    c. Control
2. Sex
    a. Males
    b. Females

1.11 Dependent Variables

1. Lower extremity kinematic variables
    a. At initial ground contact:
        i. Knee flexion angle
        ii. Knee valgus angle
        iii. Tibial rotation angle
        iv. Hip flexion angle
        v. Hip adduction angle
        vi. Hip rotation angle
    b. Peak during first 40% of stance phase:
        i. Knee flexion angle
        ii. Knee valgus angle
        iii. Tibial rotation angle
        iv. Hip flexion angle
        v. Hip adduction angle
        vi. Hip rotation angle
2. Peak of kinetic variables during first 40% of stance phase
    a. Anterior tibial shear force
    b. Knee extension moment
    c. Knee valgus moment
    d. Tibial rotation moment
3. Power
4. Maximum vertical jump height
5. Time to Stabilization

1.12 Significance

The objective of this study is to evaluate whether or not an injury prevention program for a specific population is effective at changing risk factors for injury. This study is unique because a population-specific intervention program has not been investigated before, and the benefits of designing a program that addresses the individual needs of a population are enticing. The pediatric intervention program for youth soccer players focuses on teaching proper technique and promoting neuromuscular changes without overstressing their systems. Implementing ACL prevention programs will be easier if no differences are observed between the pediatric and traditional programs, as the same program can be used for all age populations. The results of previous work may be supported if the pediatric program is found to be superior to the traditional program, indicating youth athletes require specialized training to change potential neuromuscular risk factors. A randomized controlled design will be utilized for this study, which is a lacking feature in the majority of other ACL injury prevention literature.(40) Prevention of ACL injuries is critical because these injuries are common and costly for the young athletic population. Reducing risk factors in a pediatric population before the athletes reach the age for greatest risk for injury may enhance the potential for reducing injuries. This study has the ability to answer a significant missing piece in the ACL injury prevention literature and will help future endeavors with reducing the impact of this injury and promoting overall public health.

CHAPTER 2

REVIEW OF THE LITERATURE

There is a critical need to prevent ACL injuries in youth sports due to their frequency, financial cost, and poor long-term prognosis. Previous ACL injury prevention programs have focused on changing neuromuscular risk factors for injury and showed moderate success in reducing injuries. Although these risk factors are observed in children as young as ten years of age, there is a paucity of research on whether or not children in this age group are able to change following an ACL injury prevention program. Based on previous motor development, motor learning, and youth resistance training literature, it would appear children should be able to improve these neuromuscular risk factors but may require a specialized program consistent with their stage of development to obtain optimal benefits.

The purpose of this study is to evaluate the potential for young children to modify neuromuscular risk factors following an ACL injury prevention program and to determine if a developmentally appropriate program is necessary to maximize results. This literature review provides the background and rationale for this study by discussing ACL injury prevalence, etiology, and proposed risk factors, and how this information led to the selection of the dependent variables. Previous work on ACL injury prevention and the limitations associated with these studies will also be discussed. Motor development of children through puberty will be described in relation to how motor development may influence learning and training in pediatric soccer players.

2.1 ACL Injury Epidemiology and Etiology

2.11 Youth Sport Participation and Injury

Sports and recreational activities account for over 6.8 million injuries in the United States with over 4.4 million of these injuries occurring in individuals between the ages of 5-24 years of age.(3) Injury rates as high as 91.2 per 1000 children have been reported due to sports,(95) with the majority of these injuries occurring as a result of growing participation in several youth sports, such as soccer. Currently, over 3 million children are registered to take part in organized youth soccer within the United States, and participation increases by approximately 20% every year.(1) Unfortunately, increases in participation lead to a greater potential for injuries.

2.12 ACL Injury Epidemiology

Over 1.5 million injuries occurred due to youth soccer between 1990-2003, and lower extremity injuries accounted for nearly 50% of these injuries.(96) Shea *et al.(67)* performed an insurance analysis from a youth soccer league and reported that 22% of all youth soccer league insurance claims were due to injuries to the knee alone.(67) In fact, young soccer players are more likely to sustain a knee injury compared to any other injury.(97) A prospective study of female adolescent soccer players reported similar results, as knee injuries accounted for 16% of all injuries sustained during an eight month period.(98) Not only are knee injuries common in youth soccer, but they are also severe, with approximately 20% of them requiring surgery.(97)

A severe knee injury in youth sports is a rupture of the anterior cruciate ligament (ACL). There are an estimated 200,000 cruciate ligament injuries in the United States each year, with an associated cost of over $3 billion.(4, 56) The rate of ACL injury is 1.4 - 4.6 times greater in females than males, but due to greater exposure to sports, the absolute number of ACL injuries in males is greater than the absolute number in females.(9, 99-106) Using a national injury registry, Parkkari *et al.(107)* reported similar sex differences in injury rates for adolescents. This study also adjusted the injury rates according to the amount of sports participation and found this adjustment elevated injury risk ratios to 8.5 for females and 4.0 for males. Sex differences in ACL injury rates exist in younger age groups as well as older age groups.(67) However, ACL injury rates vary between these age groups, with the ratio of ACL injuries to total knee injuries increasing as children progress in age, resulting in an elevated frequency of ACL injuries around age 11 or 12 with a steady rise until age 18.(67)

2.13 Long-term Effects of ACL Injury

Not only are ACL injuries in youth soccer common and a financial burden, but also they are detrimental to long-term health as they are associated with short and long-term disability. Physical activity is essential for a healthy lifestyle by decreasing the probability of acquiring several diseases, such as obesity, diabetes, and hypertension, while improving bone density(3) and overall mental and physical health.(108) Injury is a leading reason for physical inactivity so youth sports injuries can be especially problematic, as they can influence the child's future involvement in physical activity, which may result in poor long-term health.(2) An example of this reduction in sport participation following injury is provided in Soderman *et al.(109)* who reported that only 52% of female adolescent soccer players returned to the sport following an ACL injury and within 2-7 years after the injury, this number was down to 22%. Almost 80% of these females linked their discontinuance directly because of symptoms in their injured knee.

Osteoarthritis is a common condition that is disabling and limits normal daily functioning in adults.(6) Onset of osteoarthritis at a young age may result in long-term disability.(7) Lohmander *et al.(7)* indicated that over 50% of female soccer players with an ACL reconstruction developed radiographic osteoarthritis in the involved knee only 12 years after surgery, and about 80% of these players showed radiographic signs of osteoarthritis development. Unfortunately, the course of treatment for an ACL sprain (i.e. conservative/non-surgical versus surgical reconstruction) did not influence the high prevalence of osteoarthritis.(7) Thus, adolescent individuals who suffer an ACL injury may develop osteoarthritis by the time they reach their 20's. Sustaining one knee injury may result in osteoarthritis or an additional injury. Steffen et al.(98) found that a previous knee injury almost doubled the risk of a repeated injury in adolescent female soccer players. These consequences demonstrate the immediate need for effective ACL injury prevention, especially in young athletes.

The consequences of an ACL injury dramatically increase when the injury occurs to an immature individual, such as a prepubescent soccer player. Several years ago, intrasubstance ACL injuries in children and adolescents were rare but now are more frequent.(110) There are mixed opinions about how to treat the young patient with open physes, whose bones are still growing.(71, 110) Traditionally, children with open physes and an ACL injury are treated conservatively, or non-operatively, through rehabilitation, activity restrictions, and protective bracing until skeletal maturity is reached and only then are the ACL sprains reconstructed.(110) The rationale behind this treatment is that ACL reconstruction may cause iatrogenic growth disturbances, such as leg length discrepancies, distal femoral valgus deformities, tibial recurvatum, and genu valgum, due to physeal damage in skeletally immature individuals.(68, 70) Unfortunately, this course of treatment often produces poor outcomes, such as chronic instability, subsequent injury to the menisci and cartilage, and decreased physical activity levels.(68, 69) A recent study demonstrated that only 65% of children with an ACL injury prior to age 13 years old that were treated conservatively returned to their pre-injury activity level.(71) The percentage of children returning to sports requiring pivoting, such as soccer, decreased to 58%.(71) Recently, it has been suggested these preadolescent patients can undergo ACL reconstruction using specialized, meticulous techniques, such as transphyseal reconstructions, with low revision rates, excellent functional outcomes, few complications, and minimal growth disturbances.(68) Thus, management of ACL injuries in skeletally immature children is an evolving area and the difficulty this injury presents to this population provides further rationale for preventing ACL injuries in young individuals who are physically active.

2.14 Summary of ACL Injury Epidemiology and Consequences

ACL injuries are a relatively common injury in youth sports, especially as children approach adolescence. Not only are these injuries common, but also they are costly in financial and physical terms. An ACL injury diagnosis is a prognosis for osteoarthritis within 15 years for the majority of individuals. This consequence is devastating to a young athlete because injury is the primary reason people stop being physically active. If a child suffers an ACL injury when he/she is 12 years old, he/she will most likely have osteoarthritic changes or osteoarthritis in that knee by the time they are 30. In fact, that child’s probability of developing osteoarthritis quickly is further increased if he/she is still growing at the time of injury, because treating ACL injuries in immature children is a difficult prospect. The likelihood of that child continuing in athletics or any form of physical activity during adulthood is slim, which further damages the individual's health because of the onset of other diseases and conditions associated with physical inactivity. Therefore, ACL injuries need to be prevented in all populations, but especially in young adolescents.

2.2 Etiology of ACL Injury

2.21 ACL Loading Mechanisms

Excessive anterior tibial shear force is considered the most direct mechanism of loading the ACL.(111, 112) As a result, discussions about ACL loading factors are usually in reference to how certain conditions or movements increase or decrease anterior tibial shear force. It is well established that limited sagittal plane movement can increase anterior tibial shear force through large quadriceps contractions. However, ACL strain can also be elevated by the addition of tibial rotation or knee valgus.(112, 113) It is during this combined loading state of small knee flexion angles, excessive tibial rotation, and knee valgus that researchers have described the ACL to be the most vulnerable for injury.(14, 114)

Sagittal Plane ACL Loading

Large ground reaction forces are associated with an increased risk of lower extremity injury and increased amounts of anterior tibial shear force.(115) The primary method the body attenuates these forces is through extensor and flexor moments, or sagittal plane motion, about the lower extremity.(116-118) Therefore, there is an inverse relationship between large vertical ground reaction forces and knee flexion.(36, 49) This will result in large forces and other issues associated with limited flexion, such as ACL strain.

Besides influencing the forces transmitted through the joints of the lower extremity, knee flexion angle during movement affects ACL strain as vigorous quadriceps contractions at low knee flexion angles (0-30°) may generate enough anterior tibial shear force to rupture the ACL.(119) At these low knee flexion angles, the quadriceps are able to place an excessive load on the tibia because of the increased patellar tendon tibial shaft angle, creating anterior tibial translation, lateral tibial translation, as well as tibial internal rotation.(119) High levels of posterior ground reaction force with limited knee flexion may also influence ACL strain by creating an external knee flexion moment. Large external knee flexion moments need to be counteracted by an internal knee extension moment through the quadriceps muscles, which results in an increased anterior tibial shear force.(112, 120)

Other muscles also influence anterior tibial shear force and ACL strain. There are contrasting views regarding the influence of the gastrocnemius on ACL strain. Shermondy et al.(121) demonstrated that the gastrocnemius and soleus may actually have protective functions on the ACL by reducing anterior tibial translation. In contrast with these findings, Fleming et al.(122) showed the opposite by concluding that the gastrocnemius actually increased ACL strain especially in small amounts of knee flexion. Conclusive evidence exists demonstrating that the hamstring muscles are able to counteract the anterior tibial shear force created by the quadriceps when the knee is flexed between 15-60 degrees.(119) However, the hamstrings have a mechanical disadvantage when the knee is flexed less than 15 degrees, which provides further reason for the need to create sufficient knee flexion during movements associated with injury. Effective hamstring strength and activation also need to be present for them to resist anterior tibial translation and result in co-contraction with the quadriceps, which can promote joint stability and protect the ACL.

Frontal Plane ACL Loading

In addition to sagittal plane loading, the ACL can also be loaded through frontal plane motion. Knee abduction torque has been shown to increase anterior tibial translation and strain on the knee ligaments.(112, 123) Hewett et al.(19) supported these findings through a prospective study with high school athletes and found that excessive amounts of knee valgus and knee abduction moments predicted ACL injury risk. In another prospective study, Zazulak et al. demonstrated that insufficient frontal plane control of the trunk was predictive of ACL injury as well.(124)

Frontal plane stability does not rely as much on muscle control as the sagittal plane, but muscles can still influence motion in this plane. The quadriceps and hamstrings have been shown to support knee varus and valgus moments.(125) The position of knee valgus is related to hip adduction, hip internal rotation, knee abduction, and tibial external rotation.(126, 127) Therefore, muscles that control the hip may be able to restrict the amount of knee valgus that occurs by limiting hip internal rotation and adduction. In addition, hip abduction strength has been shown to be negatively correlated with knee valgus.(128)

Transverse Plane ACL Loading

Transverse plane motion of the lower extremity can also influence ACL strain. Internal tibial rotation strains the ACL through tension and external tibial rotation causes impingement of the ACL on the intercondylar notch, especially at low levels of knee flexion.(112, 129) Li et al.(119) demonstrated that similar to the anterior tibial translation created in the sagittal plane, tibial rotation can be increased by the quadriceps and reduced by the hamstrings. Similar to controlling knee valgus, the hip musculature may be able to control the amount of femoral rotation present during motion, which then may influence tibial rotation and protect the ACL.

2.22 Risk Factors for ACL Injury

Risk factors for ACL injury appear to be multifaceted including a variety of environmental, anatomical, hormonal, and neuromuscular characteristics.(14) Potential environmental risk factors include the type of surface, shoe, and the interaction between these two factors.(14) Anatomical characteristics include Q-angle, foot pronation, body mass index, ACL size, notch size, and ACL geometry. Q-angle has been implicated as a potential risk factor for ACL injury because of its influence on the position of knee valgus.(130) Excessive foot pronation can cause excessive tibial internal rotation, which can then lead to ACL strain. Several case control studies have produced inconclusive results on the role excessive foot pronation or navicular drop has on ACL injury risk.(131-134) There is preliminary evidence supporting the influence of another anatomical factor, high body mass index (BMI) values, on ACL injury risk. Uhorchak *et al.*(135) demonstrated that a large BMI was a significant risk factor for ACL injury in a prospective study and Brown *et al.* (136) demonstrated that increased BMI was associated with a more extended lower extremity position during landing, which may increase the amount of anterior tibial shear force present at the knee. Other anatomical factors that are being considered as potential risk factors for ACL injury include a narrow intercondylar notch, and smaller ACL size and area. These factors have been shown to result in a decreased load to failure and appear to be more common in females, which could provide some explanation for the higher ACL injury rate in females compared to males.(137-140)

Lower extremity movement patterns play a critical role in injury mechanism as they are known to influence anterior tibial shear force by altering the load and deformational forces on ligaments, meniscus/cartilage, and bone.(29, 30, 141-143) Specific movement patterns commonly occurring during ACL and lower extremity injury include decreased knee flexion, knee valgus, and excessive leg rotation.(143, 144) These motions commonly occur during cutting and jumping maneuvers, and can be large enough to generate extreme loads within the ACL, causing spontaneous rupture of the ligament.(145)

Approximately 70% of all ACL injuries occur due to a non-contact or indirect contact mechanism of injury, meaning that no direct contact from an external object or individual is made with the injured knee.(8) Olsen *et al.*(58) performed a video analysis of ACL injury mechanisms and concluded that the majority of these injuries occur when the individual is either performing a plant and cut maneuver to pass an opponent or completing a single leg landing. These authors also observed a consistent movement pattern with the knee in a slightly extended, valgus position combined with tibial rotation.(58) Olsen *et al.* and Boden *et al.*(8) also describe injuries occurring when the individual is in an excessively wide stance or the foot is not beneath the knee. This position has also been shown to result in high external knee valgus moments.(146)

An overwhelming number of studies exist comparing males to females to evaluate whether gender differences in movement, strength, anatomical position explain the frequently observed gender discrepancy in ACL injury rates. Females consistently perform common sport maneuvers with reduced trunk, hip, and knee flexion, as well as greater hip and knee transverse and frontal plane motion compared to their male counterparts.(14, 16, 19, 147-153) Females also appear to use their quadriceps muscles predominantly over their hamstring muscle group, leading to hypotheses that this quadriceps dominance may create excessive anterior tibial shear force during movements that is not overcome by the antagonistic muscles.(17, 154-156) In addition, females have also been shown to have decreased muscle stiffness around the knee joint, which may result in reduced knee joint stability during movements.(150, 157-159) As a result of these findings, neuromuscular risk factors appear to explain a large portion of the gender discrepancy in ACL injury rates, and changing these factors is emphasized in most prevention programs.

2.33 Neuromuscular Risk Factors for ACL Injury in Youth

Only a few studies have evaluated neuromuscular risk factors in a pediatric or prepubescent population. The majority of the studies that have been conducted examined lower extremity kinematics, kinetics, or muscle activation during landing tasks. Yu *et al.*(73) compared lower extremity kinematic differences during a stop jump between 11 to 18 year old males and females. The results of this study indicate that females increase their potential neuromuscular risk factors as they age while males do not change. Specifically, females decreased their knee flexion at initial ground contact as they progressed in age from 11 to 18 with large changes after age 14 and decreased their hip flexion at initial ground contact and maximum hip flexion after age 13 years old. In contrast, males actually improved by decreasing their knee valgus at landing after age 12 years old. Interestingly, on average, males land initially in a slightly internally rotated hip position and finish the landing phase in hip internal rotation while females land initially in hip external rotation and end the loading phase in a small amount of hip internal rotation.

Only one other study on young athletes observed gender differences, but only in participants in the pubertal stage of maturity. Quatman *et al.*(160) compared boys and girls over a one year period during which the participants transitioned from puberty to post-puberty. Their results showed that boys significantly increased their maximum vertical jump and decreased their peak vertical ground reaction force during landing between these stages. Girls only decreased their vertical ground reaction force during the take-off portion of the jump, which probably was detrimental instead of positive to their performance. Both boys and girls decreased their ground reaction force loading rates between pubertal stages.

Swartz *et al.*(161) also demonstrated differences between prepubertal and post-pubertal participants, however, this study used a cross-sectional design instead of a longitudinal analysis. These authors demonstrated that prepubescent children landed with increased knee valgus, decreased hip flexion at initial ground contact and at peak vertical ground reaction force, decreased knee flexion at peak vertical ground reaction force, increased peak vertical ground reaction force, and increased rate of peak vertical ground reaction force compared with adults. Hass *et al.*(72) observed similar and opposite findings when comparing prepubertal with postpubertal participants. This study found that while prepubertal participants landed with increased vertical ground reaction force and with a faster loading rate, post-pubertal participants landing with less knee flexion at initial ground contact and reduced knee extension moments. Prepubertal participants also encountered a laterally directed force at the knee, while a medially directed force at the knee occurred in the postpubertal participants. One potential difference for the findings from these two studies is a difference in tasks. Hass *et al.* utilized a single leg drop jump while Swartz *et al.* used a 50% maximum vertical jump test. In contrast with these two studies, Barber-Westin *et al.*(74) did not observe any differences between gender or age during a drop landing, but this study only evaluated frontal plane alignment through videography.

The two studies evaluating muscle activation patterns during landings between prepubertal children and post-pubescent individuals found similar results. Croce *et al.*(162) observed higher hamstring:quadriceps co-contraction ratios in post-pubescent participants prior to landing, but higher ratios in prepubescent participants after landing. Russell *et* *al.*(163) also found higher co-contraction ratios during the preparatory phase of landing in adults compared with prepubescent participants. These findings suggest landing mechanics change after puberty and the difference in co-contraction may indicate that pre-pubertal children land with less knee joint stiffness compared with their older counterparts.

2.24 Summary of ACL Injury Etiology

The ultimate cause of ACL injury appears to be multifaceted, involving poor movements in all three planes of motion. Limited trunk, hip, and knee flexion with excessive knee valgus and rotation can result in the perfect storm for injury. These findings have been supported by cadaveric, laboratory, and video observations of ACL loading. Females demonstrate a greater risk for ACL injury in sports such as soccer, and have also been shown to move differently than males. Sex comparisons of potential neuromuscular risk factors provide further support for the belief that the cause of ACL injury is multifaceted as females consistently perform sport maneuvers with small amounts of sagittal plane motion and excessive frontal and transverse plane motion. Unfortunately, the same sex differences exist in children as young as eleven years old of age. Studies that have compared young children to adults conclude there are differences in movement patterns between these age groups. Further research needs to be conducted to evaluate younger age groups prior to puberty as they are the age group where injury prevention is critical.

2.3 Prevention of ACL Injury

ACL injury prevention programs provide the potential to reduce injuries, and preliminary results of these programs are promising. An extensive array of possible exercises have been used in these programs and can be organized into the type of activity required, such as plyometric, strength or resistance, flexibility, balance or proprioceptive, and agility exercises. Augmented feedback, or instruction, is often incorporated in injury prevention programs as well. Not only is there a variety of exercises included in these programs, but programs also require different durations of training or are targeted to various populations or sexes.

Previous literature also differs based on what the studies evaluated as the outcome. Some studies report injury incidence results while others observe alterations in potential neuromuscular risk factors. The investigations using injury incidence as a dependent variable can define their injury incidence from any injury, any lower extremity injury, or an ACL injury. These studies all provide beneficial information about the success and potential for reducing sport-related injury, especially ACL injuries.

2.31 Effect of Prevention Programs on Overall Injury Rates

Over the past decade, there have been several large studies conducted that evaluate the use of an injury prevention program to reduce general injury in a healthy, active population. Five of these investigations demonstrated successful injury reduction following the completion of their respective program,(44, 45, 56, 164, 165) but three studies did not observe any decrease in injury rates.(166-168) It is difficult to determine the exact reason to explain why some programs are successful while others are not, because all differ in their target population, program type, duration, injury definition, and compliance monitoring ability.

All five successful studies implemented their injury prevention program to an adolescent, or high school, population.(44, 45, 56, 164, 165) Two of the three unsuccessful studies used adult participants.(167, 168) Adult participants may not be able to alter their neuromuscular characteristics sufficiently to result in injury prevention. The observation that the majority (5/6) of the studies using an adolescent population were successful in reducing injury rates is crucial since the frequency of sport-related injuries, especially ACL injuries, appears to increase during puberty or adolescence.(4, 67) Not only does it make sense to intervene with this age group, but it also appears that this age group has a better ability to respond to the program compared with their older counterparts. These findings also suggest that different age groups may have different needs to address with injury prevention programs.

Emery *et al.*(166) (2007) was the only study that did not observe an injury reduction with an adolescent population, however, the authors reported a decrease in acute injuries following the program. There are two reasons that may explain this finding. This study was the only investigation examining overall injury incidence with solely basketball athletes and one of three studies to utilize participant compliance self-reports with the intervention program. Soderman *et al.*(168) used self-reports and similarly did not find improvements in injury rates. Compliance self-reports in an adolescent population may be limited as it is unknown how often the participants truly complied or how reliable this population is with self-reports.

Duration of the injury prevention program does not appear to be a critical variable when designing a program according to this group of articles. Hewett *et al.*(56) was the only study to implement their program for just six weeks, but their program did require ninety minutes a day, three days per week. All seven of the other studies had participants perform the program throughout the length of the season, which varied from about four to nine months.(44, 45, 164-168) Performing a program for six weeks is enticing, but ninety minutes per day may be difficult to achieve for most people. Unfortunately, no research exists that evaluates the potential for a program to reduce injuries and requires less time per day for only six weeks. Four studies did conduct their programs for a shorter amount of time per day for the first several weeks of the program, but the participants still performed a maintenance phase, consisting of once a week, for the remainder of the season.(44, 164, 167, 168)

Not only does program duration appear to not impact the injury incidence results, but the type of activities included in an injury prevention program also does not appear to be a key factor. The studies that include flexibility, agility, and plyometric exercises, as well as the inclusion of specific technique instruction appear to have split outcomes in terms of reducing overall injury rates. Strength training exercises may be crucial as four of the five successful programs and none of the failed programs included these activities. However, both Herman et al.(169) and Hewett et al.(170) indicated strength training alone was not vital. It is possible that a combination of strengthening exercises and another mode of exercise may be critical. Balance may also be a necessary component for injury prevention programs. The only successful injury outcome study that did not incorporate balance training was Hewett *et al.*(56) (1999), whose results are questionable because there was an uneven distribution of types of athletes between their training and control groups. This study observed a significant reduction in injuries in the trained group compared with the control group. However, volleyball has been shown to have a lower incidence of injury compared with soccer and basketball(171, 172) and over twice as many volleyball players and half as many soccer players were in the training group as in the untrained group. This discrepancy may have influenced the lower injury rates observed in the trained group.

From examining all of the studies that evaluated injury incidence following an injury prevention program, it appears that the population used is the main factor that influences the outcome. In order to effectively reduce injury rates based on these results, injury prevention programs should be provided to an adolescent population and should incorporate at least balance and strength training activities. Future research should evaluate whether or not duration of the program implementation can influence results.

2.32 Effect of Prevention Programs on ACL Injury Rates

Assessing the ability to decrease ACL injury incidence through the use of an injury prevention program is critical to prevent the long-term consequences associated with this injury. Unfortunately, only five studies have attempted this objective over the past twelve years.(41-43, 173, 174) Similar to the studies evaluating the incidence of all injuries, these reports vary according to the type of exercises included in the program, the target population, and the duration of the activities.

Pfeiffer *et al.*(174) was the only study included in this group to not observe reductions in ACL injury rates following the completion of an injury prevention program. This study was also the only one to implement the program in a group of athletes from various sports, such as soccer, volleyball, and basketball. The other four studies focused exclusively on either soccer (41, 42, 173) or handball athletes.(43) Whether or not this discrepancy is the reason for the unfavorable results is unknown, but it is not the only difference between these studies.

Pfeiffer *et al.(174)* was also the only investigation to evaluate only non-contact ACL injuries. All ACL injuries have detrimental consequences, but it is feasible to think that non-contact injuries may be the only type of injury that can be prevented through a neuromuscular injury prevention program without changing game rules or equipment. More studies should discriminate between contact and non-contact injuries in order to truly understand whether these injury prevention programs are working.

The final difference between Pfeiffer *et al.* and the other four studies observing ACL injury incidence rates is that Pfeiffer *et al.* is the only program that did not incorporate either balance or strength exercises. As discussed previously. with the studies evaluating overall injury incidence, it appears these two types of activities may be influential to a program's outcome. Future research needs to evaluate this possibility further in order to fully understand whether a specific type of exercise is critical for success or perhaps including only one exercise from all of the major types of exercises would be beneficial.

Program duration does not appear to be a factor in determining the outcomes of these studies, as all five utilized a similar duration of 15-20 minutes per day for a few days per week. Heidt *et al.*(173) was the only study to limit the program to seven weeks and not the length of the season. The specific target population also does not seem to influence the outcome, as half of the studies used adult participants(41, 43) while the other half implemented the injury prevention program to high school athletes.(42, 173, 174) One potential issue about the target population utilized in these studies is that all five only used one gender with 4/5 studies including only females in their program.(42, 43, 173, 174) Even though females have a greater risk for injury compared with males in soccer and basketball, most non-contact ACL injuries occur in males.(4) Therefore, future research should include both genders in the study design in order to truly evaluate the effectiveness of these programs for reducing ACL injury rates on a population basis.

Randomization of study groups is an apparent limitation in the majority of these studies.(41-43, 174) Without random assignment, it is difficult to accurately assume that changes due to a program were actually because of the program and not because of differences in group membership. Heidt *et al.*(173) was the only study to report random assignment, but some question remains because only 14% of this study's population were "randomly assigned" to the intervention group. Unfortunately, the only study to potentially utilize true random assignment was not even able to perform statistical analysis on the ACL injury rates due to a small sample size.(173) Therefore, random assignment needs to be incorporated in future investigations.

The majority of studies using ACL injury incidence as an outcome measure found reduced rates due to the ACL injury prevention program. One limitation with this group of studies is that only one of them evaluated the injury rate change in non-contact ACL injuries specifically. Non-contact or indirect contact injuries are the target injury to prevent with neuromuscular training programs, and these specific rates need to be compared. Similar to the studies evaluating overall injury rates, based on the results of this group of studies it appears balance and strengthening exercises are vital components of a multifaceted injury prevention program. Recommendations for future studies include the need for random assignment, evaluate specific types of ACL injuries, and include both male and females into study designs.

2.33 Effect of Prevention Programs on Potential Risk Factors for Injury

There are a plethora of studies that attempt to modify potential neuromuscular risk factors associated with ACL injury. Therefore, we decided to perform a systematic review of the literature to access the most relevant studies to evaluate the current state of this research. First, we performed an electronic literature search of the PubMed database, maintained by the National Library of Medicine, for articles matching our criteria between January 1987 and December 2007.

A total of 230 articles were selected and their titles and abstracts were reviewed to determine if they matched our selection criteria. The selection criteria required the studies to be in English and evaluate the effects of an exercise training program incorporating either flexibility, balance, agility, strength, plyometric, or instructional exercises to modify potential neuromuscular risk factors for lower extremity injury. Eight articles were selected and we utilized PubMed's "Related Articles" link from these articles to select five additional studies. Finally, we reviewed the reference lists from the thirteen selected articles for any additional studies that met our criteria and selected a final six articles giving us a total of 19 articles to review.

The articles selected studied the effects of different types of injury prevention programs on potential ACL injury neuromuscular risk factors, such as kinematic and kinetic variables, muscle strength and activity, and balance. Healthy, physically active participants completed the injury prevention programs in all of the studies. The implementation of the programs varied with regard to duration, supervision, type of exercise training, and target population. All of these factors will be discussed in relation to the outcomes of these programs.

Kinematic Variables

Kinematic variables, such as trunk, hip, and knee joint angles, during landing and cutting maneuvers are often targeted with injury prevention programs because they are considered to be risk factors for ACL and other injuries.(31-39) Seven out of nine studies that evaluated changes in kinematics successfully modified lower extremity kinematics after the completion of their injury prevention program.(31, 33-37, 39) Hewett *et al.*(32) and Grandstrand *et al.*(38) did not observe changes in kinematic variables, specifically lower extremity sagittal and frontal plane angles, respectively.(32, 38)

Hewett *et al.*(32) had high school female volleyball players complete an intensive two hours per day, three days per week, six week comprehensive program including flexibility, strengthening, and plyometric exercises with an emphasis on proper technique.(32) While the authors report positive changes in muscle strength and landing forces, they did not observe improvements in hip, knee, and ankle flexion angles following the completion of the program. This study had significant limitations which may explain why these variables were not affected. Only 11 participants completed the program, and observations were made between their pre-test and post-test, with the only control group being a male comparison group of participants. With their small sample size and lack of a true control group, it is difficult to consider this study as a true representation of the ability of injury prevention programs to change lower extremity kinematics.

Grandstrand *et al.*(38) implemented a multifaceted injury prevention program in eleven 9-11 year-old soccer players with 9 players serving as a control group. No changes in knee separation distances, or medial knee displacement, or vertical jump height were observed after program completion. The authors hypothesized that the program was possibly too complex for their young participants and present examples of how some exercises were not able to be completed. For example, the Russian Hamstring exercise was too difficult for many of the children to perform. The authors concluded a specialized program for this age group may be required. In addition, no mention of randomization was mentioned. These limitations may explain why no improvements were seen with kinematic variables.

The programs that were successful with modifying kinematic variables vary with type of program implemented, the duration of the program, and the target population. Two studies observed increases in knee flexion motion during landing following a one-time augmented feedback session.(31, 36) Other studies demonstrated similar results following an injury prevention program consisting of flexibility, strengthening, agility, balance, and plyometric exercises.(33, 35, 46) Pollard *et al.*(39) observed improvements in both frontal and transverse plane hip motions following a multifaceted injury prevention program, but did not see changes at the knee joint or in hip flexion angles. No control group was used in this study, however, so it is possible the changes observed happened simply due to continued participation in sport.

Myer *et al.*(34) not only observed improvements in sagittal plane motion, but also decreases in hip adduction and ankle eversion angles at landing and decreases in knee abduction angles due to an injury prevention program utilizing several types of exercise training. Noyes *et al.*(37) also used a similar injury prevention program and demonstrated frontal plane kinematic improvements.

Kinetic Variables

The goal of reducing landing forces is a very common and feasible goal among injury prevention programs. All seven studies included in this review that aimed to achieve this objective were successful.(32, 36, 47-51) Despite the limitations previously noted with Hewett *et al.*(32), the authors did report a reduction in landing forces, as well as knee frontal plane moments. The other study to evaluate a reduction in landing forces after an exercise training intervention was Irmischer *et al.*(47) Both of these studies utilized only female participants so it is still unknown whether or not the results will be similar in male athletes.

Besides landing forces, three studies demonstrated that torques about the knee and hip can also decrease following the completion of an injury prevention program.(33-35)

Five articles demonstrated that an extensive, multifaceted exercise training program is not necessary to change kinetic variables.(36, 48-51) All five of these studies utilized a type of augmented feedback during a single testing session and found positive results with minimal study limitations. Onate *et al.*(36) demonstrated that showing participants a video of themselves landing, as well as an expert model landing, can decrease landing forces immediately and a week later. Onate *et al.*(49) also observed landing force reduction after participants were educated about proper landing through videotape and verbal instructions. McNair *et al.*(48) observed similar changes after providing participants with simple instructions to bend their knees during the landing or use the sound of the landing to guide their technique. Slightly contrary to McNair *et al.*, Prapavessis *et al.*(50) demonstrated that participants who received instruction about how to land on the balls of their feet, bend their knees, and lower their heels to the ground were more effective with reducing landing forces than participants who were told to rely on the sound during landing to change their style. Children as young as eight years old were able to follow the same instruction and reduce their landing forces, however, their adjustment did not remain three months later.(51)

Strength Variables

Neuromuscular training programs have been shown to increase muscle activity and strength in both high school and college athletes.(32, 33, 37, 52, 53) These five programs were all implemented with varying durations, therefore, program duration does not appear to affect the ability to improve strength or muscle activity. Specifically, three studies demonstrated increases in hamstring peak torque or the hamstring/quadriceps ratio, which is important because of the hamstring's role in protecting the ACL.(37, 53, 56)Lephart *et al.*(33) (2005) did not observe hamstring strength improvements, but rather increases in quadriceps strength and increases in medial hamstring peak reactivity during movement. This study also increased gluteus medius activity, which may assist with controlling lower extremity frontal plane movement. Only plyometric training was involved with the Chimera *et al.*(52) intervention and improvements were only seen with preparatory adductor activity and abductor/adductor coactivation, which may also be beneficial for frontal plane control. In contrast, Cowling *et al.*(31) attempted to elicit greater hamstring muscle activity prior to landing by providing participants with instructions to "fire their hamstrings" but did not succeed.

Balance

Only two studies(54, 55) from this review included balance as an outcome variable despite the fact that three other studies(33-35) utilized balance in their training program. Both Holm *et al.*(54) and Paterno *et al.*(55) found improvements in balance and stability following completion of their program, but their designs were different. Holm *et al.* studied the effects of their program, which consisted of balance, agility, and technique instruction exercises, using adult handball athletes over an entire season. In contrast, Paterno *et al.* used high school athletes with an intervention program focused on strengthening, balance, plyometric, and technique instruction over a shorter period of time, but more intense training sessions. These comparisons suggest that any kind of balance training may result in balance improvements.

2.34 Summary of ACL Injury Prevention

The findings of previous ACL injury prevention programs appear promising with successful reduction of injuries and neuromuscular risk factors in the majority of the studies. An interesting observation of all of the previously studied programs is the differences between them. Despite varying the exact injury prevention program according to exercise types, duration, or targeted population, the results were very similar. These findings suggest that in order for an injury prevention program to be effective, they key factor is that the program is multifaceted incorporating some flexibility, agility, plyometric, strengthening, and balance exercises. Based on the potential for large scale implementation, the program should require approximately 10-20 minutes to complete, can be performed in a group, such as a team, and should be implemented for at least 6 weeks.

Previous work is definitely limited in regard to the lack of randomization and the study populations. Only one study utilized male subject and no studies had both sexes participate. Although ACL injury rates are higher in females, ACL injuries and neuromuscular risk factors for injury still occur in males, so ACL injury prevention is still a concern for the male population. Also, the majority of studies use high school or college-aged subjects. While injury risk is the highest in these age groups, ACL injury prevention should still be an issue for adults and especially children.

Preliminary work suggests that age groups do not respond similarly to ACL injury prevention programs. Based on the differences in findings between the studies that evaluated overall injury incidence, the majority of studies with unsuccessful conclusions used adult subjects compared to high school aged subjects. This suggests that adult subjects may require specialized training. The same conclusion can be made for young subjects, as Grandstrand et al.(38) is the only study to our knowledge to implement an ACL injury prevention program to children under twelve years old. The program utilized is very similar to the programs used in older age groups and consists of dynamic flexibility, strengthening, agility, and plyometric exercises. However, no improvements were observed in lower extremity kinematics and kinetics. The authors do suggest a reason for these findings by describing how the children were unable to perform several of the exercises correctly due to the difficulty of the exercise. These findings agree with preliminary research recently presented demonstrating that younger subjects do not respond as well to injury prevention programs as their older counterparts. Sigward et al.(175) and DiStefano et al.(176) both observed improvements in landing kinematics and kinetics after high school aged subjects completed an ACL injury prevention program. However, the younger subjects in both of these studies, who were in middle school, did not obtain the same changes. Therefore, these findings appear to present a need for future research with this young population to determine if these children can respond to an injury prevention program and/or if they require an age or developmentally appropriate program.

Balance and strength are frequently incorporated into multifaceted ACL injury prevention programs, however, they are rarely assessed as outcome variables. Simple measures of strength and balance are available, so there is little reason to not include them in future assessments. Evaluating these changes will assist with program design, and if strength or performance variables do improve through injury prevention programs, implementation will be assisted, as well as more parents and coaches will be inclined to use the programs.

2.4 Pediatric Considerations in ACL Prevention Programs

2.41 Physical Development and Injury

Proper classification of a participant population is critical when comparisons are made between populations, conditions, or injury prevention programs. Every research study published includes participant demographic data presenting participants' ages; however, there are many definitions of "age" that can be used to describe an individual. These terms consist of chronological age, skeletal age, dental age, sexual age, morphological age, and biological age. Chronological age refers to the time evolved since birth and is most commonly used in society. Morphological age is based on comparing an individual's height and weight to normative standards.(76) Biological age represents an individual's progress toward maturity, is minimally related to chronological age, and can be determined by measures of morphological age, skeletal age, dental age, or sexual age.(76)

The pubescent growth spurt that accompanies the onset of adolescence, also known as the "adolescent growth spurt", is the most intense period of biological change with the exception of prenatal growth.(75, 76) In males, this growth spurt usually occurs around age 11 and concludes by 17 or 18 years of age, while females are commonly two years ahead of the male schedule. (76) Besides measuring the actual growth attained during the growth spurt, the velocity of growth is also of interest because the age when peak velocity of height change occurs is an indicator of maturity.(177) This peak height velocity usually occurs in males around age 13 and in females around age 11.(177) Skeletal, sexual, and somatic maturity are all interrelated.(177) Therefore, it is feasible that acquiring information about skeletal maturity through past growth measures may provide some evidence of an individual's biological age.

Prior to adolescence, the brain is maturing as well as the physical body characteristics. The brain undergoes pruning where infrequent connections are eliminated around ten years old. (75) Also around this age, the glucose levels in the brain and the rapid increases in myelin in the cerebral commissures decline.(75) Visual perceptual mechanisms, visual acuity, figure-ground perception, depth perception, and visual-motor coordination become fully mature around ten to twelve years of age.(76) Kinesthetic memory, visual-kinesthetic integration, visual-auditory integration, auditory skills, directional awareness, and spatial awareness are more characteristics associated with motor development that mature around the onset of adolescence.(75) These factors support the notion that the time to implement injury prevention programs may be just before or during the time when the brain is maturing.

Prior to puberty, males and females do not differ greatly in their body size. After the onset of adolescence, however, great differences are observed.(76) Not only are there differences in actual body size, but body composition also changes. Females tend to develop more adipose tissue while males gain more muscular tissue.(75, 79, 177) These changes are due to the changes in hormone levels corresponding with sexual maturity. Adult men have approximately ten times the amount of testosterone present in their body compared with children and adult females.(75) These gender differences may potentially explain the gender discrepancies in neuromuscular risk factors and injury rates during and after puberty.

2.42 Resistance Training Considerations

The rapid changes that occur during the pubertal stages provide rationale for youth physical training. During the adolescent growth spurt, bone growth usually occurs faster than muscle and tendon growth, resulting in decreased levels of joint flexibility.(76) Therefore, flexibility training may be beneficial during this time period to resist declines in flexibility. In addition to assisting flexibility, exercise prior to adolescence may also be the most effective time period to assist with bone development.(76) Unfortunately, the amount of vigorous physical activity declines during these life stages, with only 25% of children participating in any form of school physical education. (75)

Muscle strength is an important factor in the ability to properly perform common movement patterns.(177) Historically, it was believed that children should not perform resistance training because of potential injury risk and the fact that they do not have androgens in their circulation inhibiting them from attaining strength gains.(80, 178) However, Malina *et al.*(178) presented a review on youth resistance training and concluded that resistance training two to three days per week does increase muscle strength during childhood and early adolescents and these improvements are lost with detraining. While postpubertal males experience strength gains due to hypertrophy, the strength gains of prepubescent children after training are due to improved neural adaptations instead.(80, 81) Resistance training has been shown to improve stimulation of the central nervous system greater than what would occur with normal maturation.(76)

Faigenbaum *et al.*(82, 179-182) have performed several studies to determine the best resistance training program design for children. In 1999, their results indicated that one set of 13-15 repetitions produced greater strengthening effects compared with one set of 6-8 repetitions in children between the ages of 6-12 years old.(180) This study was followed-up with a more recent study by Faigenbaum *et al.* where one set of 15-20 repetitions were compared with 6-10 repetitions in 8-12 year old children.(82) The results of this study supported the previous research that a high repetition load is more effective for producing greater strength gains than a low repetition sequence in children. Flexibility was also increased in the high repetition group relative to the control group.

Traditionally, static stretching was recommended as a warm-up activity and to improve flexibility. A recent study suggests that dynamic flexibility through a dynamic warm-up may be more beneficial in children.(183) Faigenbaum *et al.*(183) performed a within-participant design using 60 11-year old children as participants to compare a static flexibility warm-up, a dynamic flexibility warm-up, and a dynamic flexibility plus plyometric training warm-up on power, speed, and agility. The static flexibility warm-up consisted of six stretches for the hip adductor muscles, hamstrings, quadriceps, hip flexors, and calf muscles. The dynamic warm-up included the following exercises: high knee walk, straight leg march, hand walk, lunge walk, backward lunge, high-knee skip, lateral shuffle, back pedal, heel-ups, and high knee run. The static warm-up actually caused a reduction in vertical jump, long jump, and shuttle run performance. The authors concluded that a dynamic flexibility warm-up is more beneficial for children than the traditional static stretching warm-up.(183)

Young physically immature individuals are at greater risk to overuse injury compared to older individuals, and this may need to be a consideration within an injury prevention program. This risk may be due to inexperience, decreased overall fitness level, incomplete physes, or because muscle strength and soft tissue growth appear to occur after bone growth.(83-86) Recovery time for children following exercise is essential to avoid these overuse injuries, so reduced frequency of a training program is recommended.(84, 86) The American Academy of pediatrics, in 2001 and revised in 2008, stated that children should perform strength, endurance, flexibility, and agility exercises with no load 2-3 times per week.(184) Faigenbaum *et al.*(182) supported this recommendation by demonstrating that two days a week of resistance training is sufficient for strength and motor changes. These findings have important implications for program design in children.

2.43 Motor Development Theories

Theories regarding motor development have evolved over the past sixty years. Some of these theories include the environmental theory, the phase-stage theory of development, the developmental task theory, the information processing model, and the dynamic systems theory. There are some common themes, such as the notion that development is interrelated between the environment through social and cultural influences and biology, or genetics. Several themes, such as the environmental theory, phase-stage theory of development, and the developmental task theory, view development as rigid sequential steps that must be followed for proper development.(76) Following and accomplishing these tasks will influence future success or failure.(76) These theories are considered rigid with individual independent components, so more recent research has focused on the information processing and the dynamic systems theories instead.

The information processing theory became known in the 1970's when computers were gaining popularity.(75) The information processing model relies on sensory input, integration, motor interpretation, movement activation, and feedback. This feedback can include knowledge of results or performance, and will influence the next steps of movement.(75, 76) Programming is also a vital component to this model and is defined as cognitive processing that creates a cognitive expression or motor program, requires attention and awareness, and the program is stored in the memory for future use.(75) A motor program has been defined as a memory representation of actions necessary for generating specific movement patterns.(75) The schema theory is similar to the information processing theory but progresses the motor program concept by describing motor programs not as strict guidelines, but as general concepts and relationships to direct movement from previous experiences and calls it a generalized motor program.(75) The generalized motor program prevents capacity issues that may occur with the information processing model, which would require a specific motor program for every task. The generalized motor program, instead, enables similar tasks to be controlled by one program with different speed, duration, and force parameters.(185)

A further progression of the information processing theory is the dynamic systems theory, which is based on the idea that the body is made of several individual self-organizing systems that interact in complex ways depending on the movement required and the available resources or constraints.(75, 76) Constraints can be factors that either facilitate or restrict development and can be from the individual, the task, or the environment.(75) Examples of individual or organismic constraints are height, weight, motivation, level of practice, degrees of freedom. Gravity, temperature, and social influences are examples of environmental constraints, while task constraints include goals and rules. The dynamic systems theory allows variable motor performance based on the constraints, which is a critical aspect of skill acquisition.(185) Altering these constraints leads to preferred patterns of movement that usually are the most efficient interactions of the subsystems. Development based on the dynamic systems theory is a discontinuous process illustrated by phase shifts, which are evident by discontinuous movements during previously continuous tasks. Therefore, a person who is just learning a task or changing a task may show excessive variability. These phase shifts result in old movements being replaced by new patterns of movement.(75, 76)

2.44 Motor Development Prior to Adolescence

Motor development is the process of continuous motor behavior change throughout life, and is linked to cognitive and perceptual development.(76) There are many terms associated with motor development, and these have been operationally defined by Gallahue in 2006:(76)

> "Motor behavior: change in motor learning, motor control, and motor development brought about by the interaction of learning and biological processes.(76)
>
> Motor control: underlying neural and physical changes in the performance of isolated tasks(76)
>
> Motor pattern: common underlying biological and mechanical processes(76)
>
> Motor skill: common underlying process of gaining control in voluntary movement of the body, limbs, and/or head (also called task or action)(76)
>
> Movement pattern: organized series of related movements(76)"

Motor development is affected by the interplay of movement tasks, the individual, and the environment.(75, 76)

In order for proper motor development to occur throughout life, several authors have discussed the need for developing acceptable levels of proficiency and efficiency of movements during various activities.(75-77) The term "fundamental motor skill" is frequently used to describe common motor activities that are the underlying framework for basic movements and complex sport and movement skills.[44, 46] Examples of these fundamental motor skills include walking, running, jumping, hopping, skipping, catching, and throwing. Physical and cognitive maturation are important for the development of these skills, but the environment via practice opportunities and social encouragement also influence whether or not these skills are effectively developed. (76) As fundamental skills are attained, they are gradually combined and progressed to become more advanced sport skills.(76) Sometimes children have difficulty acquiring these skills and these problems may differ between individuals, but are usually due to incomplete modeling of movements of other individuals, initial success with an incorrect movement, lack of motivation, inappropriate or scarce learning opportunities, or problems with sensorimotor integration.(76)

Motor development is related to age, but it is not dependent on age, and often individuals have their own timetable for movement skill acquisition.(76) Critical, or optimal, periods for attaining motor skills are present during infancy, prepuberty, and puberty.(77) Early childhood, between the ages of 2-7 years of age, is considered the time for fundamental and gross motor skill development.(75) Later childhood, between the ages of 8-12, is important for fundamental motor skill refinement and the progression of fine motor skills.(75, 76) Generally, motor development specialists believe children are capable of being at the mature stage of most fundamental motor skills by age 5 or 6 years old. (75, 76) The mastery of complex motor skills does not usually occur until approximately 10-12 years old, when growth is fairly steady, gradually resulting in an ideal environment to develop coordination and neuromuscular skill.(78, 79)

Motor skill development is intense during prepuberty and this progression declines during further stages of puberty.(77) Before puberty, males and females appear similar in most motor skill abilities. Females tend to be better with hopping, skipping, balancing, and flexibility while males are stronger with running, jumping, and throwing skills.(75) These differences are intensified after puberty and the adolescent growth spurt, and males are usually more proficient at most motor skills than females.(75)

Despite general expectations of fundamental skill mastery by age seven, many authors have noted a low prevalence of skill mastery in children as old as 15, or even a failure to succeed the elementary stages of many movements.(75, 76) Gallahue(76) noted this failure in skill development may be because many people believe children will automatically learn these fundamental skills and do not need to be taught. One reason for these findings is a decline in the quantity and quality of school physical education.

Acquisition and development of fundamental motor skills needs to be an important objective of society, because possessing these skills leads to improved physical activity levels and increased participation in games and sports.(75, 76) A failure to reach competency in a variety of the fundamental motor skills will cause limited proficiencies of sport specific skills.(76) Team sport participation peaks around age 11,(75) which is a key period for refinement of fundamental motor skills. Children need to have sufficient exposure to practice, instruction, and encouragement to help their performance of movement skills.(76) Involvement in sports and physical activity is critical for children to have good health, physical and social growth enhancement, improved motor skills, good self-esteem, reduced risk for obesity and other health problems, and a basis for healthy living and lifelong participation.(77) Youth participation in developmentally appropriate sport activities has been recommended to encourage future participation.(77),(76)

Besides leading to reduced future physical activity participation, deficiencies in correct fundamental motor skills after the critical development periods may be very difficult to change. Altering an already learned movement requires bringing the learning back to a conscious, or initial, level, and restarting the process. The tendency is for children to immediately revert to the original method when they are challenged and this is only reversed after extensive practice.(76)

Fundamental motor skills are frequently described in three stages: immature/initial, immediate/elementary, and mature.(76) The following synopsis about key fundamental motor skills is from the Gallahue(76) and Gabbard(75) text and focuses on skill attainment related to ACL injury risk factors and mechanisms of injury. Some key mature developmental characteristics of running include the elimination of lateral leg movements and toeing-out.(75) Dodging, or cutting, is considered a fundamental stability movement requiring rapid changes in direction, good reaction time, and speed. Characteristics of the initial stage of learning include segmented movements, stiff motions, and minimal knee flexion. The mature stage involves flexed knees, slight trunk flexion ("ready position"), and smooth lateral direction changes. Some developmental difficulties for the dodging skill include an inability to shift weight, slow change of direction, excessive body lean, a rigid posture, and an inability to perform multiple movements in succession.(76) As mentioned earlier in this literature review, limited sagittal plane motion at the trunk, hip, and knees, as well as lateral leg movements that may influence the position of knee valgus, and toeing-out that may result in tibial rotation, are all implicated as neuromuscular risk factors for ACL injury.

The initial stage for a jumping from a height skill consists of one foot leading on takeoff, no flight phase, and excessive use of arms for balance. The elementary stage progresses from the initial stage by involving a two-foot takeoff with one foot lead, an uncontrolled flight phase, and inhibited knee and hip flexion during landing. The mature stage for jumping and landing includes a two-foot takeoff, controlled flight phase, simultaneous foot contact with toes first, feet shoulder-width apart, and sufficient knee and hip flexion. Problems with this skill often include an excessive body lean, failure to land concurrently on both feet, landing flat-footed and limited knee flexion. The majority of these landing characteristics are all included in a clinical movement analysis tool, the Landing Error Scoring System, and are evaluated to determine if neuromuscular risk factors are present between individuals.(186) Balance, or stability, is considered to be a key aspect of learning the fundamental motor skills.(76) Therefore, it is recommended that movement experiences for children should require them to move in a number of different ways relative to their center of mass and base of support.(90)

2.45 Motor Learning

Motor learning is an integral part of developing and refining fundamental motor skills. Gallahue(76) defines motor learning as the changes involved in acquiring and refining movement skills through practice or past experiences and involves relatively permanent alterations in motor patterns. Motor learning, or skill acquisition, influences the way individuals interact with the environment, determine what information is critical, and time motor responses appropriately.(185) Learning is also considered a result of many components including experience, education, practice, and biological processes.(76) There are three phases to motor learning: acquisition phase, retention phase, and the transfer phase.(87) The retention and transfer phases are critical when evaluating whether or not actual motor learning has taken place, because motor changes are possible after instruction and practice, but these changes can be transient.(187) Retention of changes and the ability to transfer the new skill or movement to another novice skill indicates actual motor learning.(75, 76, 187)

Attention is a factor that influences whether or not learning is successful, and can be directed internally or externally. External attention means the individual focuses on an object or the effect of the action instead of on their actual movement itself, which is internal attention.(87) Many studies have shown that adults are more effective learners when they direct their attention externally.(87, 188-190) This consistent finding is believed to be because an internal focus of attention causes individuals to constrain their movements, which leads to disruptions in their automatic control processes.(188) In contrast, external focus of attention does not alter automatic control processes, which leads to more effective performances and learning.(188)

The advantage for external focus of attention is not true for all populations. Skill may impact whether an individual prefers internal or external focus of attention. Perkins-Ceccato *et al.* found that less skilled golfers' performance was enhanced when they used an internal focus of attention, while their more skilled counterparts preferred the opposite, an external focus of attention.(191) Also, Emanuel *et al.* studied the effects of focus of attention between adults and children in learning a dart throwing task. Participants were randomly assigned to either an internal or external focus group where the internal focus group received instructions about appropriate shoulder, arm, and finger movement and the external focus group were told about the target aim, the position of the darts, and the course the dart should take. The results indicated that adults in the external focus group performed better on the task immediately (acquisition phase) than the adults in the internal focus group, which supports previous literature. Performance during the acquisition phase was not affected by group assignment for the children. However, children who were in the internal focus group performed much better one day after the acquisition phase on a transfer task, where the participants threw a dart further than during the acquisition phase compared to the external focus group. The authors hypothesized that children may be considered more novel learners than adults, providing some rationale for the findings of preferred internal focus of attention. It has been previously hypothesized that children may not be detrimentally affected by internal focus of attention because their implicit learning is not mature compared with adults. Weiss *et al.* (1993) stressed the importance of showing enthusiasm, making eye-contact, and describing the key points of a skill concisely and with repeated demonstrations to maintain children's effective attention.(192)

Many textbooks describe three stages of motor learning derived from a model created by Fitts in 1967.(76, 185) The first stage of learning is the cognitive stage when the learner is exposed to simple rules and verbal instructions to understand the movement and form a conscious plan for the skill. Movement during this stage is usually variable and full of errors as the learner experiments. The second stage is the associative stage when the learner uses cues and feedback from the environment to help him/her with the task. Performance of the movement is beginning to be improved and consistent during the associative stage. The final stage is the autonomous stage when the task can be performed with minimal or no conscious attention or effort. The performance is usually error free at this stage.

Gallahue(76) expanded these traditional stages and provided suggestions for organizing practice sessions and presenting instructions. Similar to the traditional stages, the first level is when the learner develops a conscious mental plan for the task, and the result is variable error-ridden performance. Gallahue also mentions that fatigue may occur because the learner is focusing on many task components and unable to determine what information is critical. During this level, the learner progresses through three specific stages: awareness, exploratory, and discovery. The learner works to figure out how the task is performed, experiment with how his/her body can perform the task, and find efficient ways to complete the task. The instructor is recommended to provide visual demonstrations, cue the learner to the major aspects only with brief instructions, permit early practice, provide an opportunity for self-discovery of the task, and to give the learner immediate, precise, and positive feedback.(76)

The second level is an intermediate level that occurs once the learner understands the task but needs to practice. The two sub-stages of this level include a combination and application stage during which the learner uses less conscious attention to put the skills together and use them in an activity. The instructor is recommended to provide ample practice, devise progressive practice situations, organize short, fast-paced sessions with frequent breaks, help the learner analyze the task, help the learner focus on entire skill, and help him/her learn to refine and apply the task to different situations.(76)

The final level is the advanced, or fine-tuning, level when the learner completely understands the movement and tries to perform it with no conscious effort. The instructor is encouraged to promote intensity and enthusiasm during practice, be available for feedback, make practice more realistic, avoid asking the learner to analyze skill, and promote rapid decision making. It is also advisable for conditions to be internally paced first with the external environment controlled followed by externally paced activities.(76)

According to the motor development theories discussed above, motor learning is dependent on the capability of the individual, the demands of the task, and the environment or practice conditions. Based on this concept, additional recommendations for teaching motor learning have been made with regard to cueing, practice variability, and feedback. As mentioned previously, visual models benefit learning, and verbal cues can enhance what the learner perceives from these visual images by helping to stress the important information from the demonstration.(193) Observational learning has been shown to be beneficial for children, as repeated demonstrations help them focus on the basic parts of the skill.(192) Initially, the instructor should try to limit inhibiting constraints and maximize affordances by controlling the environment and the task so the individual only is concerned with his/her movement.

Using the individual, task, environment paradigm for influencing motor learning, it is plausible that children's cognitive level may inhibit them from learning some tasks if they do not comprehend the objective or if too much information is presented in a complex manner. Guadagnoli and Lee(89) discussed the idea that the task difficulty must match the cognitive ability of the learner. Individuals must be challenged enough to be motivated by a task, but too much cognitive effort may interfere with the motor learning process.(89) Wulf and Shea(90) also supported the idea that complex motor skills require great levels of information processing, especially for children, and they advised teaching one part of a task at a time. Blocked practice is practice that repeats the same skill in the same way, and has been shown to improve the effectiveness of the skill acquisition phase. However, random practice involves practicing the same skill in several different ways, and has been shown to lead to more effective retention and transfer in adults. According to a review by Wulf and Shea(90), there are mixed results on this practice variable for children because some believe random practice can be too complicated for children.(90) They suggested practices of complex skills may be more beneficial if they are initially taught with blocked practice followed by random practice upon progression of the skill.(90)

Delayed feedback is often recommended during motor learning to allow the learner to recognize their own errors and make adjustments.(194) Sullivan *et al.*(88) demonstrated that this reduced feedback frequency requires cognitive processing that children may not be able to perform. This study compared children and adults in their skill performance and retention after either constant or reduced feedback conditions. While their results support previous research for reduced feedback in adults, children who received constant feedback performed better during the retention test than children who received reduced feedback. These findings further support the notion that children do not learn the same way as adults and therefore, should not be instructed the same way.

2.46 Summary of Pediatric Considerations

Adolescence is a period of time associated with rapid physical and cognitive growth. Similar to these changes in growth, motor development is a continual process that reaches maturity at the beginning of adolescence. This is also the time period when ACL injury rates begin to increase and neuromuscular injury risk factors are present. Therefore, this may be the ideal time for intervening with an ACL injury prevention program. However, preliminary evidence suggests these young children may not respond to the program as well as their older counterparts. The reasons for these findings may be because the programs are not designed specifically for this age group.

There are several reasons to suggest young prepubescent individuals may require specialized training in order to modify injury risk factors. While this population is able to achieve strength gains, the mechanism for these gains is different than adults, and is most likely due to neural adaptations rather than muscle hypertrophy.(80, 81) Therefore, children have a reduced need for challenging strengthening programs. Instead, resistance training programs utilizing high repetitions and low weight have been encouraged.(82) Young or physically immature individuals, are at a greater risk for overuse injury compared to older individuals and this may also need to be a consideration within an injury prevention program.(83, 84) This risk may be due to inexperience, decreased overall fitness level, incomplete physes or because muscle strength and soft tissue growth appears to occur after bone growth.(83-86) Recovery time for children is essential to avoid these overuse injuries, so reduced frequency of a training program is recommended.(84, 86)

While feedback and instruction are frequently components of ACL injury prevention programs, it appears young pre-pubertal children may benefit from this type of intervention more than their older peers. Young children have been shown to require more continuous feedback and utilize different forms of attention compared with their older counterparts when learning a task.(87, 88) Task difficulty should match the cognitive ability of the learner when the learner is acquiring a new skill, which is especially true for children.(89) Wulf and Shea (2002) recommended that difficult tasks should be separated into basic components when taught to children.(90)

Recommendations for pediatric anaerobic and aerobic training programs have been made, but no one has investigated whether an ACL injury prevention program should account for the differences between adults and children in strength, physical, and motor development, as well as motor learning.(86) Based on these differences, it appears ACL injury prevention programs for children should be implemented with lower frequency, higher repetitions, basic progressions, more instruction and feedback opportunities, and encourage mature performance of basic fundamental motor skills, such as landing from a jump.

Addressing differences between children and adults may enhance the ability to change neuromuscular risk factors and reduce ACL injury risk in a young population.

2.5 Review of Literature Related to Methods

2.51 Time to Stabilization Test

The time to stabilization test (TTS) requires stabilization of a single-leg landing and was first studied by Colby et al.(147) to determine if a functional test for stability could reliably differentiate between injured and uninjured limbs. The authors concluded that the TTS was able to identify uninjured and ACL-reconstructed limbs, and recommended the use of the test for evaluating lower limb instability. Since this study, the TTS has been used frequently to distinguish differences between populations, such as patients with functionally unstable ankles or stable ankles(195-197) or sexes,(198) as well as between conditions of external ankle support.(199, 200) Stabilizing on a single leg during landing is a critical skill to prevent injury, as this movement has been associated with ACL injury.(58) Therefore, the TTS appears to be a valid and reliable measure for evaluating dynamic balance ability, and it makes sense to use this test to determine the potential effectiveness of an ACL injury prevention program.

2.52 Choice of Tasks to Evaluate Changes in Lower Extremity Movement

To our knowledge, all of the previous studies evaluating the effects of an ACL injury prevention program have compared lower extremity kinematics and kinetics during a landing task. Examples of these landing tasks include a stop jump task,(201, 202) a vertical jump,(32, 33) and a drop vertical jump.(34, 35, 38, 39, 203) While ACL injuries commonly occur during a landing, this mechanism of injury only accounts for a small percentage of ACL injuries in soccer.(56, 57) The more common mechanism of injury in soccer appears to be due to changing direction.(58) Cowley et al.(59) also demonstrated greater amounts of knee valgus in soccer players during a cutting task compared to a drop vertical jump. Therefore, evaluating the changes occurring in lower extremity kinematics and kinetics during a cutting task instead of a landing task may enhance our ability to hypothesize the potential an ACL injury prevention program to reduce injures in soccer.

Several studies have observed gender differences in lower extremity kinematics and kinetics during a sidestep cutting task.(17, 63-65) These findings support the use of a sidestep cutting task to evaluate differences in movement patterns, however, the majority of these studies and previously discussed work that studied landing patterns evaluate tasks that are anticipated, or planned. While this information is beneficial, it does not replicate what actually occurs during sport and most likely during an injury.(60-62) As a result of these conclusions, several studies have included unanticipated cutting tasks into their laboratory testing protocols. The general consensus is that unanticipated tasks result in greater amounts of neuromuscular risk factors for injury, such as increased knee joint loading, decreased initial knee flexion, increased knee flexion and valgus moments, and increased amounts of knee valgus compared with anticipated movements.(60-62, 66)

The most common way to incorporate unanticipated cutting tasks into a laboratory based testing protocol is to use a light timing system.(60, 62, 65, 66) This involves participants running toward a force plate, triggering the light system, which causes an arrow or a light to be displayed directing the participant to move in a specific direction. This method does cause reactive movements, but the task is still not realistic to a game scenario.(61) A common maneuver in sports, such as soccer, is to evade or mark an opponent. McLean et al.(61) addressed this limitation by using a stationary skeleton to simulate the presence of a “defensive opponent” while the participants performed the cutting task. The authors concluded that this opponent resulted in increases in medial ground reaction forces, hip flexion, hip abduction, knee flexion, and knee valgus compared with the sidestep cutting condition with no opponent present. This study made progress in the ability to make laboratory based testing more realistic, however, the “defensive opponent” was stationary and predictable. Using a live model as the opponent to cause the participants to decide which direction to move may be the next logical progression for simulating real game and injury scenarios.

CHAPTER 3

METHODS

3.1 Research Design

A cluster randomized controlled trial was used to evaluate changes in potential neuromuscular risk factors before and after the completion of one of three ACL injury prevention programs: pediatric (PED), traditional (TRAD), or control (CON). Six teams were originally invited to participate in this study, and were stratified by sex, and cluster randomized into one of the three programs. As a result, one boys' and one girls' team were assigned to each program. The boys' control program team had a smaller roster than originally anticipated so a seventh team was recruited and combined with the original boys' control team to ensure sufficient sample size. The four intervention teams performed their respective program as part of their normal practice warm-up during a nine-week intervention period while teams assigned to the control programs completed a warm-up designated by their coaches. Players from all seven teams performed the programs but only players who volunteered to participate in the study attended two testing sessions, one before (August 2008) and one after (October 2008) the completion of the programs. The dependent variables for this study included: lower extremity kinematics (knee flexion, knee valgus, tibial rotation, hip flexion, hip adduction, hip rotation) and kinetics (knee extension moment, knee valgus moment, tibial rotation moment, anterior tibial shear force) during an anticipated and two unanticipated sidestep cutting tasks, as well as power and jump height during a maximal vertical jump and dynamic balance ability. All testing occurred on the dominant lower extremity, which is the lower extremity preferred to kick a ball for maximal distance.

3.2 Participants

The a-priori power analysis for the majority of the dependent variables, including the primary variables of interest, indicated that in order to have a power of 80%, five to twenty participants need to be included in each group. Therefore, seventy-two pediatric (nine and ten year old) soccer players (36 males, 36 females; 24 subjects per group) from seven teams were asked to volunteer for this study. All participants were free from any injury or illness that prohibits soccer activity at the time of initial testing to reduce injury potential during testing. During a pre-season meeting, all parents and players read and completed informed consent and assent forms, which were approved by the university's Institutional Review Board. Participants and their parents completed a baseline questionnaire to gather information about the participants' injury, growth, and sport participation history, as well as their basic cognitive development. During the post-test only, participants completed another questionnaire to gather information about participation in physical activity outside of the soccer association and injuries sustained during the intervention period. These were all important factors that were not used for inclusion or exclusion criteria but were evaluated as potential covariates.

Acquiring additional information regarding the participants' injury, growth, physical activity history, in addition to their state of cognitive development greatly assisted with the interpretation and comprehension of the results. Information regarding a participant's injury history was beneficial because a prior injury strongly predicts repeated injury, and may alter movement patterns and the outcomes of the injury prevention programs.(160-162)

Differences in muscle activation and movement patterns have been observed between individuals in various stages of biological maturity.(75, 76) Therefore, the rationale for obtaining information about the participant's growth history is that growth velocity can be used as an indicator of biological maturity and rapid growth spurts may also impact a child's ability to learn new motor skills.(89) Sport activity history and knowledge of previous participation in jump training programs was also important information to gain because these factors may have influenced the manner in which the participants responded to the program and to playing soccer in general. Acquiring information about the participants' current state of cognitive development was important because according to previous motor learning research it is important for a task's difficulty to match the cognitive ability of the learner.(82, 180) Therefore, participants who possess greater cognitive maturity may have responded more effectively to the injury prevention programs.

3.3 Procedures

All participants attended two identical testing sessions lasting approximately one hour in a sports medicine research laboratory. The second session (post-test) occurred approximately nine weeks after the first session (pre-test), which coincided with completion of the intervention period (Table 1). Previous literature on youth resistance training has successfully used an eight week intervention period,(201) but the addition of one week allows three phases of three weeks to be used in this study, and is comparable to a recent investigation by Herman et al.(169) who studied the effects of strength training on lower extremity biomechanics. All participants wore standardized shorts and shirts, as well as their own running shoes. The same shoes were worn for both testing sessions. Participants' height and weight recorded upon arrival to the laboratory.

The five tasks included a maximal vertical jump test, a balance test, as well as one anticipated and two unanticipated sidestep cutting tasks. During the anticipated cutting task, participants received a verbal cue at the beginning of the task instructing them to cut toward their non-dominant side. The participants were not provided with a verbal cue for the unanticipated cutting tasks, but instead were instructed to cut toward one direction or the other during the task via visual feedback provided by a live model. The false cue unanticipated cutting task required the participants to begin cutting one direction and then change directions due to a preliminary "false" instruction that was immediately followed by an additional cue during the task. The three cutting tasks were "blocked" together, meaning they were always performed together in a randomized order as they all required motion analysis. The participants performed the vertical jump test, dynamic balance test, and the three blocked tasks (cutting tasks) in a counterbalanced order.

Maximal Vertical Jump Test

The participants performed three trials of a double leg countermovement maximal vertical jump test so that power and jump height could be assessed. The participants began with their feet shoulder width apart while standing on a force plate (Bertec Corporation, Columbus, OH). An overhead goal was used to encourage maximal performance.(196, 204) The participants were instructed to jump for maximal vertical height and try to touch the top of a stick, and arm motion was not restricted. They performed two practice trials, and the overhead target was placed slightly above the participant's highest practice jump. Thirty seconds of rest were allowed between each trial.

Dynamic Balance Test

Participants performed a dynamic balance assessment called the Time to Stabilization Test (TTS) on their dominant limb. The TTS has been shown to be a reliable and valid measure of dynamic postural stability.(196, 198) The participants stood on a 30 cm high box placed a distance of half of their body height away from the force plate (Bertec Corporation, Columbus, OH). The participants jumped forward from the box using their non-dominant foot and landed with their dominant foot in the center of the force plate while maintaining their hands on their hips and their non-dominant foot off of the ground. Participants were instructed to balance as quickly as possible without putting their non-dominant foot down, and to remain in single-leg stance for 10 seconds. This protocol was modified slightly from previous studies using the TTS to accommodate the participants' ability, as noted during pilot work. Previous studies have required participants to jump forward a distance of 70 cm and a height of 50% of their maximal vertical jump.(34, 42, 56, 183) The modified protocol standardized the jump height by requiring participants to jump down and forward a distance relative to their height without trying to touch a target. Trials were noted and repeated if the participants were unable to maintain this single-limb landing position with their hands on their hips, if a subsequent hop occurred after landing, or if a subject jumped vertically from the box instead of straight down and forward. The investigator watched the participants perform the jump to ensure they did not jump vertically. Three trials of the TTS were performed.

Sidestep Cutting Tasks

Pictures of the sidestep cutting tasks are provided in Figures 1-3. Participants completed 3 repetitions of the anticipated, unanticipated, and false cue unanticipated cutting tasks, as well as several unanticipated cutting tasks toward the wrong direction, in a randomized order.

The order of these tasks was randomized using a random number generator program in a customized software program (MatLab version 7; MathWorks, Natick, MA). For all three cutting tasks, the participants began standing on a box 30 cm high placed a distance of half of their body height away from the force plate. The participants jumped forward off both legs toward the force plate, landed with their dominant foot on the force plate, performed a 50-70° cut, and ran 3-4m. A live model was 3 m away from the far end of the force plate (relative to the participants) and jumped forward off a 30-cm high box and landed on his dominant leg. The participants were instructed to begin their jump immediately after the model jumped and to follow the model, who was the same individual for all testing sessions. Following the model simulated a task common in the game of soccer where players are required to "mark" an opponent to prevent them from obtaining the ball. Trials were excluded and repeated if the participants did not jump immediately after the model jumped, if the participant's entire foot did not make contact with the force plate, or if the participants did not perform the appropriate task. A digital timing system measured the time between the instant the model jumped and the participant jumped to ensure no more than 400 ms occurred between jumps. Participants had at least 20 seconds of rest between each repetition to reduce the likelihood of fatigue, and were given 1-2 practice trials of each task for familiarization prior to data collection.

Anticipated Sidestep Cutting Task

For the anticipated task, participants were told prior to jumping from the box which direction the model would move. The participants landed with their dominant foot in the center of the force plate, made a 50-70 degree change of direction toward their non-dominant side, and ran a distance of 3-4m to follow the model. Three trials of the anticipated task were performed, and trials were excluded and repeated if the participants performed one of the errors described previously or did not perform a 50-70 degree change of direction, which was clearly marked on the ground using tape.

Unanticipated Sidestep Cutting Task

The only difference between the anticipated and the unanticipated tasks was that the participants were not told which direction the model would move prior to completing their jump from the box. They were instructed to jump immediately after seeing the model jump and to cut in the same direction as the model. The model changed direction while the participants were in the air after jumping from the box. Three trials of the unanticipated task were performed with the participants cutting toward their non-dominant side and three trials were performed with the participants cutting toward their dominant side. Only the cuts toward the participant's non-dominant side were included for data analysis.

False Cue Unanticipated Sidestep Cutting Task

The false cue unanticipated cutting task was identical to the unanticipated task except that the model shifted his trunk either left or right while the participants were in the air and then changed direction to cut at a 50-70 degree angle. This caused participants to land prepared to cut in one direction and then have to change direction in order to follow the model. Three trials were collected with the participants making the final cut toward their non-dominant side (started toward their dominant side and changed toward their non-dominant side) and three trials were performed in the opposite direction.

3.4 Implementation of Injury Prevention Programs

Following the pre-test session, the six teams were stratified by gender and randomly assigned to one of three injury prevention programs: pediatric (PED), traditional (TRAD), or control (CON). Therefore, one male and one female team were in each program group (n=24). Teams assigned to either the PED or TRAD program completed the ten to fifteen minute program as the team's warm-up before every practice, which was two to three times per week during the nine week intervention period. The principal investigator or a research assistant taught the players the program within one week of completing the pre-test session, supervised the team's implementation of the program at every practice to provide feedback and technique instruction, and monitored compliance. Proper technique was continually stressed to all of the participants while they performed the exercises. Technique was enforced by telling the participants to "bend their knees, hips, and trunks", "land softly", "keep their knees over their toes", and "their toes pointing straight ahead" during all of the exercises. Teams assigned to the CON program conducted their normal warm-up as decided by their coach. The CON teams were also supervised once a week to ensure they did not perform any warm-up that was similar to either of the two intervention programs.

Traditional ACL Injury Prevention Program

The traditional program was modified from previous ACL injury prevention programs that have been shown to be effective with participants in high school or college, but failed with a young population.(34, 38, 42, 56, 183) This program consisted of static flexibility, balance, strengthening, agility, and plyometric exercises on both limbs. Participants ran forward a distance of 10 m after completing each exercise to make it a dynamic warm-up. The speed of this run gradually increased as the participants progressed through the warm-up. All exercises were performed on both legs, and the program required approximately 10-15 minutes to complete. Table 2 provides a description of the traditional ACL injury prevention program.

The static flexibility exercises involved stretching of the gastrocnemius, adductor, hip flexor, and quadriceps muscles. Participants also performed three balance exercises. The first balance exercise was a double limb jump with a 180 degree twist in the air followed by a double limb landing and stabilized hold for one second (“180° Jump”). The second balance exercise required participants to maintain a single limb stance with their knee slightly flexed as they threw a soccer ball back and forth with a teammate (“Single Limb Ball Toss”). The third balance exercise involved a hop forward from one limb to a single limb landing and balance (“Forward Hop to Balance”).

Strengthening, agility, and plyometric exercises composed the remainder of the traditional ACL injury prevention program. One strengthening exercise targeted the core musculature (“Hip Bridge”), while the remaining two strengthening exercises focused on the muscles of the lower extremity, specifically the quadriceps and hamstrings (“Walking Lunges”, “Single Leg Squat”). The agility exercises required lateral movement (“Sideways Shuffle), dynamic direction changes (“Z-cuts”), and forward propulsion (“Bounding”). Finally, four plyometric exercises were incorporated into the traditional program. Two plyometric exercises required primarily either horizontal or vertical motion, coordination, and strength (“Broad Jump”, “Squat Jumps”) while the remaining two plyometric exercises focused on changing either sagittal or frontal plane directions while hopping back and forth over a line (“Forward Line Hops”, “Sideways Line Hops”).

Pediatric ACL Injury Prevention Program

The pediatric program consisted of three phases. The first phase was performed twice per week, and the final two phases were performed three times per week. The three progressive phases in the pediatric program were further delineated. The first week of each phase was an introductory phase with time spent on emphasizing proper form, verbal and visual feedback, and scaled down repetitions of each exercise. The remaining weeks of each phase included the addition of one or two exercises and added movement between all exercises. Table 2 provides a detailed description of the pediatric ACL injury prevention program. All three phases required 10-15 minutes to complete.

Similar to the traditional program, the pediatric program incorporated several of the exercises into a dynamic warm-up protocol. The two programs were very similar during the first phase by requiring participants to run at progressively increasing speeds following the exercise movement (Figure 1a). However, participants completing the pediatric program performed a “timing” run after the exercise movements instead of the speed forward run during the second phase. The “timing” run involved two participants finishing the exercise movements at the same time, run at a diagonal, and crossed in front of or behind the opposite player. This movement required the participants to control their body and use visual information about another moving player to direct their motion to avoid a collision (Figure 1b). During the third phase, a sidestep cut was performed at the end of the diagonal run (Figure 1c).

Instead of static flexibility exercises, the pediatric program consisted of dynamic flexibility exercises. The dynamic flexibility exercises targeted the gastrocnemius (“Walking Calf”, “Hand Walk”), hamstrings (“Straight Limb March/Skip”, “Walking Hamstring”, “Hand Walk”), quadriceps (“Walk/run Butt Kicks”, “Walking Quadriceps”), hip flexor (“Hip Flexor Walk”, “Twisting Hip Flexor Walk”), and gluteal (“Knee to Chest”, “Leg Cradle”) muscles. The pediatric program consisted of some of the same balance exercises as the traditional program, such as the “Single Limb Ball Toss”, the “180 Degree Jump to Balance”, and the “Forward Hop to Balance”. However, the “Single Limb Ball Toss” and the “180 Degree Jump to Balance” were each only completed during one three-week phase. The “Forward Hop to Balance” exercise progressed during the second and third phases to include movement in the frontal and transverse plane (“Sideways Hop to Balance”, “Twisting Hop too Balance”). Finally, the pediatric program also performed a single limb balance exercise while a partner pushed the other partner in different directions (“Single Limb Balance with Perturbations”) during the last phase.

The pediatric program began with primarily strengthening exercises and minimal plyometric exercises and transitioned by gradually changing these proportions. As a result, the final phase included only one strengthening exercise and several plyometric exercises. Strengthening exercises for the pediatric program included lunges in three planes (“Forward/ Sideways/Transverse Lunge”), a squat progression (“Double Limb Squat”, “Single Limb Squat”), progressive core exercises (“Hip Bridge”, “Human Arrow”, “Side Plank”), and lower leg strengthening exercises (“Toe Walk”, “Double/Single Heel Raises”). The plyometric exercises emphasized rapid changes of direction with double to single leg progressions (“Forward/sideways Line Hops”), vertical jumps (“Squat Jumps”, “Tuck Jumps”), and consecutive jumps for distance (“Broad Jumps”). Finally, the pediatric program incorporated several agility exercises (“Side Shuffle”, “Z-cuts”, “High Knee Run”, “Skipping”, “Quick Cuts”).

3.5 Instrumentation

Lower extremity kinematics and kinetics were collected using Vicon motion analysis system and Vicon Nexus Software (Vicon Motion Systems, Centennial, CO) during an anticipated and an unanticipated cutting task. Seven infrared video cameras captured trajectories of reflective markers worn by the participants at a sampling rate of 150 Hz. Vertical ground reaction force was collected by a force plate (Model # 4060-08A, Bertec Corp., Columbus OH) at a sampling rate of 1,500 Hz and was synchronized with the kinematic data. Prior to data collection, the global axis system was established with the positive x-axis pointing in the direction participants ran before cutting (forward), positive z-axis directed vertically, and the y-axis directed to the left of the participants. Segment axes were aligned with the global axes. Prior to the cutting tasks, passive reflective markers were placed on the following landmarks: right and left acromion processes, right and left anterior superior iliac spines, proximal sacrum (S1), right and left greater trochanters, lateral aspects of the right and left thighs, lateral epicondyles of the right and left knee, medial epicondyles of the right and left knee, lateral aspects of the right and left shanks, right and left lateral malleoli, right and left medial malleoli, right and left posterior calcanei, the heads of the right and left 5th metatarsals, and the heads of the right and left 1st metatarsals. The markers were affixed to the skin, clothing, and shoes with double-sided adhesive tape. Following marker placement, participants were asked to stand in the center of the calibration area (2.5 m high × 2.5 m long × 1.5 m wide) with each foot on a force plate (Type 4060-08, Bertec Corporation, Worthington, OH), in order to collect a static calibration trial. After the calibration trial, the markers on the medial epicondyles and medial malleoli were removed.

A live model was used to signal the start of the cutting tasks and was the same individual for all testing sessions. A wireless timing system (Sparq XLR8 Digitial Timing System, Wausau, WI) measured the time between when the live model and the participant jumped from a box to ensure the participant was in the air when the live model changed directions. One timing gate was placed in front of the live model and a second timing gate was in front of the participant. A maximum time of 400 ms was allowed between the trigger of the live model's timing gate and the participant's timing gate.

A piezoelectric non-conductive force plate (Model #4060-NC Bertec Co., Columbus, OH) measured ground reaction forces at a sampling rate of 1,000 Hz during the vertical jump test, which was used to calculate impulse, power, and vertical jump height. The same force plate was used during the time to stabilization test at a sampling rate of 180 Hz.(205) All data for the vertical jump test and TTS were collected through Motion Monitor software (Innovative Sports Training Inc, Chicago, IL).

3.6 Data Reduction

All kinematic and kinetic data were transferred into Motion Monitor Software (Innovative Sports Training Inc, Chicago, IL) for data processing and exported into a customized software program (MatLab version 7; MathWorks, Natick, MA) for data reduction. All kinematic data were smoothed with a Butterworth (4th order, zero phase lag) low-pass digital filter at 15 Hz. The vertical ground reaction force data were normalized for bodyweight (N) and the moment data were normalized to the product of bodyweight and height (N*m).

Three dimensional coordinates were estimated from the two-dimensional trajectories of the reflective markers. Knee and ankle joint centers were estimated as centroids from the medial and lateral malleoli and epicondyles, respectively, and the hip joint center was estimated from the markers on the bilateral anterior superior iliac spines using the Bell method.(205) The three-dimensional coordinates of body landmarks determined segment locations and orientations of the pelvis, femur, and shank. The three-dimensional coordinates of the knee joint center, the ankle joint center, and the anterior tibial marker defined the tibial reference frame. The three-dimensional coordinates of the knee joint center, the hip joint center, and the anterior thigh marker defined the thigh reference frame. Finally, the three-dimensional coordinates of the hip joint centers and the proximal sacrum marker defined the pelvis reference frame. Kinematics of the shank and thigh, as well as the thigh and pelvis segments determined knee and hip joint angles, respectively. Joint motions were determined through a joint coordinate system using Euler angles.(206) The axes system established used a right-hand system. The following motions were positive: knee flexion/hip extension, adduction/varus, and internal rotation. Data were exported from the Motion Monitor software with the following order of rotations of Euler angles: flexion/extension (x-axis), adduction (varus)/abduction (valgus) (y-axis), internal/external rotation (z-axis). Using standard inverse dynamics, proximal anterior tibial shear force and three-dimensional hip and knee internal joint moments were calculated.

Knee flexion, knee valgus, tibial rotation, hip flexion, hip adduction, and hip rotation angles were selected at initial ground contact during the cutting task, which was defined as the instant the vertical ground reaction force exceeded 10N. Peak values for these same angles, as well as peak anterior tibial shear force, peak knee flexor, valgus, and rotation moments were selected during the first 40% of the stance phase during the cutting task. The stance phase was defined as the time between initial ground contact and toe-off, which occurred when the vertical ground reaction force dropped below 10N following initial ground contact. The data from the three trials of each task during pre-test and post-test were averaged together.

Data from the vertical jump test and the time-to-stabilization test were exported into a customized software program (MatLab version 7; MathWorks, Natick, MA) for reduction.

The time spent in the air during the vertical jump test, which was determined as the time between toe-off (VGRF<10N) and initial ground contact (VGRF>10N), was used to calculate vertical height with the following formula (g represents constant acceleration due to gravity):

$$\text{Height} = 0.5(g(t/2)^2)(93)$$

Power was computed using the following equation:

$$\text{Power (W)} = 61.9 \times \text{jump height (cm)} + 36.0 \times \text{mass(kg)} - 1822.(92)$$

The three trials were averaged for all analyses.

The time-to-stabilization data were reduced using a method described by Ross et al.(196) The absolute ground reaction force ranges for both the anterior-posterior (A/P) and medial-lateral (M/L) between the eighth and ninth seconds of single limb stance were divided by the participant's body weight. These values were used to determine a mean range-of-variation value for each component and across all 3 trials. Standard deviations (SDs) were also calculated for each component and three SDs were added to each mean range of variation. The A/P and M/L components of the ground reaction force were analyzed separately for each participant. The components were rectified and a decay curve was determined by fitting the data with an unbounded third-order polynomial. A horizontal line was inserted over the top of the data for each component, which was equal to the component's mean range of variation plus three SDs. The time-to-stabilization for each component and each participant's trial was the point the unbounded third-order polynomial transected the mean range of variation value. The average time-to-stabilization value from the three trials for each component were used for analyses.

3.7 Statistical Analyses

Research Questions 1-4

Seven possible covariates were evaluated for a significant relationship with the treatment effects (change scores) for all dependent variables. These covariates included variables regarding anthropometrics (Pre-test BMI, Change in BMI between testing sessions, % Predicted Adult Height), demographic information (sex, age in months), memory and learning ability (Learning and Total scores from BVMT), and the initial value of each dependent variable. Change scores were calculated for all dependent variables by subtracting the pre-test value from the post-test value.

Separate analyses of covariance were conducted for each dependent variable, and covariates were included in the model if they had a statistically significant effect on the change score. If no covariates had a significant effect on the model, separate one-way analyses of variance were performed. Significant group effects were evaluated with a Bonferroni post hoc correction. All data analyses were performed using SPSS version 16.0 (SPSS, Inc., Chicago, IL) with an *a priori* alpha level of 0.05. The clustering effect due to team instead of individual was ignored with the analyses since the number of clusters (7) was too small to permit use of established statistical methods for clustered data.

Research Questions 5

Separate one-way analyses of variance were conducted to evaluate differences between sexes during the balance and vertical jump test during both pre-test and post-test. All data analyses were performed using SPSS version 16.0 (SPSS, Inc., Chicago, IL) with an *a priori* alpha level of 0.05.

CHAPTER 4

SUMMARY OF RESULTS

4.1 Introduction

This chapter provides a summary of the results for each research question followed by a brief interpretation. A more detailed interpretation of the results for research questions one, two, and four is presented in the two manuscripts included as appendices. Chapter five provides further interpretation and discussion related to research questions three and five since these data are not addressed in the two manuscripts. The most important findings from this investigation are that the pediatric ACL injury prevention program caused changes in transverse plane knee kinematics during the anticipated and unanticipated cutting tasks, but the traditional program did not result in any changes in the joint kinematic and kinetic variables studied. The traditional program successfully improved balance and vertical jump ability, however, these changes appear to be due to the specificity of the training program with the assessment tasks. These results are important as they demonstrate children less than twelve years old can modify potential neuromuscular risk factors for ACL injury and these changes are influenced by the type of training program.

4.2 Overview

Six teams were initially invited to participate in this study because the league estimated 12 athletes per team. However, an additional team was included because one of the boys' teams fell short of the proposed number with only 8 athletes. Therefore, the original boys team that had only a small number of athletes and the seventh team were grouped together as one team for the cluster-randomization. The six teams were stratified for sex and randomized into one of three programs: pediatric, traditional or control. Sixty-six participants from these teams volunteered to participate in this investigation. Sixty-five participants completed both testing sessions and attended greater than 80% of all program sessions. One control participant only completed the pre-test session due to scheduling conflicts and was removed from the analyses. No injuries were sustained during the course of the testing sessions and intervention period. Complete demographic information for all participants included in the analyses is provided in Table 1.

4.3 Results

4.3.1. Research Question 1

The first analysis evaluated differences in lower extremity biomechanics between the pediatric, traditional, and control programs during an ***anticipated sidestep cutting task***. Means and standard deviations during the two testing sessions, change scores and measures of variability, as well as all statistical results are presented for the kinematic dependent variables at initial ground contact in Table 3, the peak of each dependent variable during the first 40% of the stance phase in Table 4, and the peak of each kinetic dependent variable during the first 40% of the stance phase in Table 5. There was a significant difference between groups in change scores for tibial rotation at initial ground contact ($F_{(2,62)}$=3.79, p=0.03, η^2=0.11) and peak tibial internal rotation ($F_{(2,63)}$=4.96, p=0.01, η^2=0.14). Post hoc testing revealed that the pediatric program caused participants to land with significantly less tibial external rotation at initial ground contact (p=0.008, Effect size=0.75)(Figure 4) and attain greater internal rotation during the stance phase compared to the control program (p=0.005, Effect size=0.93)(Figure 5). The traditional program did not cause a significant change in any dependent variable during the anticipated cutting task (p>0.05). No other significant findings were observed for any of the kinematic and kinetic variables studied (p>0.05).

Interpretation:

The results for research question one indicate the pediatric ACL injury prevention program successfully modified transverse plane knee motion during an anticipated cutting task. However, the traditional program did not cause participants to modify their cutting technique. These findings support the research hypothesis that the pediatric program would result in greater changes compared to the control or traditional program because it accounted for differences between children and adults in strength, cognitive, and motor development.

The pediatric program caused participants to land with decreased tibial external rotation, or less of a “toed-out” posture, which resulted in a more neutral tibial rotation position. Participants were encouraged throughout the pediatric program to “keep [their] toes straight ahead.” Therefore, it appears the young participants were able to learn a new strategy while performing the cutting task. This change may reduce strain on the ACL as tibial external rotation has been shown to cause a shearing force on the ACL.(207) Landing with less tibial external rotation caused greater amounts of tibial internal rotation during the first 40% of the stance phase as well. We believe this is representative of a shift in tibial rotation since tibial rotation displacement did not change dramatically between pre-test and post-test. Since ACL injuries appear to occur early in the stance phase, we believe the reduction in tibial external rotation is clinically significant. However, since excessive amounts of tibial internal rotation have been associated with ACL strain,(112) it is possible the increase in tibial internal rotation was actually a detrimental result of the pediatric program. Future research should further evaluate the relationship between tibial rotation and ACL loading.

Despite changes in tibial rotation, the pedatric program did not result in concurrent changes in other planes of motion. This is contrary to the research hypothesis that improvements in cutting technique would be observed in multiple planes. Failing to observe changes in other variables may be attributable to the nature of the assessment and the specificity of the training. This is the first study to evaluate changes in biomechanics after an injury prevention program during a cutting task that demands dynamic transverse plane control. Other studies have demonstrated success with modifying sagittal and frontal plane variables after an injury prevention program using primarily a sagittal plane task, such as a jump landing. The majority of the exercises in the pediatric injury prevention program were designed to teach proper technique during slow and controlled movements and gradually progress into more dynamic movements. Greater changes may have been observed with tasks involving only one plane of motion at a time or if the pediatric program had progressed further to include more training with the quick sport-specific movement of cutting.

4.3.2. Research Question 2

The analyses for the second research question evaluated differences in lower extremity biomechanics between the three programs during the ***unanticipated sidestep cutting task***. Means and standard deviations during the two testing sessions, change scores and measures of variability, as well as all statistical results are presented for the kinematic dependent variables at initial ground contact in Table 6, the peak of each dependent variable during the first 40% of the stance phase Table 7, and the peak of each kinetic dependent variable during the first 40% of the stance phase in Table 8. There was a significant difference between groups in change scores for tibial rotation at initial ground contact ($F_{(2,63)}=6.92$, $p=0.002$, $\eta^2=0.19$), peak tibial internal rotation ($F_{(2,63)}=6.49$, $p=0.003$, $\eta^2=0.18$), and peak tibial external rotation ($F_{(2,63)}=5.73$, $p=0.005$, $\eta^2=0.16$). Post hoc testing demonstrated that the pediatric program resulted in less tibial external rotation at initial ground contact ($p=0.001$, Effect size=0.93)(Figure 6) and reduced the maximum tibial external rotation ($p=0.001$, Effect size=0.86)(Figure 7) during the first 40% of the stance phase compared to the control program. The pediatric program also resulted in greater tibial internal rotation during the stance phase compared to the control program ($p=0.002$, Effect size=0.98) and the traditional program ($p=0.003$, Effect size=0.92)(Figure 8). The traditional program did not cause any significant changes in any dependent variable during the unanticipated sidestep cutting task ($p>0.05$). There were no other significant differences ($p>0.05$).

Interpretation:

The results of research question one and two were very similar, which suggests the changes in lower extremity biomechanics from an injury prevention program persist across different types of cutting tasks. The pediatric ACL injury prevention program caused changes in the transverse plane, but the traditional program was ineffective with modifying lower extremity biomechanics. This agrees with the research hypothesis that a program designed for the pediatric population by adding more time for instruction, feedback, as well as incorporating more progressions and variety would result in greater changes compared to a traditional injury prevention program.

The unanticipated cutting task was evaluated in this investigation to determine whether changes from an injury prevention program would transfer between various assessment tasks. Unanticipated cutting has been shown to increase the load on the ACL compared to anticipated cutting and is considered to be more realistic to a game scenario.(60, 208) The results were similar between anticipated and unanticipated conditions. The similarity across tasks may indicate an injury prevention program consistently results in the same changes during any type of cutting task. Another possible explanation for the similarity is that the cutting task itself was challenging for the youth participants resulting in little room for variability. Unfortunately, this is the first study to evaluate the effects of an injury prevention program using a cutting task, so comparisons to other investigations are minimal. Future research should compare changes due to an injury prevention program across cutting and landing tasks to enhance the understanding of the effects of an injury prevention program in a youth population.

4.3.3. Research Question 3

The third research question was addressed by evaluating change scores in lower extremity biomechanics between the three programs during the ***false cue unanticipated cutting task***. The false cue unanticipated cutting task was an extremely challenging task for the young participants. Only 18 participants were able to successfully complete the task during both the pre-test and the post-test. Originally, an acceptable trial during this task required the participant to land with only one foot on the force plate and cut in the direction of the live model. The false cue prevented many participants from cutting in the correct direction or from landing with only one foot on the force plate. The low number of successful trials led to the expansion of the inclusion criteria. An acceptable trial was redefined as a trial where the participant performed a cut in the correct direction regardless of whether one or two feet landed on the force plate. The operational definition change permitted the inclusion of 42 participants into the analysis for this research question. Only the kinematic data were analyzed because the kinetic data were invalid during a double foot landing.

Means and standard deviations during the two testing sessions, change scores and measures of variability, as well as all statistical results are presented for the kinematic dependent variables at initial ground contact in Table 9 and the peak of each dependent variable during the first 40% of the stance phase Table 10. There were no significant differences between groups in any dependent variable during the false cue unanticipated cutting task ($p>0.05$).

Interpretation:

The false cue unanticipated cutting task was a novel assessment tool, which may have contributed to a lack of significant changes between programs. This task required participants to not only respond to a cue directing them which way to move, but also to quickly adjust themselves and change directions. While this action is common during intense sports, such as soccer, it may have been too challenging for the young participants in this study. As discussed previously, the majority of the training exercises required proper lower extremity control during relatively slow movements. It appears any improvements in movement technique and transverse plane control did not transfer to this novel task. Future research should evaluate this task in older populations and after more training progressions that include unanticipated cues.

4.3.4. Research Question 4

The fourth set of analyses evaluated differences in dynamic balance ability and vertical jump performance between the three programs. Means and standard deviations during the two testing sessions, as well as change scores and measures of variability are presented for the two time-to-stabilization dependent variables and the two vertical jump variables in Table 11. An analysis of covariance was used to analyze change scores in anterior-posterior (A/P) time-to-stabilization between groups with sex and the pre-test anterior-posterior time-to-stabilization value as the covariates. The group mean change scores were adjusted for sex (1.43) and the pre-test A/P value (2.71s) and a significant difference between groups was detected ($F_{(2,60)}$=6.34, p=0.003, η^2=0.17). Post hoc testing demonstrated that the traditional program caused greater improvements in A/P time-to-stabilization compared with the control program (p<0.001, Effect size=0.82)(Figure 9). However, the changes due to the pediatric program were not significantly different than the control or traditional programs (p>0.05). An analysis of variance was performed to evaluate differences in medial-lateral (M/L) time-to-stabilization between groups and did not detect any significant differences ($F_{(2,61)}$=0.59, p=0.56, η^2=0.02).

An analysis of covariance was performed to evaluate changes in vertical jump height between programs because the pre-test vertical jump height value had a significant effect on the ability to improve vertical jump height. After adjusting the group change scores for the pre-test value (25 cm), this analysis demonstrated a significant difference between change scores ($F_{(2,61)}$=3.45, p=0.04, η^2=0.10). Post hoc testing revealed that the traditional program resulted in greater improvements in vertical jump height ability compared with the control program ($p=0.15$, Effect size=0.71)(Figure 10). There were no differences between the pediatric program and either the control or traditional programs ($p>0.05$). There were no significant difference between groups in power using an analysis of variance ($F_{(2,61)}=2.79$, $p=0.07$, $\eta^2=0.08$).

Interpretation:

Contrary to the research hypothesis, the traditional program caused improvements in anterior-posterior time-to-stabilization and maximum vertical jump height while the pediatric program did not result in any significant changes. These findings are most likely due to the specificity of the training programs. Participants in the traditional program performed a forward hop to balance exercise for nine consecutive weeks, which was almost identical to the time-to-stabilization task. Therefore, it appears training the hop to balance activity results in improvements in that specific task. While the pediatric program did perform that specific exercise, it was only performed for the first three weeks after which multiplanar progressions of that exercise were added. It is reasonable to hypothesize that if the assessment task had involved movement in the frontal or transverse plane, the pediatric program may have caused greater improvements compared to the traditional program.

The traditional program also completed maximum vertical jumps for nine consecutive weeks. This is in contrast to the pediatric program, which included similar types of jumps but only after the first few weeks were spent focusing on proper movement technique during less dynamic exercises. The design of the pediatric program was focused on teaching the participants how to move correctly, build a foundation of strength to prevent injury during more dynamic exercises including plyometrics. However, the specific training of the traditional program appears to correlate with significant improvements in maximum vertical jump height and did not result in any overuse injury. In conclusion, specificity of training should be considered in future designs of injury prevention programs.

4.3.5. Research Question 5

Differences in lower extremity biomechanics were evaluated between sexes during the anticipated, unanticipated, and false cue unanticipated cutting tasks both before and after completion of the intervention period. Complete means, measures of variability, and statistical results are presented in Tables 20-27. The findings across the three tasks were similar. Males initially made ground contact with increased hip abduction compared to females during the anticipated (pre-test: $F_{(1,63)}=12.46$, p=0.001, Effect size=0.89; post-test: $F_{(1,62)}=12.57$, p=0.001, Effect size=0.89) and unanticipated (pre-test: $F_{(1,63)}=13.28$, p=0.01, Effect size=0.92) cutting tasks. Males performed the anticipated (pre-test: $F_{(1,63)}=12.02$, p=0.001, Effect size=0.72; post-test: $F_{(1,62)}=16.38$, p<0.001, Effect size=1.03) and unanticipated (pre-test: $F_{(1,61)}=15.54$, p<0.001, effect size=0.99; post-test: $F_{(1,61)}=6.44$, p=0.014, Effect size=0.67) cutting tasks with greater hip abduction compared to females.

In addition to changes with hip frontal plane angle differences, knee frontal plane differences were observed during the unanticipated task at pre-test when females demonstrated greater knee valgus moments ($F_{(1,63)}=5.11$, p=0.03, Effect size=0.55). However, the false cue unanticipated task revealed differences in peak knee valgus during both testing sessions (pre-test: $F_{(1,40)}=4.31$, p=0.04, Effect size=0.63; post-test: $F_{(1,40)}=4.99$, p=0.03, Effect size=0.69). Females performed the false cue unanticipated task with more knee valgus motion compared to males. Finally, females achieved greater knee flexion during the anticipated cutting task at the post-test session compared to males ($F_{(1,62)}$=4.18, p=0.045, Effect size=0.52).

Means and measures of variability for sex comparisons in the balance and vertical jump variables are displayed in Table 28. There were no significant differences observed between sexes in either anterior-posterior time-to-stabilization ($F_{(1,62)}$=2.10, p=0.15, Effect size=0.37) or medial-lateral time-to-stabilization ($F_{(1,62)}$=0.40, p=0.53, Effect size=0.12) during the pre-test. However, at post-test, females stabilized quicker in the anterior-posterior direction compared to males ($F_{(1,62)}$=7.40, p=0.008, Effect size=0.71). There were still no significant differences between sexes in the medial-lateral direction ($F_{(1,62)}$=1.24, p=0.27, Effect size=0.30). There were significant differences between sexes observed in vertical jump height (pre-test: $F_{(1,64)}$=9.04, p=0.004, Effect size=0.75; post-test: $F_{(1,64)}$=10.21, p=0.002, Effect size=1.0) and power (pre-test: $F_{(1,64)}$=6.34, p=0.01, Effect size=0.63; post-test: $F_{(1,64)}$=9.50, p=0.003, Effect size=0.78). Males consistently jumped higher and generated more power compared to females during the maximum vertical jump test.

Interpretation:

Females injure their ACL at a higher rate than males who compete in similar sports.(4) There have also been several studies that have documented sex differences in various possible neuromuscular risk factors for injury. However, very few studies have observed these sex differences in prepubertal children. Therefore, the research hypothesis was that no sex differences would be present in any of the dependent variables before or after the intervention period. The results do not support this hypothesis as sex differences were seen in a few lower extremity biomechanical variables, as well as in the variables during the vertical jump test. Previous research demonstrates that females consistently land and cut with less sagittal plane motion and greater movements in the frontal and transverse planes compared to their male counterparts. The differences observed in this study were primarily in the frontal plane, so while there were differences observed, males and females did perform the cutting task similarly on several other variables. These findings suggest children under 11 years old are already beginning to display some sex differences.(170)

Table 28 provides information regarding how many trials were required during each task between groups. A repeated measures analyses of variance evaluated these data for a significant group by time interaction but did not observe any significant changes ($p>0.05$).

CHAPTER 5

DISCUSSION OF RESULTS

5.1 Introduction

This chapter provides a discussion of data not included in the two manuscripts. These data address research questions three and five. A discussion regarding the results from research question three is presented first followed by the discussion for research question five.

5.2 Research Question 3

The most important finding from these results is that neither the traditional nor the pediatric injury prevention program successfully changed any lower extremity biomechanical variable during a false cue unanticipated cutting task. The task used in this study is a novel assessment for a cutting maneuver as it not only includes an unanticipated component with a live model, but also requires a second response from the participant to change directions twice. These findings are in contrast to the research hypothesis and suggest that children under 12 years old may not be able to modify their movement technique during a very dynamic and challenging task.

Previous research has demonstrated that ACL injury prevention programs can modify lower extremity biomechanics in older populations.(32, 33, 35, 176) These conclusions are not supported by the current findings, and are most likely due to the nature of the task as well as the population used in this investigation. To our knowledge, this is the first study to compare lower extremity biomechanics during a cutting task before and after an injury prevention program. Every other study that has examined the effect of an injury prevention program on lower extremity biomechanics studied the variables during a stop jump task,(201, 202) a vertical jump,(32, 33) or a drop vertical jump.(34, 35, 38, 39, 203) One possible explanation for the differences between tasks is that cutting tasks demand greater transverse and frontal plane control compared to a landing task, which occurs predominantly in the sagittal plane. Therefore, it may be harder for individuals to change movement during cutting tasks. Secondly, not only was the task in this study a cutting movement, but it was also unanticipated and involved a second change of direction. Multiple studies have shown that individuals demonstrate greater potential neuromuscular risk factors for injury during an unanticipated cutting task compared to an anticipated movement. The complexity of the false cue unanticipated task may have inhibited participants from demonstrating any improvement in movement control.

The two other studies that have evaluated the effects of an injury prevention program on lower extremity movement technique in a population under twelve years old both concluded this population may require specialized training. Grandstrand et al.(38) failed to see improvements in knee separation distances after 9-11 year olds completed an injury prevention program that had been previously successful with an older population. The authors commented that the children had difficulty performing a few of the exercises, which may have contributed to their results. DiStefano et al.(176) found that a population of soccer athletes under 13 years old could improve their landing technique, however, a high school aged population sustained larger improvements. Due to the results of these two previous studies, the pediatric ACL injury prevention program was designed to target the preadolescent population specifically.

Children develop strength(80, 81) and learn motor skills(87, 88) differently than adults, so the pediatric program included sequential progressions of exercises to build a foundation of neuromuscular control with proper technique and advance to more dynamic and explosive exercises. Extensive time was provided for instruction and feedback as continuous feedback is more effective with a youth population.(88) Anecdotally, the participants appeared to improve their movement technique during all of the exercises suggesting improvements in biomechics may have been present but not demonstrated during the challenging false cue unanticipated cutting task. It is possible that further progressions of the pediatric program to include more dynamic and unanticipated training may result in different results. The principle of exercise specificity states that individuals tend to improve tasks that they receive training for, but it is possible that some training effects do not transfer to other dynamic tasks. Future research should explore this theory further with the youth population and injury prevention programs.

A limitation of this study is the false cue unanticipated cutting task was more difficult than originally expected with the young participants. As discussed previously, many of the participants were unable to perform more than one or two trials successfully. The participants performed two other cutting tasks during the same testing session and consequently completed 13 cutting trials on average. This high number of repetitions prevented further attempts with the false cue unanticipated cutting task.

In conclusion, neither the pediatric nor the traditional injury prevention programs were able to successfully modify lower extremity kinematics during a false cue unanticipated cutting task. The false cue task was very challenging for the young participants, which may have prevented improvements in movement technique from being displayed during this task. In addition, while the pediatric program was designed to improve movement control, the participants did not perform dynamic unanticipated exercises until the very last phase of the program. Therefore, future programs with this age group may be more effective by including additional training time with more sport-specific exercises.

5.3 Research Question Five

The findings from this study indicate that sex differences in possible neuromuscular risk factors for ACL injury are present in children between the ages of 9-11 years old. These differences may explain why females sustain ACL injuries approximately 1.4-4.6 times more than their male counterparts in similar sports.(4) In agreement with the current results, several studies have shown that females consistently perform sport related movements with less knee flexion and greater knee valgus, knee and hip rotation, and hip adduction than males.(14, 16, 19, 147-153) However, there is limited information about when these sex differences in lower extremity biomechanics emerge since the discrepancy in injury rates does not occur until puberty.(67) Therefore, the research hypothesis was that no sex differences would be observed in children under twelve years old, which was not supported by the results.

To our knowledge, only one study has evaluated a population under 12 years old for sex differences in lower extremity kinematics. Yu et al.(73) compared males and females between the ages of 11 and 18 for lower extremity kinematic differences during a stop jump task. Their results indicated that females reduce the amount of knee and hip flexion as they age while males do not change. Specifically, large changes were observed after 14 years of age. Hamstra-Wright et al.(209) supported the theory of sex differences emerging after puberty by demonstrating no sex differences in hamstring and quadriceps strength, as well as vertical leg stiffness, in children under 10 years old. Recently, Schmitz et al.(210) found that males reduce dynamic knee valgus as they mature while the opposite occurs with females. Our findings expand this body of literature by showing that some sex differences do occur in what is considered to be a preadolescent population.

Several studies have indicated that females perform cutting tasks with different movement patterns compared to males. Females tend to cut with increased hip interal rotation,(61, 64, 211) knee valgus,(17, 65) hip adduction moments,(64) and reduced lower extremity sagittal plane motion.(17, 63, 64) Our results show that females consistently demonstrate an adducted hip position relative to males across all three cutting tasks, which agrees with the work of Pollard et al.(64) who reported increased hip adductor moments. Females also moved with greater knee valgus angles during the most difficult cutting task, the false cue unanticipated movement. This finding may have occurred because the task was very difficult to complete. McLean et al.(61) found that individuals cut with greater knee valgus when a defensive opponent was placed in front of them while cutting, which corresponds to our results. However, there were no significant differences in sagittal or transverse plane motion. This lack of finding may suggest sex differences are beginning to emerge with this age group.

Besides observing sex differences in lower extremity biomechanics, sex differences were also present in vertical jump height and power. Males consistently jumped higher and generated more power compared to females even at these young ages. It is well documented that males and females change body composition as they encounter adolescence. Females develop more adipose tissue while males gain more muscular tissue. This difference in physical and hormonal development may explain the differences in power and performance. Despite these findings, no sex differences were present for the balance variables except after the intervention period. Unfortunately, there is limited knowledge about how sexes differ with respect to balance in a preadolescent population.

A limitation of this study is we did not collect information about the participants' maturity status. Therefore, it is possible that part of our cohort had already begun puberty, which could influence the sex differences observed. Future research should further evaluate the potential for sex differences in lower extremity biomechanics, balance, and performance while accounting for maturity status.

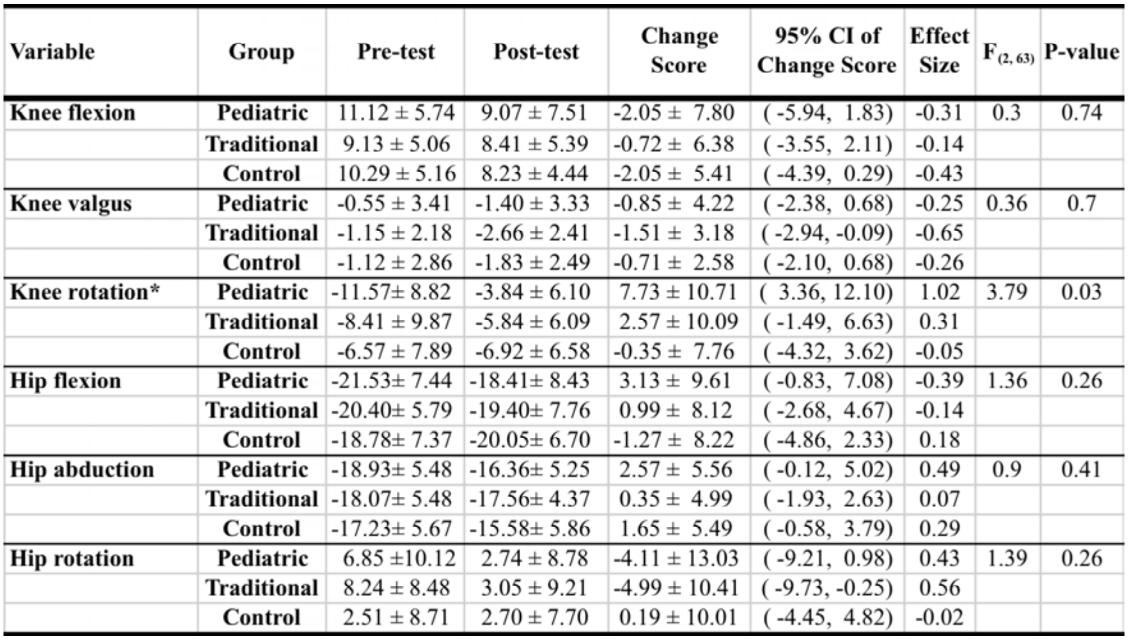
		PROGRAM		
EXERCISES	**Traditional Program**	**Pediatric Program**		
		Phase I	**Phase 2**	**Phase 3**
Time	**12-14 minutes**	**12-14 minutes**	**12-14 minutes**	**12-14 minutes**
Duration	**3 days/week**	**2 days/week**	**3 days/week**	**3 days/week**
	9 weeks	**3 weeks**	**3 weeks**	**3 weeks**
Lower Extremity	Forward Lunge	Forward Lunge	Sideways Lunge	Twisting Lunge
Strengthening	Broad Jump	Double Leg Squat	DL to SL Squat	
	SL Squat	Toe Walk	Broad Jump	
		DL Heel Raise		
Repetitions	**1x5 each leg**	**1x15**	**1x15**	**1x15**
Core Strengthening	Hip Bridge	Hip Bridge	Human Arrow	Sideways Plank
Repetitions	**1x10; hold 3 sec**	**1x10; hold 3 sec**	**1x10; hold 3 sec**	**1x10; hold 3 sec**
Flexibility Type	***Static***	***Dynamic***	***Dynamic***	***Dynamic***
	Calf	Straight Leg March	Straight Leg Skip	Straight Leg Skip
	Hip Flexor	Hand Walk	Walking Calf Stretch	Leg Cradle
	Adductor	Walking Butt Kicks	Hip Flexor Walk	Twisting Hip Flexor Walk
		Walking Quad Stretch	Knee to Chest	Running Butt Kicks
				High Knee Run
Repetitions	**30 sec. each**	**30 sec. each**	**30 sec. each**	**30 sec. each**
Plyometric	Squat Jumps	DL Forward Line Hops	SL Forward Line Hops	SL Sideways Line Hops
	DL Forward Hops (SL)		DL Sideways Line Hops	Squat Jumps
	DL Sideways Hops (SL)		Up and Down Hops	Tuck Jumps
Repetitions	**10 repetitions**	**20 repetitions**	**20 repetitions**	**20 repetitions**
Balance	180° Jump to Balance	180° Jump to Balance	Sideways Hop to Balance	Twisting Hop to Balance
	SL Forward Hop to Bal.	Forward Hop to Balance	Single Leg Ball Toss	SL Balance Perturbations
	SL Ball Toss			
Repetitions	**1x10 each leg**	**1x10**	**1x10**	**1x10**
Agility	Toe-Heel Walk	Forward Skipping	For & Back Skipping	Unanticipated Side Cuts
	High Knee Run	Sideways Shuffle	Side Cuts	
	Sideways Shuffle			
	Z Cuts			
Repetitions	**30 sec. each**	**30 sec. each**	**30 sec. each**	**30 sec. each**

Table 1. Program Comparisons

Group	Sample Size	Age	Mass	Height
Pediatric	11 males, 8 females	10 ± 1 years	33.31 ± 5.02 kg	140.43 ± 7.06 cm
Traditional	11 males, 11 females	10 ± 1 years	35.06 ± 5.60 kg	144.41 ± 6.01 cm
Control	14 males, 9 females	10 ± 1 years	33.57 ± 5.39 kg	141.48 ± 5.95 cm

Table 2. Participant demographics

Table 3. Kinematic variables at initial ground contact during the ***anticipated cutting task*** (*p<0.05)

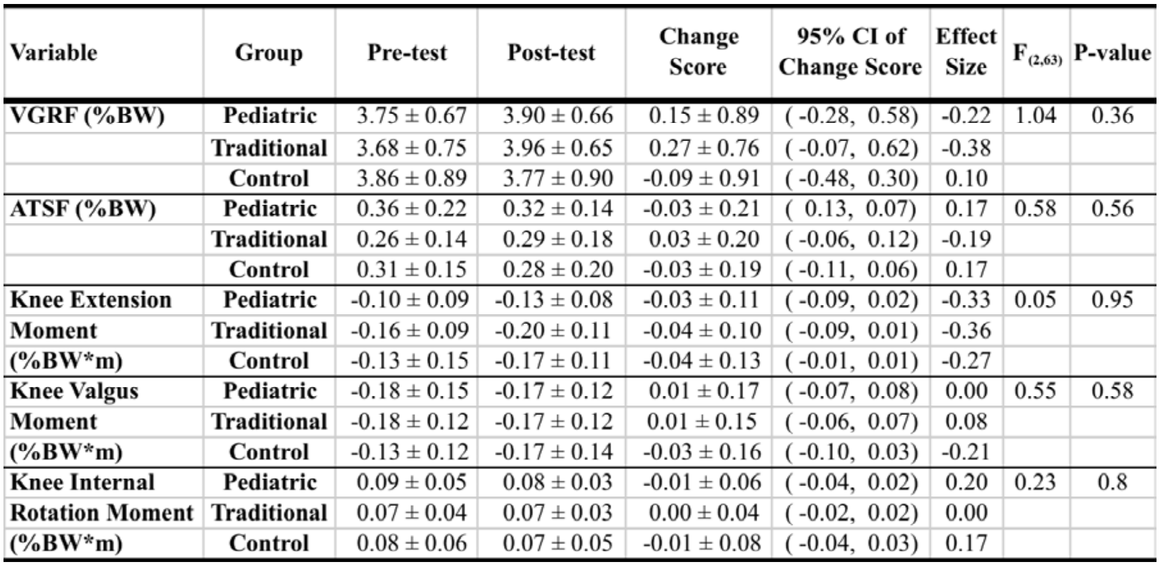


Variable	Group	Pre-test	Post-test	Change Score	95% CI of Change Score	Effect Size	$F_{(2,63)}$	P-value
Knee flexion	**Pediatric**	11.12 ± 5.74	9.07 ± 7.51	-2.05 ± 7.80	(-5.94, 1.83)	-0.31	0.3	0.74
	Traditional	9.13 ± 5.06	8.41 ± 5.39	-0.72 ± 6.38	(-3.55, 2.11)	-0.14		
	Control	10.29 ± 5.16	8.23 ± 4.44	-2.05 ± 5.41	(-4.39, 0.29)	-0.43		
Knee valgus	**Pediatric**	-0.55 ± 3.41	-1.40 ± 3.33	-0.85 ± 4.22	(-2.38, 0.68)	-0.25	0.36	0.7
	Traditional	-1.15 ± 2.18	-2.66 ± 2.41	-1.51 ± 3.18	(-2.94, -0.09)	-0.65		
	Control	-1.12 ± 2.86	-1.83 ± 2.49	-0.71 ± 2.58	(-2.10, 0.68)	-0.26		
Knee rotation*	**Pediatric**	-11.57± 8.82	-3.84 ± 6.10	7.73 ± 10.71	(3.36, 12.10)	1.02	3.79	0.03
	Traditional	-8.41 ± 9.87	-5.84 ± 6.09	2.57 ± 10.09	(-1.49, 6.63)	0.31		
	Control	-6.57 ± 7.89	-6.92 ± 6.58	-0.35 ± 7.76	(-4.32, 3.62)	-0.05		
Hip flexion	**Pediatric**	-21.53± 7.44	-18.41± 8.43	3.13 ± 9.61	(-0.83, 7.08)	-0.39	1.36	0.26
	Traditional	-20.40± 5.79	-19.40± 7.76	0.99 ± 8.12	(-2.68, 4.67)	-0.14		
	Control	-18.78± 7.37	-20.05± 6.70	-1.27 ± 8.22	(-4.86, 2.33)	0.18		
Hip abduction	**Pediatric**	-18.93± 5.48	-16.36± 5.25	2.57 ± 5.56	(-0.12, 5.02)	0.49	0.9	0.41
	Traditional	-18.07± 5.48	-17.56± 4.37	0.35 ± 4.99	(-1.93, 2.63)	0.07		
	Control	-17.23± 5.67	-15.58± 5.86	1.65 ± 5.49	(-0.58, 3.79)	0.29		
Hip rotation	**Pediatric**	6.85 ±10.12	2.74 ± 8.78	-4.11 ± 13.03	(-9.21, 0.98)	0.43	1.39	0.26
	Traditional	8.24 ± 8.48	3.05 ± 9.21	-4.99 ± 10.41	(-9.73, -0.25)	0.56		
	Control	2.51 ± 8.71	2.70 ± 7.70	0.19 ± 10.01	(-4.45, 4.82)	-0.02		

Variable	**Group**	**Pre-test**	**Post-test**	**Change Score**	**95% CI of Change Score**	**Effect Size**	**$F_{(2,63)}$**	**P-value**
Knee flexion	**Pediatric**	44.55 ± 7.33	44.98 ± 7.21	0.43 ± 7.49	(-2.99, 3.85)	-0.06	0.02	0.98
	Traditional	44.45 ± 7.00	44.66 ± 6.81	0.20 ± 7.92	(-2.98, 3.38)	-0.03		
	Control	43.90 ± 7.53	43.92 ± 6.56	0.02 ± 6.97	(-3.09, 3.13)	0.00		
Knee valgus	**Pediatric**	-3.18 ± 6.37	-5.18 ± 4.65	-2.00 ± 6.73	(-4.32, 0.32)	-0.36	0.78	0.46
	Traditional	-4.15 ± 3.46	-6.61 ± 3.84	-2.46 ± 3.94	(-4.62, -0.30)	-0.67		
	Control	-4.65 ± 4.36	-5.29 ± 4.20	-0.64 ± 4.38	(-2.75, 1.47)	-0.15		
Knee Internal Rotation*	**Pediatric**	2.35 ± 7.85	8.80 ± 7.06	6.44 ± 9.05	(2.08, 10.81)	-0.86	4.96	0.01
	Traditional	7.38 ± 9.03	6.19 ± 5.88	0.03 ± 9.26	(-4.19, 4.25)	0.00		
	Control	6.71 ± 9.40	4.74 ± 7.33	-1.97 ± 8.38	(-5.60, 1.65)	0.23		
Knee External Rotation	**Pediatric**	-10.19±10.96	-4.67 ± 5.38	5.52 ±13.13	(0.84, 10.20)	0.64	2.01	0.14
	Traditional	-9.00± 9.88	-7.00 ± 5.47	2.00 ± 9.74	(-2.35, 6.35)	0.25		
	Control	-7.35 ± 8.03	-8.17 ± 6.50	-0.81 ± 7.55	(-5.07, 3.44)	-0.11		
Hip Flexion	**Pediatric**	-29.87± 8.25	-26.59± 9.23	3.28 ± 8.90	(-0.85, 7.40)	-0.37	1.53	0.23
	Traditional	-26.87± 7.28	-28.04± 8.67	-1.17 ± 8.07	(-5.00, 2.66)	0.15		
	Control	-25.03± 9.01	-25.90± 6.46	-0.88 ± 9.87	(-4.71, 2.96)	0.11		
Hip Adduction	**Pediatric**	-14.84± 6.40	-11.53± 7.14	3.31 ± 6.28	(0.47, 6.15)	0.49	0.13	0.88
	Traditional	-14.58± 6.60	-11.81± 5.81	2.78 ± 5.62	(0.14, 5.42)	0.45		
	Control	-12.79± 8.08	-10.48± 8.60	2.31 ± 6.64	(-0.33, 4.95)	0.28		
Hip Abduction	**Pediatric**	-21.54± 5.44	-19.14± 5.89	2.41 ± 5.50	(-0.23, 5.04)	0.42	0.25	0.78
	Traditional	-20.95± 6.52	-19.53± 5.21	1.42 ± 6.19	(-1.03, 3.87)	0.24		
	Control	-19.62± 6.40	-18.42± 7.04	1.20 ± 5.47	(-1.25, 3.65)	0.18		
Hip Internal Rotation	**Pediatric**	10.73 ± 7.78	6.74 ± 9.46	-3.99 ±11.64	(-8.55, 0.56)	0.46	2.42	0.1
	Traditional	10.95 ± 7.97	6.86 ± 9.33	-4.09 ± 9.49	(-8.32, 0.14)	0.47		
	Control	5.51 ± 7.65	7.23 ± 5.69	1.72 ± 8.65	(-2.51, 5.95)	-0.26		
Hip External Rotation	**Pediatric**	-0.62 ± 8.48	-5.02 ± 8.55	-4.41 ±10.41	(-8.88, 0.06)	-0.52	0.8	0.45
	Traditional	-2.12 ± 6.62	-4.13 ± 8.34	-2.01 ± 9.46	(-6.17, 2.14)	-0.27		
	Control	-5.30 ± 8.25	-5.87 ± 7.62	-0.56 ± 9.41	(-4.72, 3.59)	-0.07		

Table 4. Peak kinematic variables during first 40% of stance phase of ***anticipated cutting task***

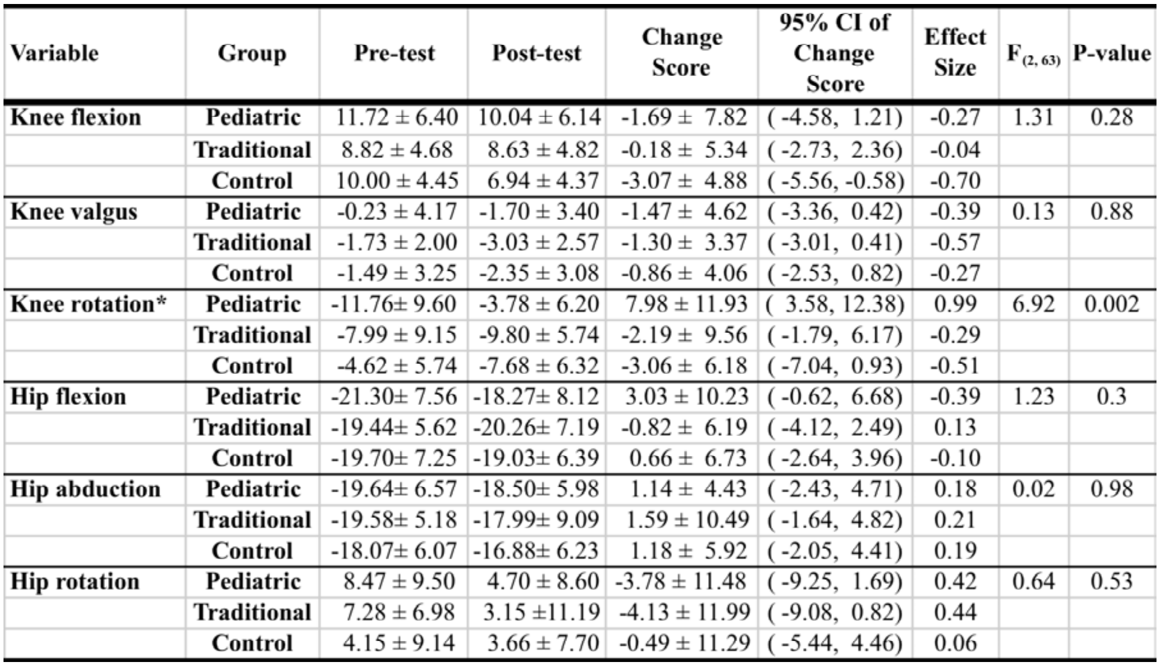
(*p<0.05)



Variable	Group	Pre-test	Post-test	Change Score	95% CI of Change Score	Effect Size	$F_{(2,63)}$	P-value
VGRF (%BW)	**Pediatric**	3.75 ± 0.67	3.90 ± 0.66	0.15 ± 0.89	(-0.28, 0.58)	-0.22	1.04	0.36
	Traditional	3.68 ± 0.75	3.96 ± 0.65	0.27 ± 0.76	(-0.07, 0.62)	-0.38		
	Control	3.86 ± 0.89	3.77 ± 0.90	-0.09 ± 0.91	(-0.48, 0.30)	0.10		
ATSF (%BW)	**Pediatric**	0.36 ± 0.22	0.32 ± 0.14	-0.03 ± 0.21	(0.13, 0.07)	0.17	0.58	0.56
	Traditional	0.26 ± 0.14	0.29 ± 0.18	0.03 ± 0.20	(-0.06, 0.12)	-0.19		
	Control	0.31 ± 0.15	0.28 ± 0.20	-0.03 ± 0.19	(-0.11, 0.06)	0.17		
Knee Extension	**Pediatric**	-0.10 ± 0.09	-0.13 ± 0.08	-0.03 ± 0.11	(-0.09, 0.02)	-0.33	0.05	0.95
Moment	**Traditional**	-0.16 ± 0.09	-0.20 ± 0.11	-0.04 ± 0.10	(-0.09, 0.01)	-0.36		
(%BW*m)	**Control**	-0.13 ± 0.15	-0.17 ± 0.11	-0.04 ± 0.13	(-0.01, 0.01)	-0.27		
Knee Valgus	**Pediatric**	-0.18 ± 0.15	-0.17 ± 0.12	0.01 ± 0.17	(-0.07, 0.08)	0.00	0.55	0.58
Moment	**Traditional**	-0.18 ± 0.12	-0.17 ± 0.12	0.01 ± 0.15	(-0.06, 0.07)	0.08		
(%BW*m)	**Control**	-0.13 ± 0.12	-0.17 ± 0.14	-0.03 ± 0.16	(-0.10, 0.03)	-0.21		
Knee Internal	**Pediatric**	0.09 ± 0.05	0.08 ± 0.03	-0.01 ± 0.06	(-0.04, 0.02)	0.20	0.23	0.8
Rotation Moment	**Traditional**	0.07 ± 0.04	0.07 ± 0.03	0.00 ± 0.04	(-0.02, 0.02)	0.00		
(%BW*m)	**Control**	0.08 ± 0.06	0.07 ± 0.05	-0.01 ± 0.08	(-0.04, 0.03)	0.17		

Table 5. Peak kinetic variables during first 40% of stance phase of ***anticipated cutting task***

(*$p<0.05$)



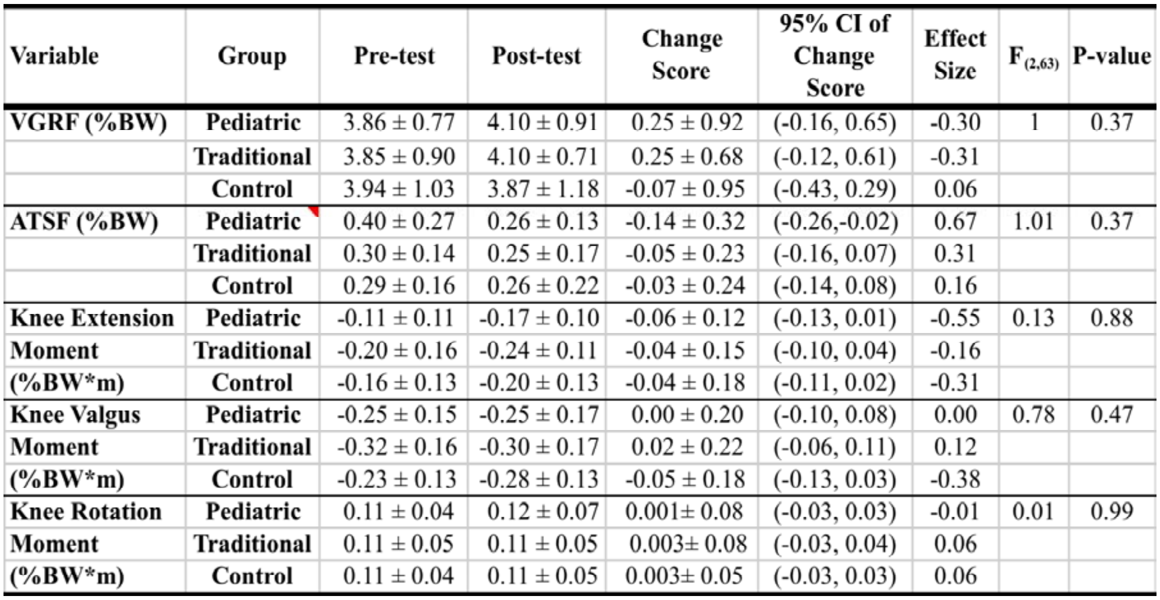
Variable	Group	Pre-test	Post-test	Change Score	95% CI of Change Score	Effect Size	$F_{(2, 63)}$	P-value
Knee flexion	**Pediatric**	11.72 ± 6.40	10.04 ± 6.14	-1.69 ± 7.82	(-4.58, 1.21)	-0.27	1.31	0.28
	Traditional	8.82 ± 4.68	8.63 ± 4.82	-0.18 ± 5.34	(-2.73, 2.36)	-0.04		
	Control	10.00 ± 4.45	6.94 ± 4.37	-3.07 ± 4.88	(-5.56, -0.58)	-0.70		
Knee valgus	**Pediatric**	-0.23 ± 4.17	-1.70 ± 3.40	-1.47 ± 4.62	(-3.36, 0.42)	-0.39	0.13	0.88
	Traditional	-1.73 ± 2.00	-3.03 ± 2.57	-1.30 ± 3.37	(-3.01, 0.41)	-0.57		
	Control	-1.49 ± 3.25	-2.35 ± 3.08	-0.86 ± 4.06	(-2.53, 0.82)	-0.27		
Knee rotation*	**Pediatric**	-11.76± 9.60	-3.78 ± 6.20	7.98 ± 11.93	(3.58, 12.38)	0.99	6.92	0.002
	Traditional	-7.99 ± 9.15	-9.80 ± 5.74	-2.19 ± 9.56	(-1.79, 6.17)	-0.29		
	Control	-4.62 ± 5.74	-7.68 ± 6.32	-3.06 ± 6.18	(-7.04, 0.93)	-0.51		
Hip flexion	**Pediatric**	-21.30± 7.56	-18.27± 8.12	3.03 ± 10.23	(-0.62, 6.68)	-0.39	1.23	0.3
	Traditional	-19.44± 5.62	-20.26± 7.19	-0.82 ± 6.19	(-4.12, 2.49)	0.13		
	Control	-19.70± 7.25	-19.03± 6.39	0.66 ± 6.73	(-2.64, 3.96)	-0.10		
Hip abduction	**Pediatric**	-19.64± 6.57	-18.50± 5.98	1.14 ± 4.43	(-2.43, 4.71)	0.18	0.02	0.98
	Traditional	-19.58± 5.18	-17.99± 9.09	1.59 ± 10.49	(-1.64, 4.82)	0.21		
	Control	-18.07± 6.07	-16.88± 6.23	1.18 ± 5.92	(-2.05, 4.41)	0.19		
Hip rotation	**Pediatric**	8.47 ± 9.50	4.70 ± 8.60	-3.78 ± 11.48	(-9.25, 1.69)	0.42	0.64	0.53
	Traditional	7.28 ± 6.98	3.15 ±11.19	-4.13 ± 11.99	(-9.08, 0.82)	0.44		
	Control	4.15 ± 9.14	3.66 ± 7.70	-0.49 ± 11.29	(-5.44, 4.46)	0.06		

Table 6. Kinematic variables at initial ground contact during ***unanticipated cutting task***

(*$p<0.05$)

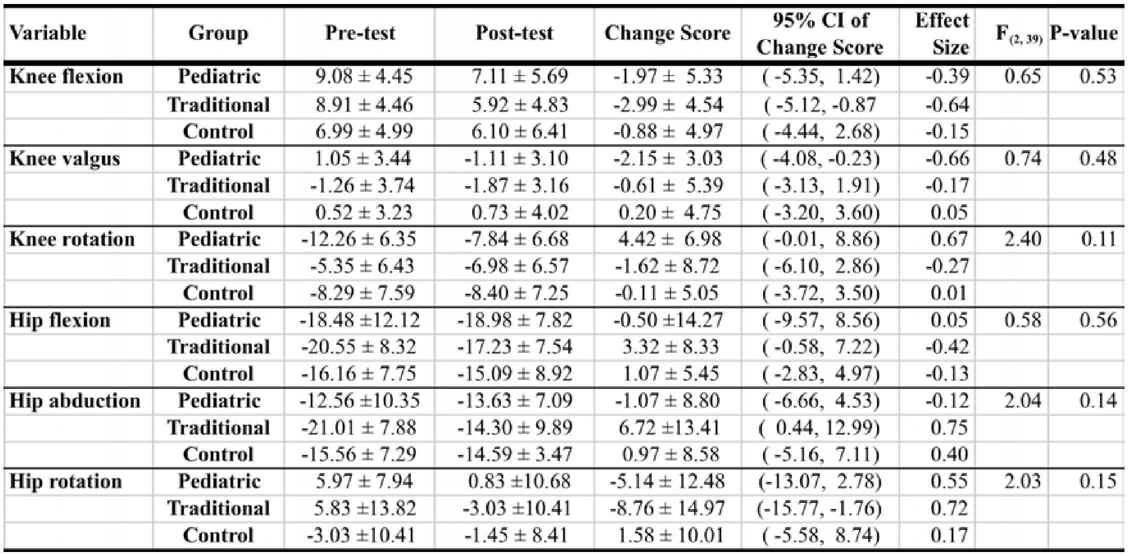
Variable	Group	Pre-test	Post-test	Change Score	95% CI of Change Score	Effect Size	$F_{(2,62)}$	P-value
Knee flexion	**Pediatric**	47.37 ± 6.84	46.27 ± 7.08	-1.09 ± 5.77	(-4.15, 1.97)	-0.16	1.44	0.25
	Traditional	45.63 ± 6.54	47.83 ± 5.87	2.21 ± 6.89	(-0.56, 4.97)	0.35		
	Control	46.18 ± 8.43	45.94 ± 6.67	-0.24 ± 6.61	(-2.95, 2.47)	-0.03		
Knee valgus	**Pediatric**	-3.34 ± 7.12	-5.93 ± 4.62	-2.60 ± 7.07	(-5.10, -0.10)	-0.43	0.92	0.4
	Traditional	-4.82 ± 3.55	-6.91 ± 4.20	-2.09 ± 4.77	(-4.35, 0.18)	-0.54		
	Control	-5.26 ± 4.35	-5.74 ± 4.27	-0.48 ± 4.05	(-2.69, 1.73)	-0.11		
Knee Internal Rotation*	**Pediatric**	2.74 ± 8.65	9.90 ± 7.17	7.15 ± 9.72	(2.80, 11.51)	-0.90	6.49	0.003
	Traditional	8.17 ± 8.12	6.38 ± 5.43	-1.80 ± 9.55	(-5.73, 2.14)	0.26		
	Control	8.05 ± 8.50	5.65 ± 6.98	-2.40 ± 8.49	(-6.25, 1.45)	0.31		
Knee External Rotation*	**Pediatric**	-12.32± 9.33	-4.40 ± 5.75	7.92 ± 11.40	(3.59, 12.24)	1.02	5.73	0.005
	Traditional	-8.65 ± 9.09	-6.65 ± 5.00	2.00 ± 9.24	(-1.91, 5.91)	0.27		
	Control	-6.47 ± 6.80	-8.30 ± 6.11	-1.84 ± 6.87	(-5.66, 1.99)	0.28		
Hip Flexion	**Pediatric**	-32.44± 9.01	-29.16± 9.16	3.27 ± 10.38	(-1.25, 7.79)	-0.36	2.5	0.09
	Traditional	-28.60± 8.66	-32.08± 8.35	-3.48 ± 7.94	(-7.57, 0.61)	0.41		
	Control	-30.04± 8.38	-29.69± 8.05	-0.35 ± 10.38	(-3.74, 4.44)	-0.04		
Hip Adduction	**Pediatric**	-14.78± 7.87	-14.30± 7.81	0.48 ± 5.09	(-3.11, 4.07)	0.06	0.5	0.61
	Traditional	-15.51± 6.31	-12.72± 9.39	2.79 ± 10.08	(-0.45, 6.04)	0.35		
	Control	-13.02± 7.83	-11.83± 7.60	1.20 ± 6.32	(-2.05, 4.44)	0.16		
Hip Abduction	**Pediatric**	-21.53± 6.85	-20.91± 6.63	0.62 ± 5.01	(-2.87, 4.10)	0.09	0.49	0.62
	Traditional	-22.30± 5.46	-19.62± 9.25	2.67 ± 9.89	(-0.48, 5.82)	0.35		
	Control	-19.91± 6.45	-19.06± 6.76	0.85 ± 5.93	(-2.30, 4.00)	0.13		
Hip Internal Rotation	**Pediatric**	13.27 ± 7.63	8.56 ± 8.64	-4.72 ± 9.97	(-9.67, 0.24)	0.58	0.4	0.67
	Traditional	10.05 ± 5.78	7.40 ± 9.54	-2.65 ± 9.87	(-7.13, 1.83)	0.34		
	Control	9.44 ± 9.62	7.67 ± 7.41	-1.77 ± 11.47	(-6.25, 2.71)	0.21		
Hip External Rotation	**Pediatric**	1.23 ± 8.39	-2.05 ± 8.34	-3.28 ± 10.72	(-8.04, 1.47)	-0.39	0.24	0.79
	Traditional	-1.61 ± 4.52	-3.01 ± 9.06	-1.41 ± 9.74	(-5.71, 2.89)	-0.20		
	Control	-2.42 ± 8.46	-3.71 ± 7.77	-1.29 ± 9.88	(-5.59, 3.01)	-0.16		

Table 7. Peak kinematic variables during first 40% of stance phase of unanticipated cutting task (*p<0.05)



Variable	Group	Pre-test	Post-test	Change Score	95% CI of Change Score	Effect Size	$F_{(2,63)}$	P-value
VGRF (%BW)	**Pediatric**	3.86 ± 0.77	4.10 ± 0.91	0.25 ± 0.92	(-0.16, 0.65)	-0.30	1	0.37
	Traditional	3.85 ± 0.90	4.10 ± 0.71	0.25 ± 0.68	(-0.12, 0.61)	-0.31		
	Control	3.94 ± 1.03	3.87 ± 1.18	-0.07 ± 0.95	(-0.43, 0.29)	0.06		
ATSF (%BW)	**Pediatric**	0.40 ± 0.27	0.26 ± 0.13	-0.14 ± 0.32	(-0.26,-0.02)	0.67	1.01	0.37
	Traditional	0.30 ± 0.14	0.25 ± 0.17	-0.05 ± 0.23	(-0.16, 0.07)	0.31		
	Control	0.29 ± 0.16	0.26 ± 0.22	-0.03 ± 0.24	(-0.14, 0.08)	0.16		
Knee Extension	**Pediatric**	-0.11 ± 0.11	-0.17 ± 0.10	-0.06 ± 0.12	(-0.13, 0.01)	-0.55	0.13	0.88
Moment	**Traditional**	-0.20 ± 0.16	-0.24 ± 0.11	-0.04 ± 0.15	(-0.10, 0.04)	-0.16		
(%BW*m)	**Control**	-0.16 ± 0.13	-0.20 ± 0.13	-0.04 ± 0.18	(-0.11, 0.02)	-0.31		
Knee Valgus	**Pediatric**	-0.25 ± 0.15	-0.25 ± 0.17	0.00 ± 0.20	(-0.10, 0.08)	0.00	0.78	0.47
Moment	**Traditional**	-0.32 ± 0.16	-0.30 ± 0.17	0.02 ± 0.22	(-0.06, 0.11)	0.12		
(%BW*m)	**Control**	-0.23 ± 0.13	-0.28 ± 0.13	-0.05 ± 0.18	(-0.13, 0.03)	-0.38		
Knee Rotation	**Pediatric**	0.11 ± 0.04	0.12 ± 0.07	0.001± 0.08	(-0.03, 0.03)	-0.01	0.01	0.99
Moment	**Traditional**	0.11 ± 0.05	0.11 ± 0.05	0.003± 0.08	(-0.03, 0.04)	0.06		
(%BW*m)	**Control**	0.11 ± 0.04	0.11 ± 0.05	0.003± 0.05	(-0.03, 0.03)	0.06		

Table 8. Peak kinetic variables during first 40% of stance phase during ***unanticipated cutting task*** (*p<0.05)

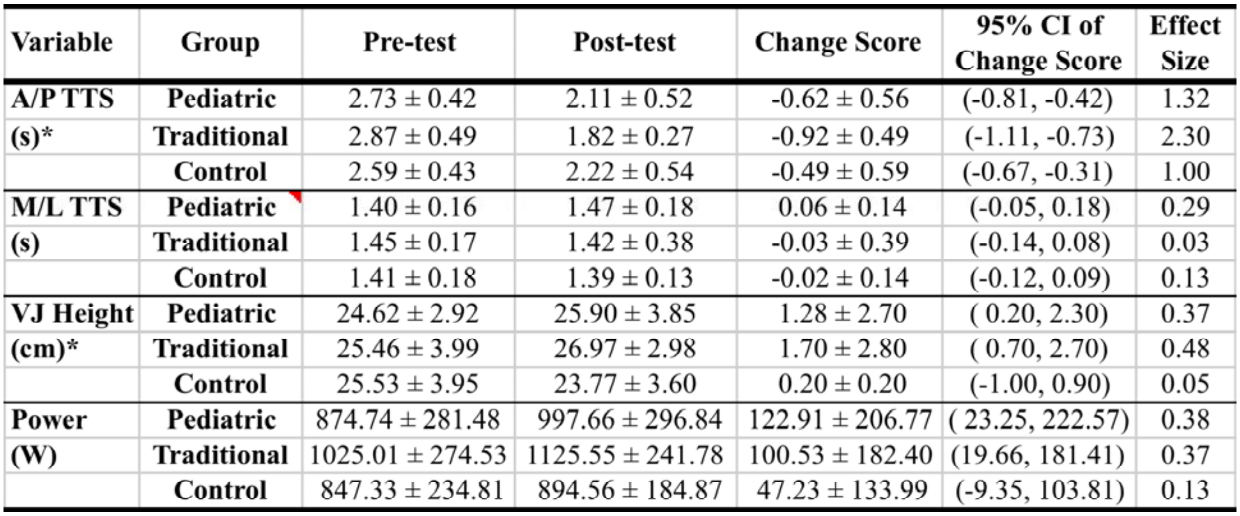


Variable	Group	Pre-test	Post-test	Change Score	95% CI of Change Score	Effect Size	$F_{(2, 39)}$	P-value
Knee flexion	**Pediatric**	9.08 ± 4.45	7.11 ± 5.69	-1.97 ± 5.33	(-5.35, 1.42)	-0.39	0.65	0.53
	Traditional	8.91 ± 4.46	5.92 ± 4.83	-2.99 ± 4.54	(-5.12, -0.87	-0.64		
	Control	6.99 ± 4.99	6.10 ± 6.41	-0.88 ± 4.97	(-4.44, 2.68)	-0.15		
Knee valgus	**Pediatric**	1.05 ± 3.44	-1.11 ± 3.10	-2.15 ± 3.03	(-4.08, -0.23)	-0.66	0.74	0.48
	Traditional	-1.26 ± 3.74	-1.87 ± 3.16	-0.61 ± 5.39	(-3.13, 1.91)	-0.17		
	Control	0.52 ± 3.23	0.73 ± 4.02	0.20 ± 4.75	(-3.20, 3.60)	0.05		
Knee rotation	**Pediatric**	-12.26 ± 6.35	-7.84 ± 6.68	4.42 ± 6.98	(-0.01, 8.86)	0.67	2.40	0.11
	Traditional	-5.35 ± 6.43	-6.98 ± 6.57	-1.62 ± 8.72	(-6.10, 2.86)	-0.27		
	Control	-8.29 ± 7.59	-8.40 ± 7.25	-0.11 ± 5.05	(-3.72, 3.50)	0.01		
Hip flexion	**Pediatric**	-18.48 ±12.12	-18.98 ± 7.82	-0.50 ±14.27	(-9.57, 8.56)	0.05	0.58	0.56
	Traditional	-20.55 ± 8.32	-17.23 ± 7.54	3.32 ± 8.33	(-0.58, 7.22)	-0.42		
	Control	-16.16 ± 7.75	-15.09 ± 8.92	1.07 ± 5.45	(-2.83, 4.97)	-0.13		
Hip abduction	**Pediatric**	-12.56 ±10.35	-13.63 ± 7.09	-1.07 ± 8.80	(-6.66, 4.53)	-0.12	2.04	0.14
	Traditional	-21.01 ± 7.88	-14.30 ± 9.89	6.72 ±13.41	(0.44, 12.99)	0.75		
	Control	-15.56 ± 7.29	-14.59 ± 3.47	0.97 ± 8.58	(-5.16, 7.11)	0.40		
Hip rotation	**Pediatric**	5.97 ± 7.94	0.83 ±10.68	-5.14 ± 12.48	(-13.07, 2.78)	0.55	2.03	0.15
	Traditional	5.83 ±13.82	-3.03 ±10.41	-8.76 ± 14.97	(-15.77, -1.76)	0.72		
	Control	-3.03 ±10.41	-1.45 ± 8.41	1.58 ± 10.01	(-5.58, 8.74)	0.17		

Table 9. Kinematic variables at initial ground contact during the ***false cue unanticipated*** cutting task

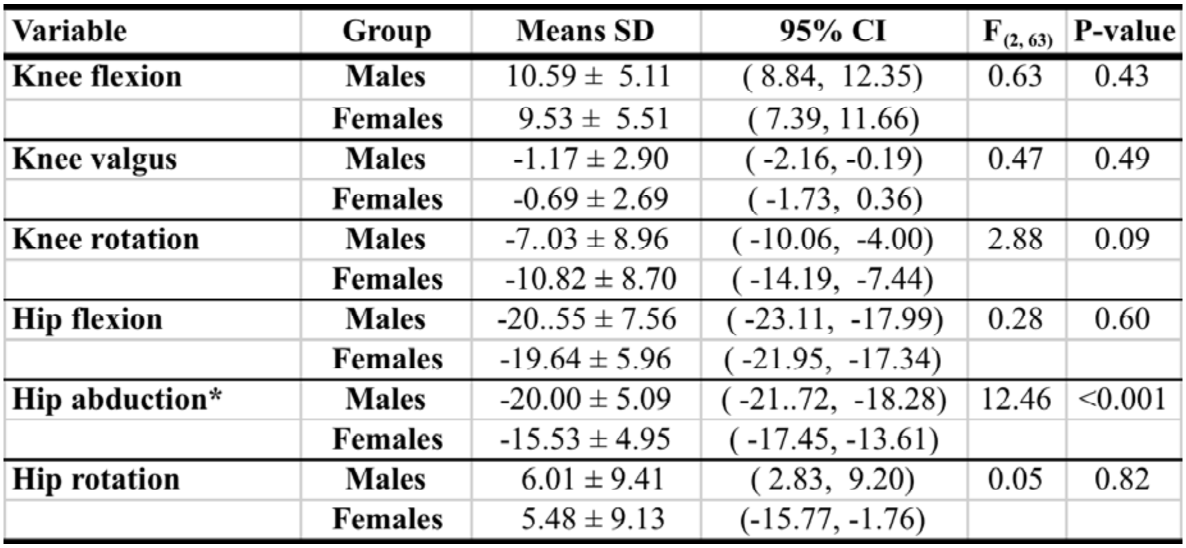
Variable	Group	Pre-test	Post-test	Change Score	95% CI of Change Score	Effect Size	$F_{(2,63)}$	P-value
Knee flexion	**Pediatric**	39.28 ± 7.03	43.67 ± 9.44	4.39 ± 13.13	(-3.95, 12.73)	0.53	0.69	0.51
	Traditional	46.57 ±10.79	45.22 ±16.46	-1.35 ± 16.56	(-9.10, 6.40)	0.10		
	Control	42.37 ± 21.47	47.39 ± 19.25	5.04 ± 20.20	(-9.41, 19.48)	-0.25		
Knee valgus	**Pediatric**	-1.94 ± 4.38	-4.67 ± 4.49	-2.74 ± 3.77	(-5.13, -0.34)	-0.61	0.30	0.74
	Traditional	-3.17 ± 4.65	-4.99 ± 4.56	-1.82 ± 6.69	(-4.95, 1.31)	-0.40		
	Control	-2.23 ± 4.42	-2.99 ± 5.72	-0.76 ± 6.48	(-5.39, 3.88)	-0.15		
Knee Internal Rotation	**Pediatric**	2.99 ± 8.69	4.98 ± 6.97	1.62 ± 9.05	(-4.13, 7.37)	-0.20	1.27	0.29
	Traditional	7.64 ± 8.55	3.75 ± 6.03	-3.88 ± 8.91	(-8.46, 0.70)	0.52		
	Control	3.31 ± 7.23	3.34 ± 7.17	0.03 ± 11.26	(-8.02, 8.09)	0.00		
Knee External Rotation	**Pediatric**	-13.52 ± 7.53	-7.79 ± 7.59	3.88 ± 9.57	(-2.20, 9.96)	0.51	1.00	0.38
	Traditional	-6.83 ± 7.67	-7.41 ± 6.47	-0.58 ± 9.80	(-5.62, 4.46)	-0.08		
	Control	-6.48 ±10.77	-6.65 ±10.01	-0.17 ± 5.19	(-3.88, 3.54)	-0.02		
Hip Flexion	**Pediatric**	-35.24 ±13.33	-33.21 ±10.18	2.03 ± 19.86	(-10.59, 14.65)	-0.17	0.14	0.87
	Traditional	-34.89 ±12.72	-33.93 ±10.10	0.96 ± 12.97	(-5.11, 7.03)	-0.08		
	Control	-29.22 ± 9.55	-30.44 ±11.44	-1.21 ± 8.90	(-7.58, 5.16)	-0.11		
Hip Adduction	**Pediatric**	-7.92 ± 6.75	-8.26 ± 8.43	-0.61 ± 9.20	(-6.46, 5.24)	-0.08	0.45	0.64
	Traditional	-11.18 ± 7.48	-8.30 ±11.49	2.88± 12.21	(-3.19, 8.96)	0.30		
	Control	-7.68 ±10.01	-7.65 ± 6.76	0.02 ± 9.73	(-6.94, 6.98)	0.00		
Hip Abduction	**Pediatric**	-16.88 ± 7.10	-14.55 ± 8.43	1.34 ± 6.81	(-2.98, 5.67)	0.17	1.23	0.30
	Traditional	-20.33 ± 6.84	-16.13 ± 6.57	4.21 ± 7.60	(0.35, 8.07)	0.63		
	Control	-14.82 ± 7.97	-15.14 ± 4.89	-0.31 ± 8.45	(-6.36, 5.73)	-0.05		
Hip Internal Rotation	**Pediatric**	9.34 ± 9.38	3.85 ±11.73	-4.90 ± 13.25	(-13.32, 3.52)	0.50	3.03	0.06
	Traditional	9.44 ±11.30	2.99 ± 9.28	-6.45 ± 10.71	(-11.78, -1.12)	0.62		
	Control	0.82 ±10.00	5.20 ± 9.43	4.38 ± 10.52	(-3.15, 11.90)	0.45		
Hip External Rotation	**Pediatric**	-1.87 ± 5.65	-5.58 ±10.28	-3.70 ± 10.77	(-10.54, 3.15)	-0.45	2.87	0.07
	Traditional	1.32 ± 7.67	-5.27 ± 9.40	-6.59 ± 9.35	(-11.24, -1.94)	-0.77		
	Control	-4.47 ± 9.65	-2.11 ± 7.25	2.36 ± 7.86	(-3.26, 7.99)	0.28		

Table 10. Peak kinematic variables during first 40% of stance phase during ***false cue unanticipated cutting task***



Variable	Group	Pre-test	Post-test	Change Score	95% CI of Change Score	Effect Size
A/P TTS (s)*	**Pediatric**	2.73 ± 0.42	2.11 ± 0.52	-0.62 ± 0.56	(-0.81, -0.42)	1.32
	Traditional	2.87 ± 0.49	1.82 ± 0.27	-0.92 ± 0.49	(-1.11, -0.73)	2.30
	Control	2.59 ± 0.43	2.22 ± 0.54	-0.49 ± 0.59	(-0.67, -0.31)	1.00
M/L TTS (s)	**Pediatric**	1.40 ± 0.16	1.47 ± 0.18	0.06 ± 0.14	(-0.05, 0.18)	0.29
	Traditional	1.45 ± 0.17	1.42 ± 0.38	-0.03 ± 0.39	(-0.14, 0.08)	0.03
	Control	1.41 ± 0.18	1.39 ± 0.13	-0.02 ± 0.14	(-0.12, 0.09)	0.13
VJ Height (cm)*	**Pediatric**	24.62 ± 2.92	25.90 ± 3.85	1.28 ± 2.70	(0.20, 2.30)	0.37
	Traditional	25.46 ± 3.99	26.97 ± 2.98	1.70 ± 2.80	(0.70, 2.70)	0.48
	Control	25.53 ± 3.95	23.77 ± 3.60	0.20 ± 0.20	(-1.00, 0.90)	0.05
Power (W)	**Pediatric**	874.74 ± 281.48	997.66 ± 296.84	122.91 ± 206.77	(23.25, 222.57)	0.38
	Traditional	1025.01 ± 274.53	1125.55 ± 241.78	100.53 ± 182.40	(19.66, 181.41)	0.37
	Control	847.33 ± 234.81	894.56 ± 184.87	47.23 ± 133.99	(-9.35, 103.81)	0.13

Table 11. Time-to-Stabilization and Vertical Jump Variables (*p<0.05)



Variable	**Group**	**Means SD**	**95% CI**	**$F_{(2, 63)}$**	**P-value**
Knee flexion	**Males**	10.59 ± 5.11	(8.84, 12.35)	0.63	0.43
	Females	9.53 ± 5.51	(7.39, 11.66)		
Knee valgus	**Males**	-1.17 ± 2.90	(-2.16, -0.19)	0.47	0.49
	Females	-0.69 ± 2.69	(-1.73, 0.36)		
Knee rotation	**Males**	-7..03 ± 8.96	(-10.06, -4.00)	2.88	0.09
	Females	-10.82 ± 8.70	(-14.19, -7.44)		
Hip flexion	**Males**	-20..55 ± 7.56	(-23.11, -17.99)	0.28	0.60
	Females	-19.64 ± 5.96	(-21.95, -17.34)		
Hip abduction*	**Males**	-20.00 ± 5.09	(-21..72, -18.28)	12.46	<0.001
	Females	-15.53 ± 4.95	(-17.45, -13.61)		
Hip rotation	**Males**	6.01 ± 9.41	(2.83, 9.20)	0.05	0.82
	Females	5.48 ± 9.13	(-15.77, -1.76)		

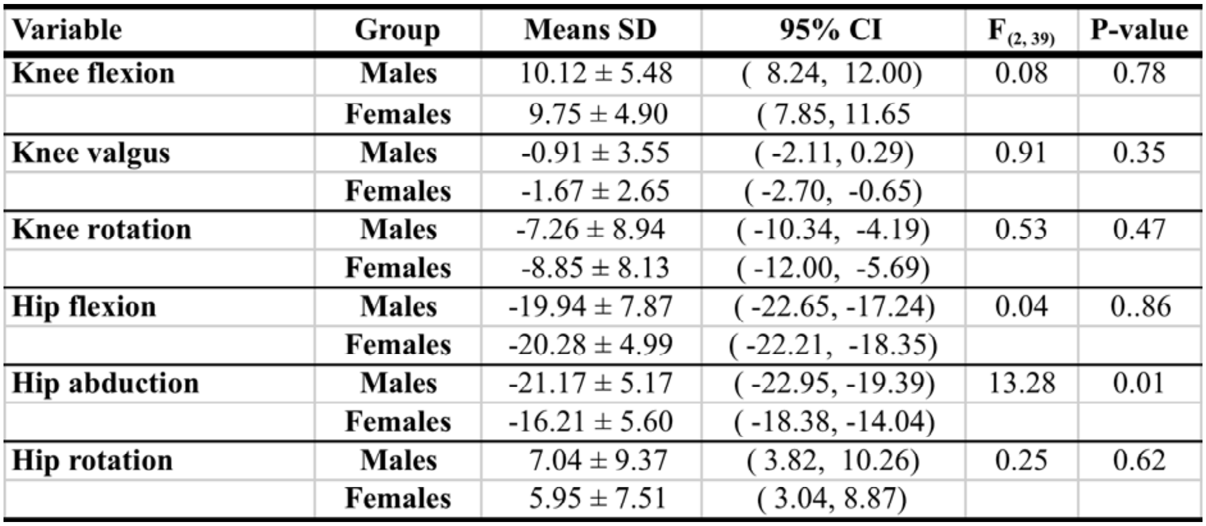
Table 12. Sex differences: Kinematic variables at initial ground contact during pre-test anticipated cutting task (*p<0.05)

Variable	Group	Means SD	95% CI	$F_{(2,63)}$	P-value
Knee flexion	**Males**	43.23 ± 6.94	(40.88, 45.57)	1.81	0.18
	Females	45.64 ± 6.94	(42.78, 48.50)		
Knee valgus	**Males**	-4.25 ± 4.85	(-5.89, -2.60)	0.15	0.70
	Females	-3.78 ± 4.69	(-4.95, 1.31)		
Knee Internal	**Males**	7.25 ± 8.91	(4.23, 10.26)	2.69	0.11
Rotation	**Females**	3.59 ± 8.76	(0.19, 6.99)		
Knee External	**Males**	-7.86 ± 9.00	(-10.90, -4.81)	0.73	0.40
Rotation	**Females**	-9.92 ±10.21	(-13.88, -5.96)		
Hip Flexion	**Males**	-27.67 ± 8.58	(-30.57, -24.77)	0.35	0.56
	Females	-26.42 ± 8.04	(-29.60, -23.24)		
Hip Adduction*	**Males**	-16.68 ± 6.78	(-18.96, -14..39)	14.40	<0.001
	Females	-10.51 ± 5..81	(-12.81, -8.21)		
Hip Abduction*	**Males**	-22.80 ± 5.55	(-24.68, -20.92)	12.02	<0.001
	Females	-17.82 ± 5.77	(-20.10, -15.53)		
Hip Internal	**Males**	9.29 ± 8.01	(6.58, 12.00)	0.12	0.73
Rotation	**Females**	8.58 ± 8.34	(5.28, 11.87)		
Hip External	**Males**	-3.32 ± 8.07	(-6.05, -0.59)	0.39	0.54
Rotation	**Females**	-2.06 ± 7.79	(-5.14, 1.02)		

Table 13. Sex differences: Peak kinematic variables during first 40% of stance phase during pre-test ***anticipated*** cutting task (*p<0.05)

Variable	**Group**	**Means SD**	**95% CI**	**$F_{(2,63)}$**	**P-value**
VGRF (%BW)	**Males**	3.84 ± 0.78	(3.58, 4.10)	0.71	0.40
	Females	3.67 ± 0.77	(3.38, 3.97)		
ATSF (%BW)*	**Males**	0.36 ± 0.18	(0.30, 0.42)	8.89	0.00
	Females	0.24 ± 0.14	(0.19, 0.29)		
Knee Extension	**Males**	-0.13 ± 0.12	(-0.17, -0.09)	0.01	0.93
Moment (%BW*m)	**Females**	-0.13 ± 0.11	(-0.17, -0.09)		
Knee Valgus	**Males**	-0.15 ± 0.12	(-0.19, -0.11)	0.38	0.54
Moment (%BW*m)	**Females**	-0.17 ± 0.14	(-0.22, -0.12)		
Knee Rotation	**Males**	-0.08 ± 0.06	(-0.06, -0.10)	0.20	0.66
Moment (%BW*m)	**Females**	-0.08 ± 0.05	(-0.05, -0.10)		

Table 14. Sex differences: Peak kinetic variables during first 40% of stance phase during pre-test ***anticipated cutting task*** (*$p<0.05$)

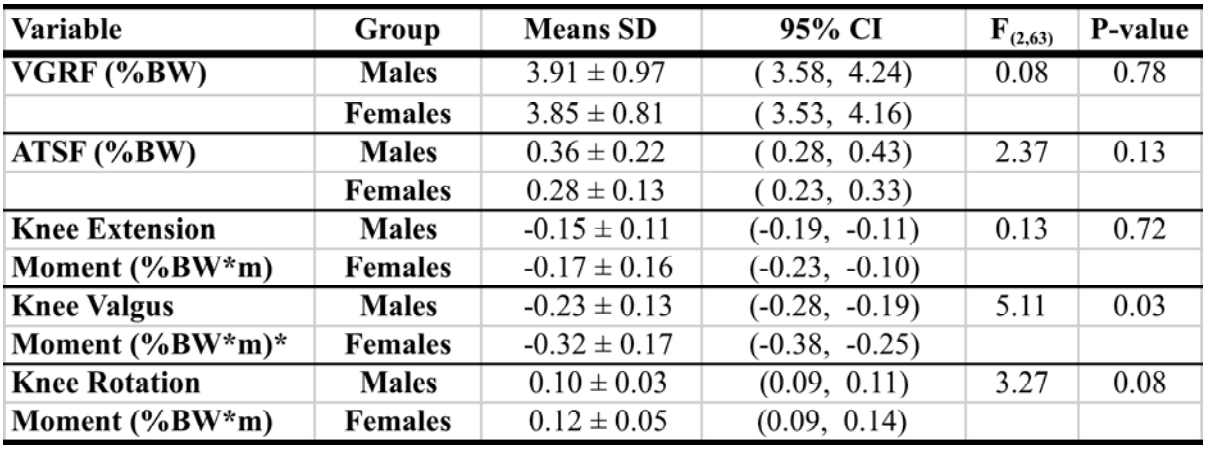


Variable	Group	Means SD	95% CI	$F_{(2, 39)}$	P-value
Knee flexion	**Males**	10.12 ± 5.48	(8.24, 12.00)	0.08	0.78
	Females	9.75 ± 4.90	(7.85, 11.65		
Knee valgus	**Males**	-0.91 ± 3.55	(-2.11, 0.29)	0.91	0.35
	Females	-1.67 ± 2.65	(-2.70, -0.65)		
Knee rotation	**Males**	-7.26 ± 8.94	(-10.34, -4.19)	0.53	0.47
	Females	-8.85 ± 8.13	(-12.00, -5.69)		
Hip flexion	**Males**	-19.94 ± 7.87	(-22.65, -17.24)	0.04	0..86
	Females	-20.28 ± 4.99	(-22.21, -18.35)		
Hip abduction	**Males**	-21.17 ± 5.17	(-22.95, -19.39)	13.28	0.01
	Females	-16.21 ± 5.60	(-18.38, -14.04)		
Hip rotation	**Males**	7.04 ± 9.37	(3.82, 10.26)	0.25	0.62
	Females	5.95 ± 7.51	(3.04, 8.87)		

Table 15. Sex differences: Kinematic variables at initial ground contact during pre-test ***unanticipated cutting task*** (*p<0.05)

Variable	Group	Means SD	95% CI	$F_{(2,63)}$	P-value
Knee flexion	**Males**	45.16 ± 6.89	(42.82, 47.49)	2.55	0.16
	Females	48.04 ± 7.53	(45.12, 50.96)		
Knee valgus	**Males**	-4.38 ± 5.50	(-6.24, -2.52)	0.08	0.78
	Females	-4.74 ± 4.41	(-6.45, -3.02)		
Knee Internal Rotation	**Males**	8.15 ± 9.52	(4.93, 11.37)	3.56	0.06
	Females	4.11 ± 7.03	(1.38, 6.83)		
Knee External Rotation	**Males**	-8.41 ± 9.07	(-11.48, 5.34)	0..36	0.55
	Females	-9.70 ± 7.92	(-12.78, -6.63)		
Hip Flexion	**Males**	-29.99 ± 9.66	(-33.31, -26.67)	0..09	0.76
	Females	-30.66 ± 7.23	(-33.46, -27.86)		
Hip Adduction*	**Males**	-17.58 ± 5.97	(-19.63, -15.53)	20.59	<0.001
	Females	-10.30 ± 6.75	(-12.92, -7.68)		
Hip Abduction*	**Males**	-23.67 ± 5.19	(-25.46, -21.89)	15.54	<0.001
	Females	-18.12 ± 5.99	(-20.44, -15.80)		
Hip Internal Rotation	**Males**	11.05 ± 8.90	(7.99, 14.11)	0.07	0.79
	Females	10.51 ± 6.39	(8.03, 12.99)		
Hip External Rotation	**Males**	-1.81 ± 8.02	(-4.56, 0.95)	1.00	0.32
	Females	0.04 ± 6.26	(-2.38, 2.47)		

Table 16. Sex differences: Peak kinematic variables during first 40% of stance phase during pre-test ***unanticipated cutting task*** (*$p<0.05$)



Variable	Group	Means SD	95% CI	$F_{(2,63)}$	P-value
VGRF (%BW)	**Males**	3.91 ± 0.97	(3.58, 4.24)	0.08	0.78
	Females	3.85 ± 0.81	(3.53, 4.16)		
ATSF (%BW)	**Males**	0.36 ± 0.22	(0.28, 0.43)	2.37	0.13
	Females	0.28 ± 0.13	(0.23, 0.33)		
Knee Extension	**Males**	-0.15 ± 0.11	(-0.19, -0.11)	0.13	0.72
Moment (%BW*m)	**Females**	-0.17 ± 0.16	(-0.23, -0.10)		
Knee Valgus	**Males**	-0.23 ± 0.13	(-0.28, -0.19)	5.11	0.03
Moment (%BW*m)*	**Females**	-0.32 ± 0.17	(-0.38, -0.25)		
Knee Rotation	**Males**	0.10 ± 0.03	(0.09, 0.11)	3.27	0.08
Moment (%BW*m)	**Females**	0.12 ± 0.05	(0.09, 0.14)		

Table 17. Sex differences: Peak kinetic variables during first 40% of stance phase during pre-test ***unanticipated cutting task*** (*$p<0.05$)

Variable	Group	Means SD	95% CI	$F_{(2, 39)}$	P-value
Knee flexion	**Males**	8.63 ± 5.05	(6.40, 10.87)	0.04	0.85
	Females	8.35 ± 4.06	(6.45, 10.25)		
Knee valgus	**Males**	0.70 ± 3.66	(3.66, 0.78)	2.85	0.10
	Females	-1.14 ± 3.39	(-2.73, 0.45)		
Knee rotation	**Males**	-8.06 ± 7.51	(-11.57, -4.54)	0.02	0.88
	Females	-8.42 ± 7.01	(-11.80, -5.04)		
Hip flexion	**Males**	-20.98 ±11.47	(-26.07,-15.89)	2.33	0.14
	Females	-16.64 ± 5.82	(-19.36,-13.91)		
Hip abduction	**Males**	-17.80 ± 8.79	(-21.70,-13.91)	0.14	0.71
	Females	-16.75 ± 9.67	(-21.28,-12.22)		
Hip rotation	**Males**	1.66 ±14.39	(-4.72, 8.04)	1.43	0.24
	Females	6.08 ± 8.44	(2.13, 10.03)		

Table 18. Sex differences: Kinematic variables at initial ground contact during pre-test ***false cue unanticipated*** cutting task (*p<0.05)

Variable	Group	Means SD	95% CI	F$_{(2,63)}$	P-value
Knee flexion	**Males**	42.51 ± 14.67	(36.00, 49.00)	0.24	0.63
	Females	44.56 ± 12.04	(38.92, 50.19)		
Knee valgus*	**Males**	-1.29 ± 4.24	(-3.17, 0.59)	4.31	0.04
	Females	-4.03 ± 4.33	(-6.06, -2.01)		
Knee Internal Rotation	**Males**	4.73 ± 9.85	(0.12, 9.34)	0.14	0.71
	Females	5.78 ± 6.37	(2.50, 9.06)		
Knee External Rotation	**Males**	-8.55 ± 9.39	(-12.95, -4.16)	0.00	1.00
	Females	-8.53 ± 8.52	(-12.91, -4.16)		
Hip Flexion	**Males**	-35.18 ± 15.84	(-42.20,-28.15)	0.72	0.40
	Females	-31.96 ± 6.19	(-34.85,-29.06)		
Hip Adduction	**Males**	-8.16 ± 8.17	(-11.79, -4.54)	1.08	0.31
	Females	-10.77 ± 7.49	(-14.49, -7.04)		
Hip Abduction	**Males**	-17.09 ± 7.13	(-20.42,-13.75)	0.48	0.49
	Females	-18.77 ± 7.82	(-22.86,-14.88)		
Hip Internal Rotation	**Males**	4.01 ± 11.52	(-1.39, 9.40)	3.80	0.06
	Females	10.56 ±9.30	(6.08, 15.05)		
Hip External Rotation	**Males**	-2.85 ± 8.94	(-7.03, 1.34)	2.14	0.15
	Females	0.81 ± 6.38	(-2.27, 3.89)		

Table 19. Peak kinematic variables during first 40% of stance phase during pre-test ***false cue unanticipated cutting task*** (*$p<0.05$)

Variable	Group	Means SD	95% CI	$F_{(2, 63)}$	P-value
Knee flexion	**Males**	8.74 ± 5.98	(6.72, 10.77)	0.05	0.82
	Females	8.41 ± 5.34	(6.34, 10.48)		
Knee valgus	**Males**	-1.91 ± 3.11	(-2.96, -0.85)	0.07	0.79
	Females	-2.09 ± 2.24	(-2.96, -1.23)		
Knee rotation	**Males**	-5.41 ± 7.16	(-7.84, -2.99)	0.10	0.75
	Females	-5.92 ± 5.12	(-7.91, -3.94)		
Hip flexion	**Males**	-18.66 ± 8.90	(-21.68, -15.66)	0.65	0.42
	Females	-20.20 ± 5.26	(-22.24, -18.16)		
Hip abduction*	**Males**	-18.44 ± 4.51	(-19.97, -16.92)	12.57	0.00
	Females	-14.16 ± 5.14	(-16.15, -12.17)		
Hip rotation	**Males**	3.15 ± 9.36	(-0.01, 6.32)	0.07	0.80
	Females	2.61 ± 7.08	(-0.14, 5.35)		

Table 20. Sex differences: Kinematic variables at initial ground contact during post-test ***anticipated cutting task*** (*$p<0.05$).

Variable	Group	Means SD	95% CI	$F_{(2,63)}$	P-value
Knee flexion	**Males**	43.00 ± 7.00	(40.64, 45.37)	4.18	0.05
	Females	46.39 ± 6.00	(44.07, 48.73)		
Knee valgus	**Males**	-5.16 ± 4.37	(-6.64, -3.69)	1.42	0.24
	Females	-6.42 ± 3.96	(-7.96, -4.86)		
Knee Internal	**Males**	6.63 ± 7.54	(4.08, 9.18)	0.06	0.81
Rotation	**Females**	6.20 ± 6.05	(3.86, 8.55)		
Knee External	**Males**	-6.81 ± 6.60	(-9.04, -4.58)	0.02	0.90
Rotation	**Females**	-6.62 ± 5.04	(-8.57, -4.66)		
Hip Flexion	**Males**	-26.15 ± 9.30	(-29.29, -23.00)	0.97	0.33
	Females	-28.17 ± 6..28	(-30.60, -25.73)		
Hip Adduction*	**Males**	-13.79 ± 6.99	(-16.16, -11.43)	12.04	0.00
	Females	-8.04 ± 6.00	(-10.37, -5.72)		
Hip Abduction*	**Males**	-21.41 ± 5.73	(-23.35, -19.47)	16.38	<0.001
	Females	-15.94 ± 4.83	(-17.82, -14.07)		
Hip Internal	**Males**	7.46 ± 9.04	(4.40, 10.52)	0.24	0.62
Rotation	**Females**	6.44 ± 6.84	(3.79, 9.10		
Hip External	**Males**	-5.89 ± 8.70	(-8.83, -2.94)	1.03	0.32
Rotation	**Females**	1.32 ± 7.67	(-6.55, -1.14)		

Table 21. Sex differences: Peak kinematic variables during first 40% of stance phase during post-test ***anticipated cutting task*** (*p<0.05)

Variable	Group	Means SD	95% CI	$F_{(2,63)}$	P-value
VGRF (%BW)	**Males**	3.95 ± 0.81	(3.67, 4.22)	0.80	0.37
	Females	3.78 ± 0.63	(3.53, 4.02)		
ATSF (%BW)	**Males**	0.32 ± 0.20	(0.25, 0.39)	2.20	0.14
	Females	0.26 ± 0.13	(0.20, 0.31)		
Knee Extension	**Males**	-0.16 ± 0.10	(-0.20, -0.13)	0.53	0.47
Moment (%BW*m)	**Females**	-0.18 ± 0.11	(-0.23, -0.14)		
Knee Valgus	**Males**	-0.16 ± 0.11	(-0.20, -0.12)	0.64	0.43
Moment (%BW*m)	**Females**	-0.18 ± 0.15	(-0.24, -0.13)		
Knee Rotation	**Males**	0.07 ± 0.04	(0.06, 0.09)	0.46	0.50
Moment (%BW*m)	**Females**	0.08 ± 0.04	(0.06, 0.10)		

Table 22. Sex differences: Peak kinetic variables during first 40% stance phase during post-test ***anticipated cutting task*** (*p<0.05)

Variable	Group	Means SD	95% CI	$F_{(2, 39)}$	P-value
Knee flexion	**Males**	8.64 ± 5.88	(6.65, 10.63)	0.29	0.59
	Females	7.94 ± 3.92	(6.39, 9.49		
Knee valgus	**Males**	-2.45 ± 3.35	(-3.58, -1.31)	0.02	0.89
	Females	-2.34 ± 2.55	(-3.35, -1.33)		
Knee rotation	**Males**	-5.67 ± 7.08	(-8.06, -3.27)	0.14	0.71
	Females	-6.25 ± 4.73	(-8.13, 4.38)		
Hip flexion	**Males**	-18.42 ± 8.26	(-21.22, -15.63)	1.14	0.29
	Females	-20.35 ± 5.04	(-22.34, -18.36)		
Hip abduction	**Males**	-19.25 ± 7.92	(-21.93, -16.57)	3.92	0.05
	Females	-15.72 ± 5.54	(-17.91, -13.53)		
Hip rotation	**Males**	4.76 ±10.49	(1.21, 8.31)	0.97	0.33
	Females	2.48 ± 6.87	(-0.24, 5.19)		

Table 23. Sex differences: Kinematic variables at initial ground contact during post-test ***unanticipated cutting task*** (*$p<0.05$)

Variable	**Group**	**Means SD**	**95% CI**	**$F_{(2,63)}$**	**P-value**
Knee flexion	**Males**	46.17 ± 7.23	(43.72, 48.62)	0.55	0.46
	Females	47.40 ± 5.35	(45.28, 49.51)		
Knee valgus	**Males**	-5.93 ± 4.54	(-7.46, -4.39)	0.34	0.56
	Females	-6.57 ± 4.04	(-8.16, -4.97)		
Knee Internal Rotation	**Males**	7.62 ± 7.34	(5.14, 10.11)	0.48	0.49
	Females	6.44 ± 5.73	(4.17, 8.71)		
Knee External Rotation	**Males**	-6.50 ± 6.60	(-8.74, -4.27)	0.03	0.87
	Females	-6.75 ± 4.53	(-8.54, -4.96)		
Hip Flexion	**Males**	-30.44 ± 9.77	(-33.74, -27.13)	0.17	0.90
	Females	-30.15 ± 6.28	(-32.64, -27.67)		
Hip Adduction	**Males**	-15.15± 8..56	(-18.05, -12.26)	7.55	0.08
	Females	-9.69 ± 6.66	(-12.33, -7.06)		
Hip Abduction*	**Males**	-21.77 ± 8.09	(-24.50, -19.03)	6.44	0.01
	Females	-17.08 ± 5.94	(-19.43, -14.74)		
Hip Internal Rotation	**Males**	8.87 ± 9.26	(5.74, 12.01)	1.29	0.26
	Females	6.47 ± 6.94	(3.71, 9.20)		
Hip External Rotation	**Males**	-3.00 ± 9.75	(-6.30, 0.30)	0.00	0.99
	Females	-2.98 ± 5.80	(-5.27, -0.68)		

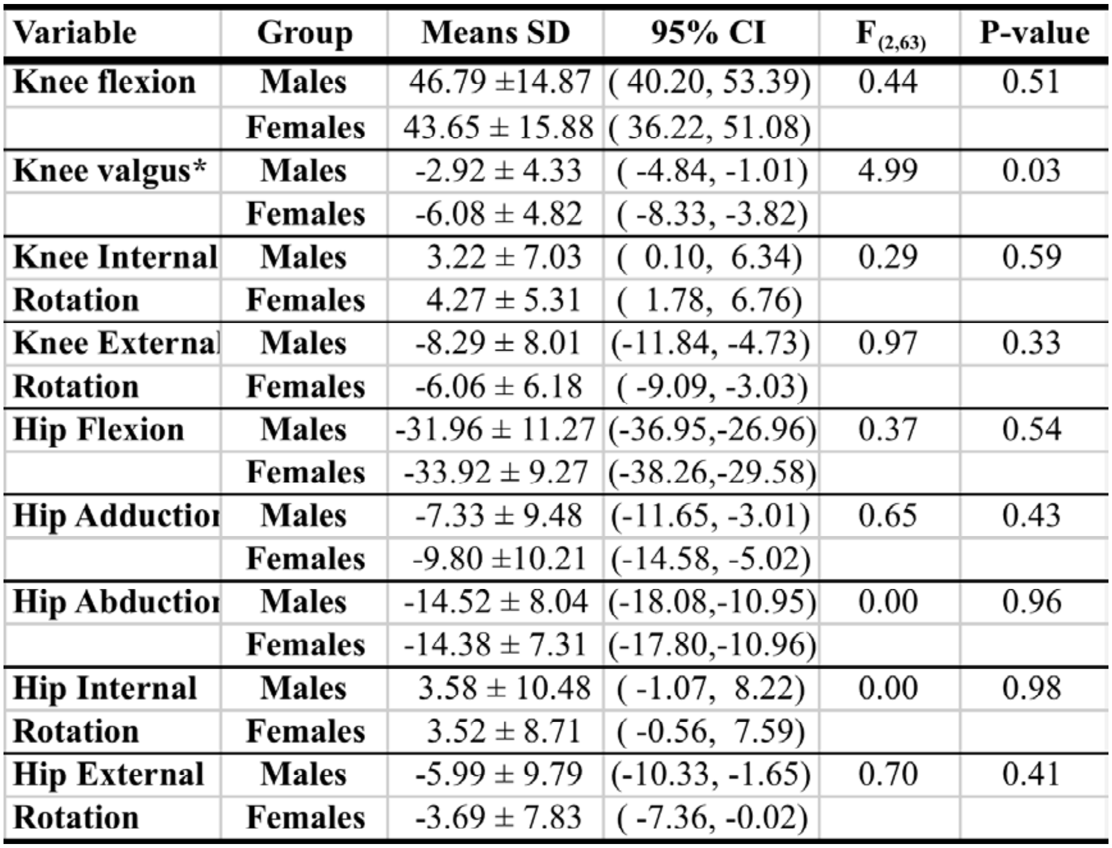
Table 24. Sex differences: Peak kinematic variables during first 40% of stance phase during post-test ***unanticipated cutting task*** (*p<0.05)

Variable	**Group**	**Means SD**	**95% CI**	**$F_{(2,63)}$**	**P-value**
VGRF (%BW)	**Males**	4.19 ± 1.10	(3.81, 4.56)	2.73	0.10
	Females	3.79 ± 0.66	(3.53, 4.05)		
ATSF (%BW)	**Males**	0.29 ± 0.19	(0.22, 0.35)	2.39	0.13
	Females	0.22 ± 0.17	(0.15, 0.28)		
Knee Extension	**Males**	-0.21 ± 0.12	(-0.25, -0.17)	0.58	0.45
Moment (%BW*m)	**Females**	-0.19 ± 0.12	(-0.24, -0.15)		
Knee Valgus	**Males**	-0.28 ± 0.17	(-0.34, -0.27)	0.09	0.77
Moment (%BW*m)	**Females**	-0.27 ± 0.14	(-0.33, -0.22)		
Knee Rotation	**Males**	0.12 ± 0.06	(0.10, 0.14)	1.95	0.17
Moment (%BW*m)	**Females**	0.10 ± 0.04	(0.08, 0.12)		

Table 25. Sex differences: Peak kinetic variables during first 40% stance phase during post-test ***unanticipated cutting task*** (*p<0.05)

Variable	**Group**	**Means SD**	**95% CI**	**$F_{(2, 39)}$**	**P-value**
Knee flexion	**Males**	6.76 ± 6.19	(4.02, 9.51)	0.34	0.57
	Females	5.79 ± 4.39	(3.74, 7.85)		
Knee valgus	**Males**	-0.43 ± 3.98	(4.63, 7.97)	1.42	0.24
	Females	-1.69 ± 2.68	(-2.20, 1.33)		
Knee rotation	**Males**	-7.43 ± 8.26	(-11.09, -3.77)	0.00	1.00
	Females	-7.43 ± 4.49	(-9.53, -5.33)		
Hip flexion	**Males**	-17.49 ± 8.90	(-21.44,-13.55)	0.05	0.82
	Females	-16.93 ± 6.82	(-20.12, -13.73)		
Hip abduction	**Males**	-12.94 ± 8.36	(-16.65, -9.24)	1.14	0.29
	Females	-15.53 ± 4.95	(-18.91,-12.16)		
Hip rotation	**Males**	-2.90 ±10.08	(-7.36, 1.57)	0.90	0.35
	Females	5.48 ± 9.13	(-4.60, 4.66)		

Table 26. Sex differences: Kinematic variables at initial ground contact during post-test ***false cue unanticipated*** cutting task (*p<0.05)

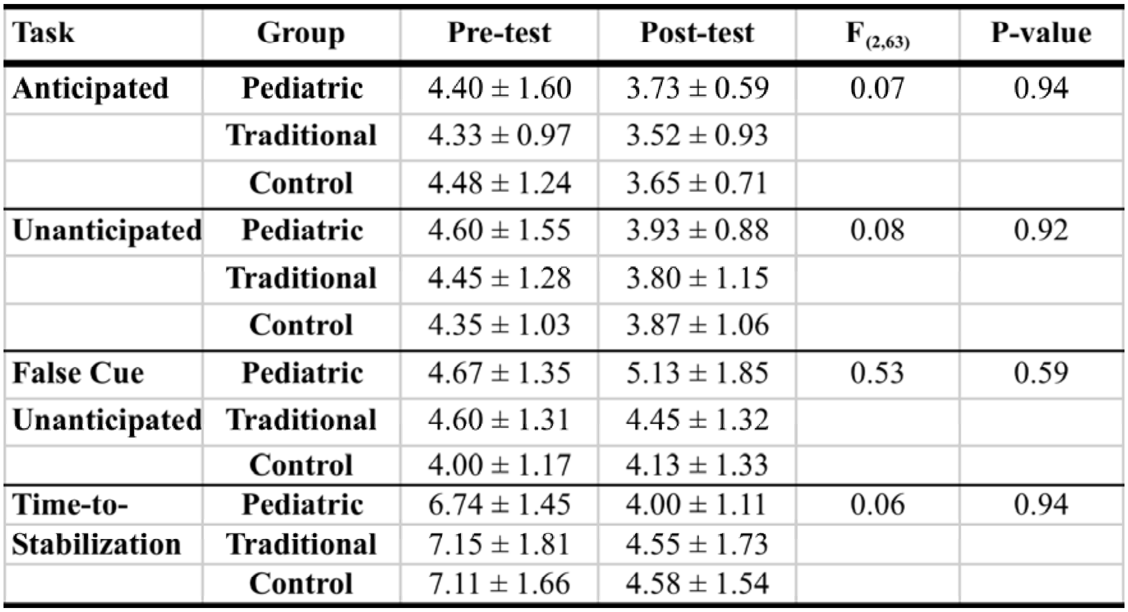


Variable	Group	Means SD	95% CI	$F_{(2,63)}$	P-value
Knee flexion	**Males**	46.79 ±14.87	(40.20, 53.39)	0.44	0.51
	Females	43.65 ± 15.88	(36.22, 51.08)		
Knee valgus*	**Males**	-2.92 ± 4.33	(-4.84, -1.01)	4.99	0.03
	Females	-6.08 ± 4.82	(-8.33, -3.82)		
Knee Internal	**Males**	3.22 ± 7.03	(0.10, 6.34)	0.29	0.59
Rotation	**Females**	4.27 ± 5.31	(1.78, 6.76)		
Knee External	**Males**	-8.29 ± 8.01	(-11.84, -4.73)	0.97	0.33
Rotation	**Females**	-6.06 ± 6.18	(-9.09, -3.03)		
Hip Flexion	**Males**	-31.96 ± 11.27	(-36.95,-26.96)	0.37	0.54
	Females	-33.92 ± 9.27	(-38.26,-29.58)		
Hip Adductio	**Males**	-7.33 ± 9.48	(-11.65, -3.01)	0.65	0.43
	Females	-9.80 ±10.21	(-14.58, -5.02)		
Hip Abductio	**Males**	-14.52 ± 8.04	(-18.08,-10.95)	0.00	0.96
	Females	-14.38 ± 7.31	(-17.80,-10.96)		
Hip Internal	**Males**	3.58 ± 10.48	(-1.07, 8.22)	0.00	0.98
Rotation	**Females**	3.52 ± 8.71	(-0.56, 7.59)		
Hip External	**Males**	-5.99 ± 9.79	(-10.33, -1.65)	0.70	0.41
Rotation	**Females**	-3.69 ± 7.83	(-7.36, -0.02)		

Table 27. Peak kinematic variables during first 40% of stance phase during post-test false cue unanticipated cutting task (*p<0.05)

Variable	Time	Sex	Means SD	95% CI	$F_{(2,63)}$	P-value
A/P TTS	**Pre**	**Males**	2.62 ± 0.43	(2.48, 2.77)	2.10	0.15
(s)		**Females**	2.80 ± 0.53	(2.59, 3.01)		
A/P TTS*	**Post**	**Males**	2.19 ± 0.51	(2.02, 2.37)	7.40	0.01
(s)		**Females**	1.87 ± 0.39	(1.72, 2.03)		
M/L TTS	**Pre**	**Males**	1.43 ± 0.17	(1.38, 1.49)	0.40	0.53
(s)		**Females**	1.41 ± 0.16	(1.34, 1.47)		
M/L TTS	**Post**	**Males**	1.45 ± 0.31	(1.35, 1.56)	1.24	0.27
(s)		**Females**	1.38 ± 0.41	(1.33, 1.44)		
VJ Height*	**Pre**	**Males**	25.66 ± 3.69	(24.45, 26.88)	9.04	0.00
(cm)		**Females**	22.96 ± 3.28	(21.67, 24.26)		
VJ Height*	**Post**	**Males**	26.66 ± 3.73	(25.42, 27.90)	10.21	0.002
(cm)		**Females**	23.89 ± 3.05	(22.71, 25.08)		
Power*	**Pre**	**Males**	979.03 ± 265.38	(891.80,1066.26)	6.34	0.01
(W)		**Females**	826.04 ± 256.35	(724.63, 927.45)		
Power*	**Post**	**Males**	1083.03±258.35	(996.89, 1169.16)	9.5	0.003
(W)		**Females**	896.96±215.88	(813.25, 980.67)		

Table 28. Sex differences: Time-to-Stabilization and Vertical Jump Variables (*$p<0.05$)



Task	Group	Pre-test	Post-test	$F_{(2,63)}$	P-value
Anticipated	**Pediatric**	4.40 ± 1.60	3.73 ± 0.59	0.07	0.94
	Traditional	4.33 ± 0.97	3.52 ± 0.93		
	Control	4.48 ± 1.24	3.65 ± 0.71		
Unanticipated	**Pediatric**	4.60 ± 1.55	3.93 ± 0.88	0.08	0.92
	Traditional	4.45 ± 1.28	3.80 ± 1.15		
	Control	4.35 ± 1.03	3.87 ± 1.06		
False Cue Unanticipated	**Pediatric**	4.67 ± 1.35	5.13 ± 1.85	0.53	0.59
	Traditional	4.60 ± 1.31	4.45 ± 1.32		
	Control	4.00 ± 1.17	4.13 ± 1.33		
Time-to-Stabilization	**Pediatric**	6.74 ± 1.45	4.00 ± 1.11	0.06	0.94
	Traditional	7.15 ± 1.81	4.55 ± 1.73		
	Control	7.11 ± 1.66	4.58 ± 1.54		

Table 29. Trials completed between groups across time for each task

Figure 1. Sidestep Cutting Tasks

Figure 2. Starting position for all cutting tasks

Figure 3. Participant “chasing” model

Figure 4. Tibial rotation at initial ground contact during ***anticipated cutting task*** (*p<0.05)

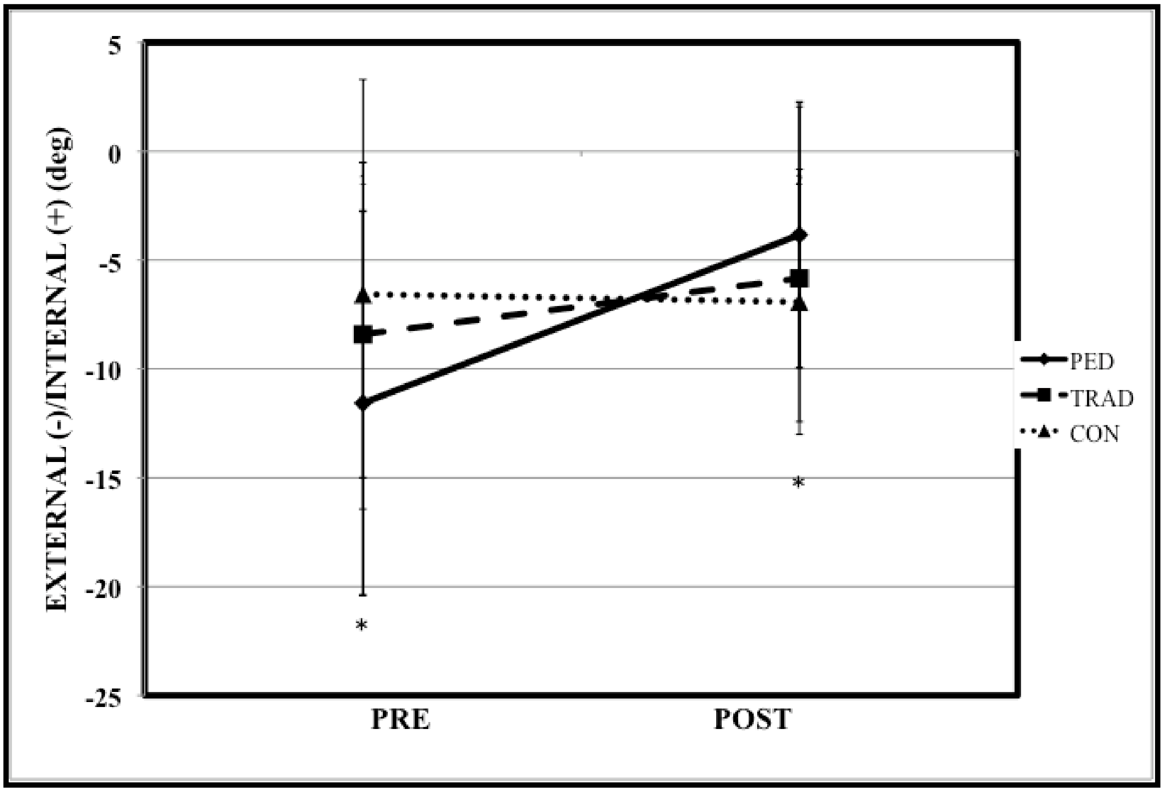


Figure 5. Peak tibial internal rotation during ***anticipated cutting task*** (*p<0.05)

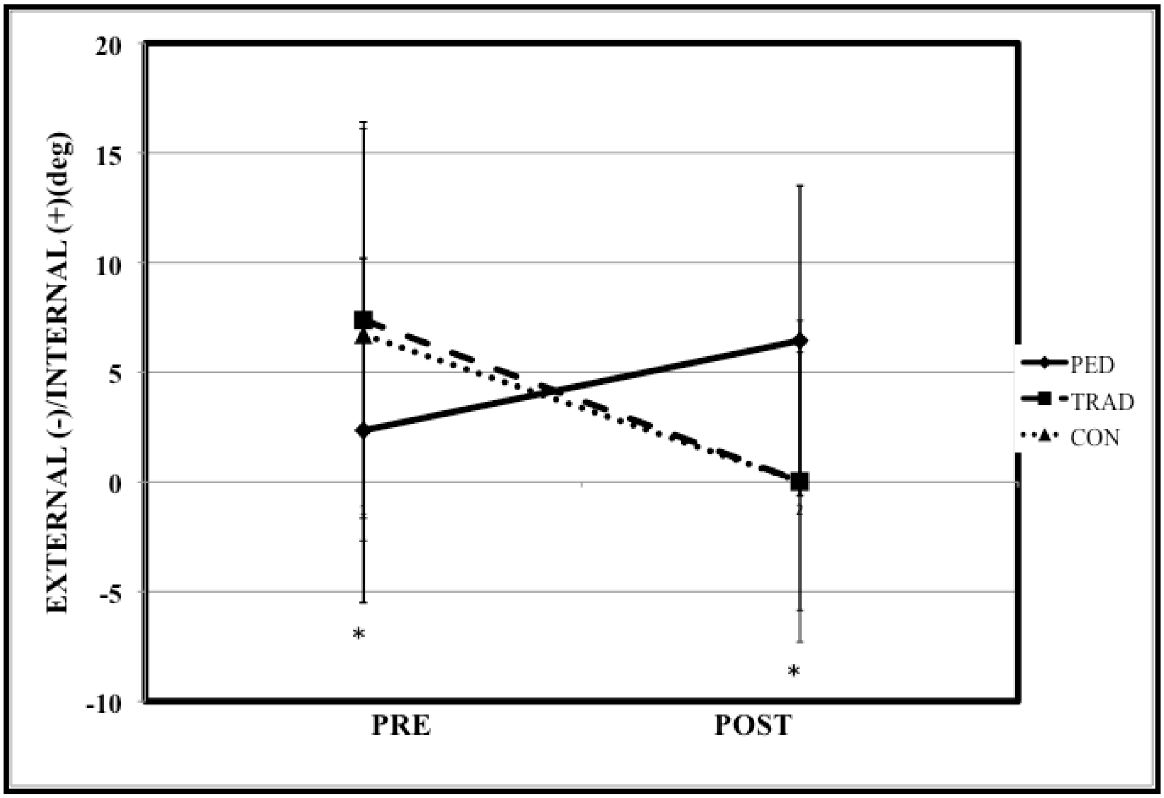


Figure 6. Tibial rotation at initial ground contact during ***unanticipated cutting task*** (*p<0.05)

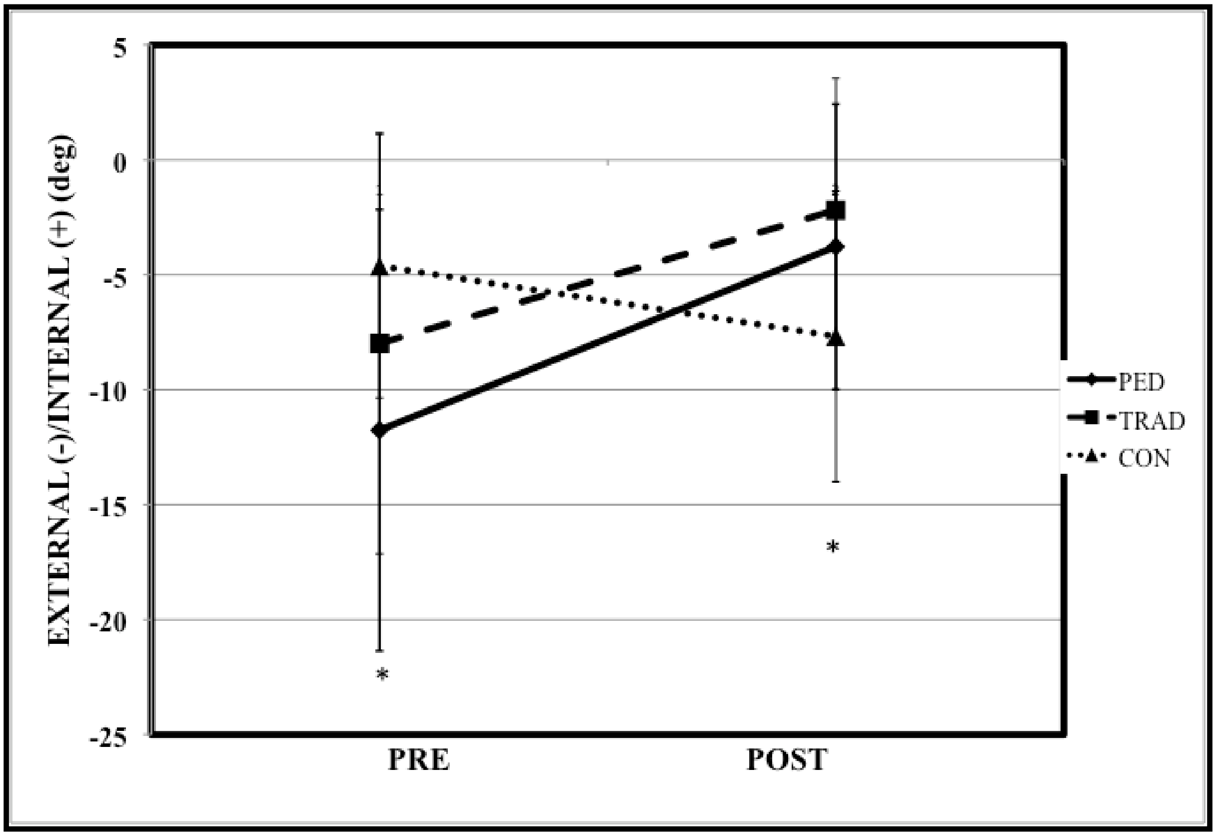


Figure 7. Peak tibial internal rotation during first 40% of stance phase during ***unanticipated cutting task*** (*p<0.05)

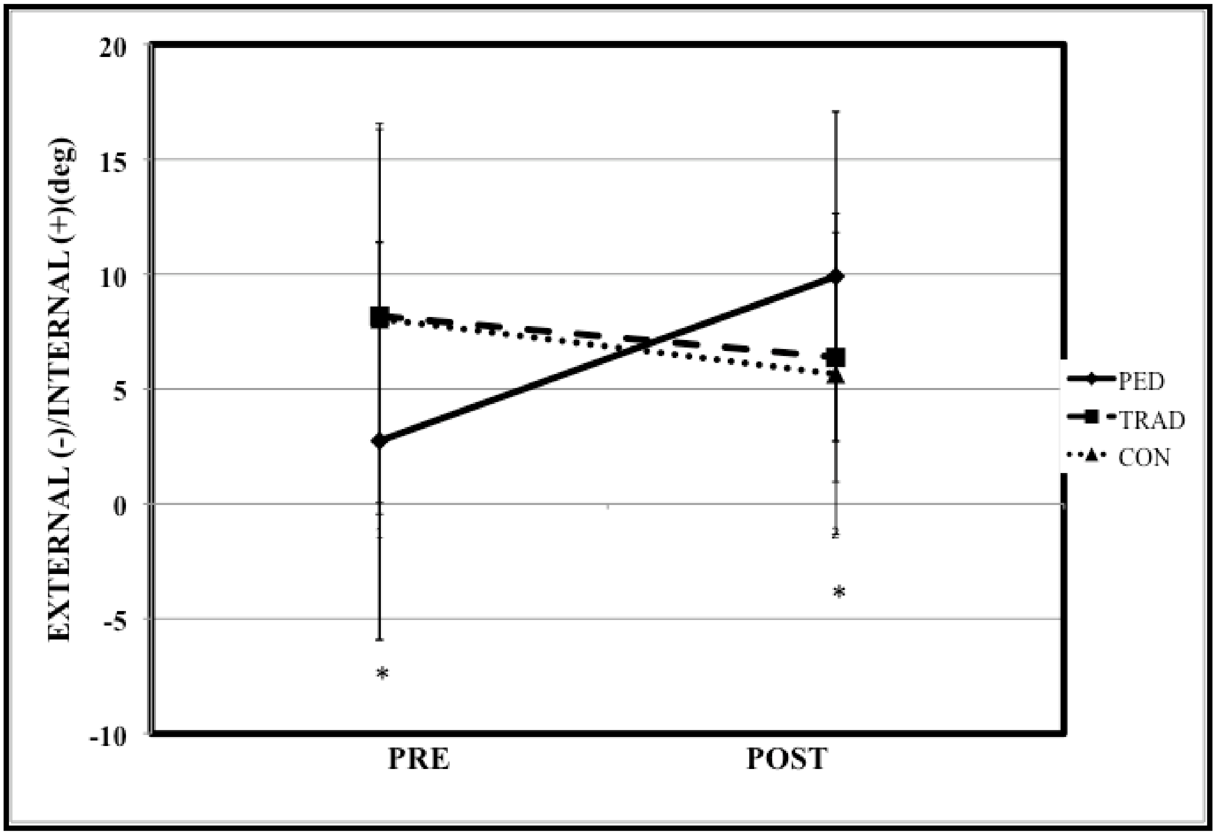


Figure 8. Peak tibial external rotation during first 40% of stance phase during ***unanticipated cutting task*** (*$p<0.05$)

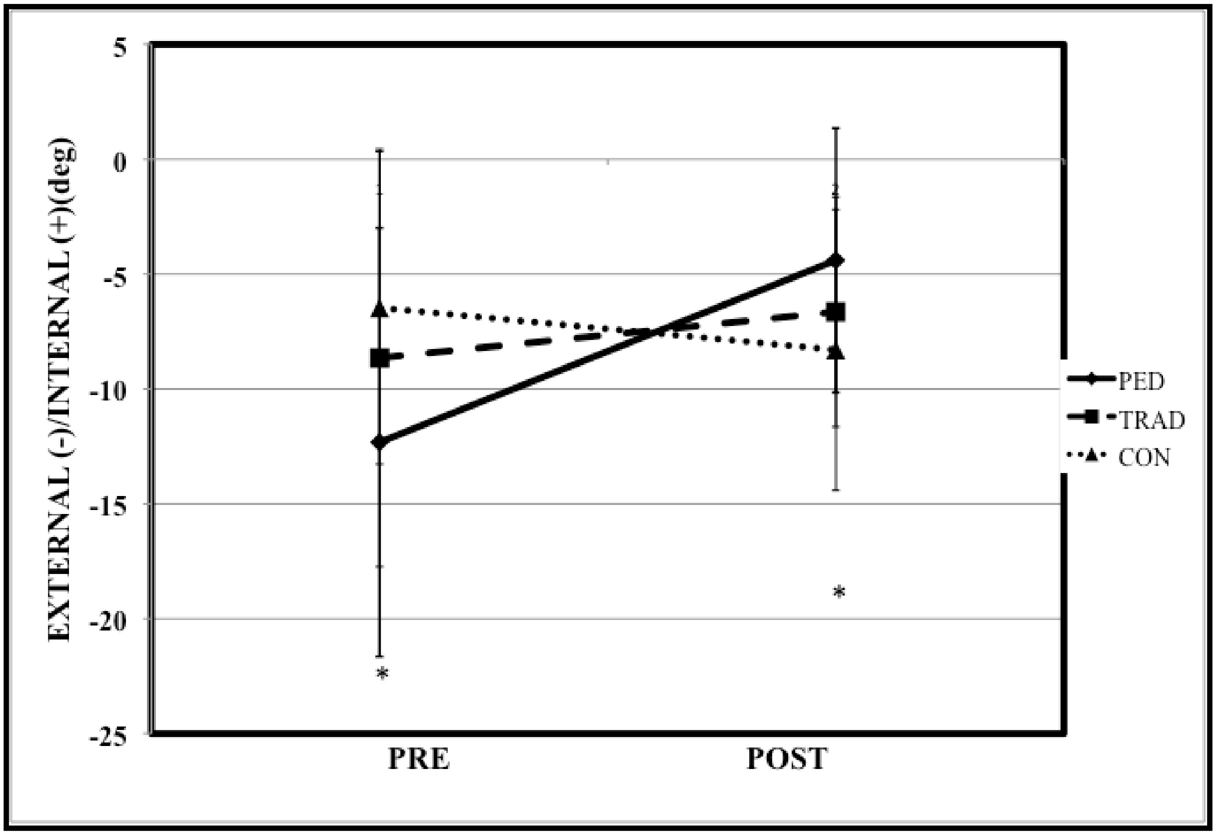


Figure 9. Anterior-posterior time-to-stabilization results (*p<0.05)

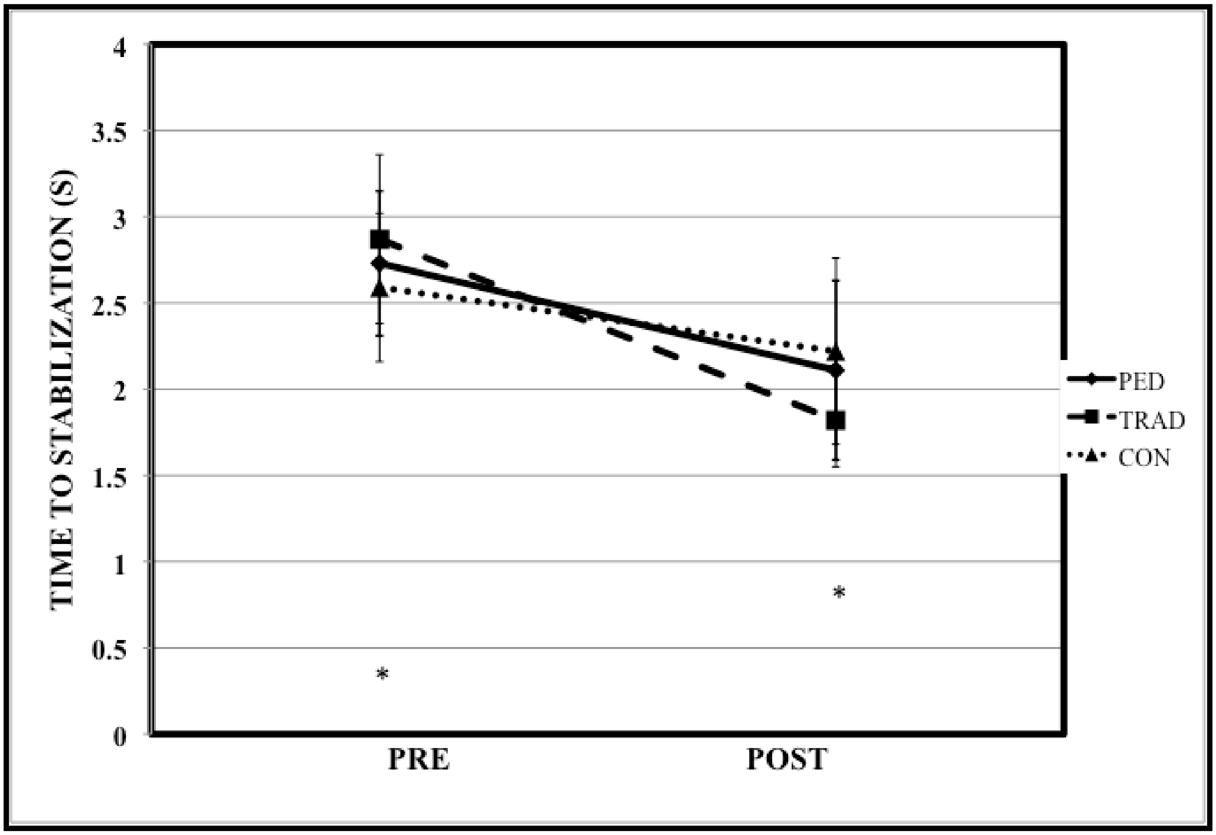
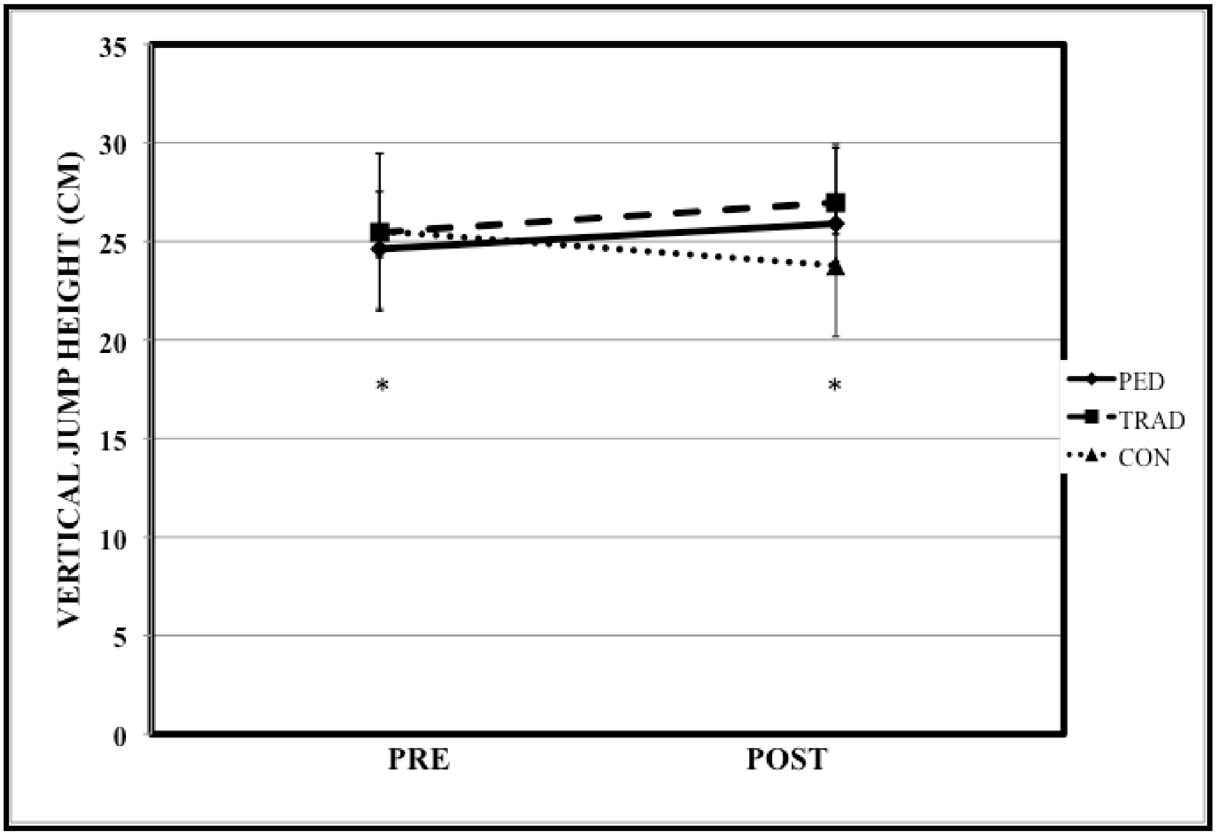


Figure 10. Vertical jump height results (*p<0.05)



APPENDIX A. MANUSCRIPT I

Manuscript I

The Effects of an Age-Specific ACL Injury Prevention Program on Lower Extremity Biomechanics in Pediatric Athletes

(American Journal of Sports Medicine)

ABSTRACT

Background: Implementing an ACL injury prevention program to athletes prior to the age at which the greatest injury risk occurs may result in better long-term outcomes. There is limited knowledge regarding whether a pediatric population can modify lower extremity biomechanics after completing an injury prevention program or if specialized training is required.

Purpose: To compare the effects of a traditional and an age-specific pediatric ACL injury prevention program on lower extremity biomechanics during cutting tasks in youth athletes.

Study Design: Cluster-randomized controlled trial

Methods: 65 youth soccer athletes (Males: n=38, mass=34.16±5.36 kg, height=143.07±6.27 cm, age=10±1 years; Females: n=27, mass=33.82±5.37 kg, height=141.02±6.59 cm) volunteered to participate. Teams were cluster-randomized to either a pediatric or traditional injury prevention program, or a control group. Teams performed their respective programs as part of their normal warm-up routine. Lower extremity biomechanics were assessed during an anticipated and an unanticipated sidestep cutting task before and after completion of the intervention period.

Results: The pediatric program reduced the amount of tibial external rotation at initial contact during the anticipated ($F_{(2,62)}$=3.79, p=0.03; Change Mean±SD: pediatric=7.73±10.71°, control=-0.35±7.76°) and the unanticipated ($F_{(2,62)}$=6.92, p=0.002; Change: pediatric=7.98±11.93°, control=-3.06±6.18°) compared to the control group after the intervention period. No other significant changes were observed (p>0.05).

Conclusion: The injury prevention program designed specifically for a pediatric population modified transverse plane lower extremity biomechanics, which suggests athletes under 12 years of age can change some potential neuromuscular risk factors for injury with specialized training. However, the traditional injury prevention program did not result in any changes, which indicates injury prevention programs should be age-specific.

Key words: injury prevention, tibial rotation, unanticipated cutting task

INTRODUCTION

Injuries to the anterior cruciate ligament (ACL) occur approximately 200,000 times in the United States each year with an associated cost of over $3 billion annually.[44, 51] In addition to high financial costs, ACL injuries are also associated with the early development of osteoarthritis, which may result in life-long disability.[37] Individuals between the ages of 16-18 years appear to be at the highest risk for ACL injuries, but the frequency of ACL injury increases steadily starting in 11 and 12 year old children.[66] Injuries are relatively uncommon at these young ages compared with the later years of adolescence, but treatment for an ACL injury in this population presents a complicated dilemma for health care professionals because these individuals are skeletally immature.[34, 47, 49] Conservative treatment may cause further joint damage and decreased physical activity levels,[47, 48] while surgical treatment is technically difficult and may result in iatrogenic growth disturbances.[34, 47, 49] These consequences demonstrate the immediate need for effective ACL injury prevention, especially in young athletes.

Previous research demonstrates children as young as 10 years old perform sport-related movements with possible neuromuscular risk factors for ACL injury, such as limited knee flexion, excessive knee valgus, and large vertical ground reaction forces.[10, 25, 69] Not only are these factors present during late childhood, but late childhood is also considered to be a critical period for fundamental motor skill refinement and motor development.[18, 20, 32] Growth is fairly steady and gradual during late childhood resulting in an ideal environment for children to develop coordination and neuromuscular skill.[19] Therefore, late childhood may be an ideal time to improve motor skills and correct neuromuscular risk factors for injury.

While it appears that intervening with children at a young age may be critical, it is unclear whether this age group will respond to an ACL injury prevention program. Only two studies have evaluated lower extremity movement patterns following an injury prevention program in children under 13 years old.[10, 21] Grandstrand et al.[21] did not observe any improvements in knee separation distance in 9-11 year old children who completed an injury prevention program. DiStefano et al.[10] studied the effects of an injury prevention program on landing technique in two age groups of children. The older age group (14-17 years old) sustained greater improvements compared to the younger age group (10-13 years old) despite the fact that the younger age group performed the program for a longer period of time. Both of these investigations used an injury prevention program that included challenging exercises and lacked progressions, which caused the authors to conclude that the younger athletes may require specialized training. These studies suggest that injury prevention programs that have been shown to improve lower extremity biomechanics in high school and college age populations may not be successful when implemented to younger children.

Many current ACL injury prevention programs are not progressive[38, 58, 62] and begin with difficult plyometric and strengthening exercises.[27, 53] Children respond to strengthening programs through neural adaptations rather than muscle hypertrophy[24, 59] and physically immature children are prone to overuse injury.[16, 43] A progressive and gradual program will allow neural adaptations to occur without excessively loading a child's body, provide variety to help keep a child attentive,[33] as well as allow ample time for feedback and instruction. Young children learn better when difficult tasks are separated into basic components and when continuous feedback is provided.[13, 68, 70]

Addressing differences between children and adults may enhance the ability to change neuromuscular risk factors and prevent ACL injuries in a young population.

Therefore, the purpose of this study was to evaluate the effects of an ACL injury prevention program designed specifically for a pediatric age group in children under 12 years of age on lower extremity biomechanics during cutting tasks and to compare these changes to the effects of a traditional program. We hypothesized that the program designed for the pediatric population would result in greater changes in lower extremity biomechanics compared to the traditional program.

METHODS AND MATERIALS

Research Design

We used a cluster-randomized controlled trial study design to evaluate changes in lower extremity biomechanics before and after the completion of one of two ACL injury prevention programs: pediatric (PED), traditional (TRAD), or no program at all (control (CON)). Six teams were initially recruited from a local soccer league. All athletes on a team performed their team's respective program as part of their normal warm-up, but only athletes who volunteered to participate completed two testing sessions. Following the first testing session (pre-test), the six teams were stratified by sex and cluster-randomized into one of the three programs resulting in one boys' and one girls' team for each program. A seventh team was additionally recruited due to a roster change with the boys' control team to ensure sufficient sample size. The dependent variables included: lower extremity kinematics (knee flexion, knee valgus, tibial rotation, hip flexion, hip adduction, hip rotation) and kinetics (knee extension moment, knee valgus moment, tibial rotation moment, anterior tibial shear force) during an anticipated and an unanticipated sidestep cutting tasks. These variables were compared between the pre-test and post-test sessions and between groups.

Participants

Sixty-five youth soccer players (Males: n=38, age= 10 ± 1 years, mass= 34.16 ± 5.36 kg, height= 143.07 ± 6.27 cm; females: n=27, age= 10 ± 1 years, mass= 33.82 ± 5.37 kg, height= 141.02 ± 6.59 cm) from seven teams volunteered to participate in this study (Table 1). All participants were healthy and free from any injury or illness that prohibited soccer activity at the pre-test session. All parents and players read and completed informed consent and assent forms, respectively, which were approved by the university's Institutional Review Board before the initial testing session.

Instrumentation

Lower extremity kinematics and kinetics were collected using Vicon Nexus Software (Vicon Motion Systems, Centennial, CO) during an anticipated and an unanticipated cutting task. Seven infrared video cameras (Vicon MX-40; Vicon Motion Systems, Centennial, CO) captured trajectories of reflective markers worn by the participants at a sampling rate of 150 Hz. Ground reaction forces were collected by a force plate (Model # 4060-08A, Bertec Corp., Columbus OH), sampled at 1500 Hz, and were synchronized with the kinematic data. Prior to data collection, the global axis system was established with the positive x-axis pointing in the direction participants ran before cutting (forward), positive z-axis directed vertically, and the y-axis directed to the left of the participants. Segment axes were aligned with the global axis. Prior to the cutting tasks, passive reflective markers were placed on the following landmarks: right and left acromion processes, right and left anterior superior iliac spines, proximal sacrum (S1), right and left greater trochanters, lateral aspects of the right and left thighs, lateral epicondyles of the right and left knees, medial epicondyles of the right and left knees, lateral aspects of the right and left shanks, right and left lateral malleoli, right and left medial malleoli, right and left posterior calcanei, the heads of the right and left 5th metatarsals, and the heads of the right and left 1st metatarsals. The markers were affixed to the skin, tight-fitting clothing, and shoes with double-sided adhesive tape. Following marker placement, participants were asked to stand in the center of the calibration area (2.5 m high × 2.5 m long × 1.5 m wide) with each foot on a force plate (Type 4060-08, Bertec Corporation, Worthington, OH) in order to collect a static calibration trial. After the calibration trial, the markers on the medial epicondyles and medial malleoli were removed.

A live model was used to signal the start of the cutting tasks and was the same individual for all testing sessions. A wireless timing system (Sparq XLR8 Digitial Timing System, Wausau, WI) measured the time between when the live model and the participant jumped from a box to ensure the participant was in the air when the live model changed directions. One timing gate was placed in front of the live model and a second timing gate was in front of the participant. A maximum time of 400 ms was allowed between the trigger of the live model's timing gate and the participant's timing gate or the trial was repeated.

Procedures

Participants attended two identical testing sessions in a sports medicine research laboratory. A nine-week intervention period began one week after the first session, or pre-test, while the second (post-test) session occurred within one week of completing the intervention period. All participants wore standardized shorts and shirt, as well as their own running shoes, during both testing sessions. Participants' height and weight were measured and recorded upon arrival to the laboratory. All testing occurred on participants' dominant limbs, which was the limb preferred to kick a ball for maximal distance.

Participants performed three trials of an anticipated sidestep, an unanticipated sidestep, and an unanticipated cross-over cutting task in a randomized order. The unanticipated cross-over task was only used to permit an unanticipated testing condition and the data from this task were not analyzed. All cutting tasks began with participants standing on a box 30 cm high and a distance of half of their body height away from the front edge of a force plate.(Figure 1) A live model was positioned 3 m from the far end of the force plate (relative to the participant), jumped forward off a 30cm high box, landed on his dominant leg, and performed a cut either to the participant's dominant or non-dominant side. Participants were instructed to begin their jump immediately after the model jumped for all three cutting tasks. Participants jumped forward off of their non-dominant limb toward the force plate, landed with their dominant foot in the middle of a force plate, performed either a 60° (Range: 50-70°) sidestep (Figure 2) or cross-over cut, and ran 2-3m. For the unanticipated cutting tasks, the participants were instructed to cut in the same direction that the live model moved. The participants performed a sidestep cut if the live model moved towards the participants' non-dominant side and a cross-over cut if the live model moved in the other direction. The advantage of using a live model to dictate cutting direction is that it simulates a common soccer task when players are required to "mark" an opponent to prevent them from obtaining the ball. The main difference between the anticipated and unanticipated cutting tasks is that the participants were not told which direction the model would move prior to completing their jump from the box during the unanticipated trials. The model changed direction while the participant was in the air after jumping from the box.

Trials were excluded and repeated if the participant did not jump immediately after the model jumped (within 400ms), if the participant's entire foot did not make contact with the force plate, the participant did not perform a 60° cut, or if the participant did not perform the appropriate task (i.e. side-step vs. cross-over cut). Adhesive tape marked the ground to ensure the participant performed the cut between 50-70°. Participants had at least 20 seconds of rest between each repetition to prevent fatigue, and were given practice trials of each task until the participants indicated they were comfortable with the task.

Injury Prevention Program Implementation

Teams assigned to either the pediatric or traditional programs completed the ten to fifteen minute program as the team's warm-up during the nine week intervention period. Both programs consisted of flexibility, balance, strengthening, agility, and plyometric exercises. The principal investigator or a research assistant taught the players the program within one week of completing the pre-test session, supervised the team's implementation of the program at every practice to provide feedback and technique instruction, and monitored compliance. Proper technique was continually stressed to all of the participants while they performed the exercises. Teams assigned to the control group conducted their normal warm-up as determined by their coach. The control group teams were supervised once per week to ensure that they did not perform any warm-up that was similar to either of the intervention programs.

The traditional program was modified from previous ACL injury prevention programs and designed to be a dynamic warm-up.[14, 21, 27, 38, 52] Participants performed one of the exercises while they moved forward a distance of 10 m. After completing the exercise, participants ran forward an additional 10 m. The 10 m run speed gradually increased as the warm-up progressed. All exercises were performed bilaterally and the program was completed three times per week for nine weeks. Table 2 provides a detailed description of the traditional ACL injury prevention program.

The pediatric ACL injury prevention program was similar to the traditional program by integrating balance, flexibility, strengthening, plyometric, and agility exercises. However, it differed because the pediatric program used more progressive exercises, included more variety, taught smaller task components, provided more time for instruction, practice, and utilized cues designed for children's focus of attention, and included repetitions and frequencies appropriate for gaining neuromuscular improvements in strength. In addition, the pediatric program included dynamic flexibility exercises instead of static flexibility exercises because dynamic flexibility exercises have been recommended for pre-participation warm-up activities in children.[14] The pediatric program consisted of three progressive phases. The first phase was only performed two times per week while the final two phases were completed three times per week. The three progressive phases were further divided to allow additional time for proper technique and feedback during the first week of each phase. The remaining weeks of each phase included small progressions of the exercises and an addition of one or two exercises.

Similar to the traditional program, the pediatric program incorporated several of the exercises into a dynamic warm-up protocol. The two programs were very similar during the first phase as participants ran at progressively increasing speeds following the exercise movement. However, the pediatric program included a "timing" run after the exercise movements instead of the speed forward run during the second phase. The "timing" run required two participants finishing the exercise movements at the same time to run at a diagonal and cross in front of or behind the opposite player. This movement required the participants to control their body and use visual information about another moving player to direct their motion to avoid a collision. During the third phase, participants performed a sharp sidestep cut at the end of the run.

Another difference between the pediatric and traditional programs was that the pediatric program began with primarily strengthening exercises and minimal plyometric exercises and transitioned by gradually changing these proportions. As a result, the final phase included only one strengthening exercise and several plyometric exercises. In contrast, the traditional program included the same number of strengthening and plyometric exercises throughout the nine week program. Table 2 provides a detailed description of the pediatric ACL injury prevention program.

Data Reduction

All kinematic and kinetic data were transferred into Motion Monitor Software (Innovative Sports Training Inc, Chicago, IL) for data processing and exported into a customized software program (MatLab version 7; MathWorks, Natick, MA) for data reduction. All kinematic data were smoothed with a Butterworth (4^{th} order, zero phase lag) low-pass digital filter at 15 Hz. Ground reaction forces were normalized to body weight (N), and moment data were normalized to the product of body weight and height (N*m).

Three dimensional coordinates were estimated from the two-dimensional trajectories of the reflective markers. Knee and ankle joint centers were estimated as centroids from the medial and lateral malleoli and epicondyles, respectively, and the hip joint center was estimated from the markers on the bilateral anterior superior iliac spines using the Bell method.[4] The three-dimensional coordinates of body landmarks determined segment locations and orientations of the pelvis, femur, and shank. The three-dimensional coordinates of the knee joint center, the ankle joint center, and the anterior tibial marker defined the tibial reference frame. The three-dimensional coordinates of the knee joint center, the hip joint center, and the anterior thigh marker defined the thigh reference frame. Finally, the three-dimensional coordinates of the hip joint centers and the proximal sacrum marker defined the pelvis reference frame. Kinematics of the shank and thigh, as well as the thigh and pelvis segments determined knee and hip joint angles, respectively. Joint motions were determined through a joint coordinate system using Euler angles.[23] The axis system established used a right-hand coordinate system, such that the following joint motions were positive: knee flexion/hip extension, adduction/varus, and internal rotation. Joint angles were calculated using the Motion Monitor software as Euler angles rotated in a flexion/extension (x-axis), adduction (varus)/abduction (valgus) (y-axis), internal/external rotation (z-axis) sequence. Using standard inverse dynamics, proximal anterior tibial shear force and three-dimensional hip and knee internal joint moments were calculated.

Knee flexion, knee valgus, tibial rotation, hip flexion, hip adduction, and hip rotation angles were identified at initial ground contact during the cutting task, which was defined as the instant the vertical ground reaction force exceeded 10N. Peak values for these same angles, as well as peak anterior tibial shear force, peak knee extension, valgus, and rotation moments were identified during the first 40% of the stance phase during the cutting task. The stance phase was defined as the time between initial ground contact and toe-off, which occurred when the vertical ground reaction force dropped below 10N following initial ground contact. The data from the three trials of each task during pre-test and post-test were averaged together.

Statistical Analyses

We calculated change scores for all dependent variables by subtracting the pre-test value from the post-test value. We performed separate one-way analyses of variance (ANOVA) on the change scores for each dependent variable. We conducted independent t-tests and corrected the alpha level using a Bonferroni correction in the presence of a significant group effect. All data analyses were performed using SPSS version 16.0 (SPSS, Inc., Chicago, IL) with an *a priori* alpha level of <0 .05.

Results

Every participant except one control subject completed both testing sessions. All participants assigned to either ACL injury prevention program attended greater than 80% of all program sessions. No participants sustained an injury over the course of the intervention period that required time lost from soccer activity. There were also no group differences in height ($F_{(2, 63)} = 2.24$, $p = 0.12$) or weight ($F_{(2, 63)} = 0.66$, $p = 0.52$) prior to beginning the intervention period.

During the anticipated cutting task, we observed group differences in change scores for tibial rotation at initial ground contact ($F_{(2, 62)}=3.79$, $p=0.03$)(Figure 1) and peak tibial internal rotation ($F_{(2, 63)}=4.96$, $p=0.01$)(Figure 2). Post hoc testing revealed that the pediatric program caused participants to land with significantly less tibial external rotation at initial ground contact ($p=0.008$) and attain greater internal rotation during the stance phase compared to the control group ($p=0.005$). The traditional program did not cause a significant change in any dependent variable during the anticipated cutting task ($p>0.05$). No other significant findings were observed ($p>0.05$). Means, measures of variability, and statistical measures for each dependent variable are reported in Tables 3-5.

Similar to the anticipated cutting task results, significant group differences were observed during the unanticipated cutting task in change scores for tibial rotation at initial ground contact ($F_{(2, 63)}=6.92$, $p=0.002$, Effect size=0.19)(Figure 3) and peak tibial internal rotation($F_{(2, 63)}=6.49$, $p=0.003$, Effect size=0.18)(Figure 4). In addition, we observed significant group differences for peak tibial external rotation ($F_{(2, 63)}=5.73$, $p=0.005$, Effect size=0.16)(Figure 5). Post hoc testing demonstrated that the pediatric program caused participants to land with less tibial external rotation at initial ground contact ($p=0.001$, Effect size=0.93) and reduce the total amount of tibial external rotation ($p=0.001$, Effect size=0.86) during the first 40% of the stance phase compared to the control group. The pediatric program also resulted in greater tibial internal rotation during the stance phase compared to the control group ($p=0.002$, Effect size=0.98) and the traditional program (p=0.003, Effect size=0.92). The traditional program did not significantly change any dependent variable during the unanticipated cutting task (p>0.05). We did not observe any other significant differences (p>0.05). Complete means, measures of variability, and statistical results for the dependent variables during the unanticipated cutting task are shown in Tables 6-8.

Discussion

There is great potential for reducing ACL injury rates and improving long-term health by changing neuromuscular risk factors for injury prior to the ages associated with greatest injury risk. The most important finding from this study is that an injury prevention program designed for a pediatric population can successfully alter lower extremity kinematics during a sidestep cutting task in children under 12 years old in a manner suggested as being consistent with reduced ACL injury risk. However, an injury prevention program that was modeled after programs that have been successful with changing lower extremity biomechanics in older populations was not effective with young athletes. This finding supports our hypothesis that young athletes need age-specific training. To our knowledge, this is the first study to demonstrate successful intervention with a young age group after adjusting the program to account for differences in motor learning, cognitive level, and physical development between children and adults.

The majority of ACL injuries occur due to a non-contact mechanism when no direct contact is made between the individual and another player or object.[7, 44] A non-contact ACL injury usually occurs while an individual is trying to rapidly decelerate during a landing or cutting maneuver.[1, 2, 6, 46, 55] Specifically, landing or cutting with limited knee flexion can result in excessive anterior tibial shear force from the quadriceps muscle, which can damage the ACL.[5, 12, 15, 29, 36, 42, 65] The addition of excessive knee valgus or lower extremity rotation increases stress and places the ACL at a high risk for injury.[3, 39] Tibial internal rotation can produce tensile strain on the ACL, while tibial external rotation is associated with the creation of a shearing force on the ligament against the intercondylar notch.[17, 22] Interestingly, a “toed-out”, or externally rotated lower leg position, during landing and cutting tasks is also considered a developmental difficulty during the acquisition of fundamental motor skills.[18, 20] Therefore, changing lower extremity biomechanics during these types of tasks is emphasized in most ACL injury prevention programs.

Our results demonstrate that a pediatric injury prevention program can modify tibial rotation during both an anticipated and an unanticipated cutting task. The participants initially made ground contact with significantly less external rotation following completion of the pediatric injury prevention program compared to the control group. This indicates participants landed with their lower leg in a neutral alignment after completing the pediatric program compared to before the program. One of the main instruction points used with the pediatric program was to “keep your toes forward” during all of the exercises. Therefore, it appears the participants were able to change this movement pattern and concurrently correct the developmental deficiency of a “toed-out” posture.

Participants in the pediatric program performed the cutting tasks with greater amounts of peak tibial internal rotation. We believe this change was due to the adjustment in the participants’ position at initial ground contact because the total tibial rotation range of motion during the task did not change drastically (Pre-test= 12.55°, Post-test = 13.47°). Therefore, the pediatric program caused a shift in tibial rotation from external rotation to internal rotation by reducing the amount of initial tibial external rotation. While excessive tibial internal rotation with concurrent low levels of knee flexion has been shown to significantly load the ACL, an exact threshold of how much internal rotation is detrimental has not been determined. Future research should further evaluate the role of tibial rotation in ACL loading mechanisms.

In 1999, Ireland[30] coined the phrase “position of no return” to illustrate the alignment of the lower extremity prior to a non-contact ACL injury. This position consists of hip adduction, hip internal rotation, limited knee flexion, knee valgus, and tibial external rotation. Not only did we observe a decrease in the amount of knee, or tibial, external rotation, but also a simultaneous reduction in the amount of hip internal rotation. Both the pediatric and traditional programs resulted in 40-60% less hip internal rotation at initial ground contact and throughout the early stance phase during both tasks. Although these changes were not statistically significant, we believe the medium effect sizes in combination with separating confidence intervals demonstrates this reduction may be clinically meaningful. Therefore, these findings of reduced tibial external rotation and hip internal rotation suggest the pediatric program decreased the “position of no return”.

Despite a recent surge in the amount of studies attempting to modify lower extremity biomechanics with an ACL injury prevention program, only two previous studies have examined lower extremity transverse plane motion. Chappell et al.[8] is the only study that evaluated tibial rotation after the completion of an injury prevention program, but did not report any significant changes. This conclusion disagrees with the current results, but there are several differences between the two studies that provide a possible explanation for the discrepancy in findings. Elite college female athletes participated in the study by Chappell et al., which is a different population than the current study, and tibial rotation was assessed during a stop jump task versus a cutting task. The stop jump task primarily involves movement in the sagittal plane, while a cutting task demands transverse plane control. Despite also using a different task than the current study, Pollard et al.[62] reported a decrease in hip internal rotation during a drop landing after high school female soccer athletes completed an injury prevention program, which agrees with our findings. Even though Pollard et al. used a different population and assessment technique, the combination of their results and our current findings suggest integrated injury prevention programs can modify hip internal rotation.

Excessive anterior tibial shear force is considered the most direct mechanism for loading the ACL.[40, 41] Unfortunately, only one previous study has studied the effects of an ACL injury prevention program on anterior tibial shear force and failed to see any significant changes during a stop jump task.[26] Although we did not observe a statistically significant improvement, the pediatric program appeared to decrease anterior tibial shear force by nearly 15% bodyweight, which accounts for a 35% reduction with a moderate effect size. Due to the strong relationship between anterior tibial shear force and ACL strain and the paucity of previous research examining this variable after an injury prevention program, we believe this finding is clinically meaningful and important. Future research should further examine the relationship between anterior tibial shear force and transverse plane motion.

There are several studies that have reported improvements in other lower extremity biomechanical variables, such as increased knee flexion,[8, 52] decreased knee valgus,[35, 52] and reduced vertical ground reaction forces.[28, 31] Our results do not agree with the findings of these studies, but it is difficult to make comparisons because this is the only study to evaluate lower extremity biomechanics after an injury prevention program using a cutting task. Every other study has used a sagittal plane landing task, such as a stop jump, drop jump, or vertical jump. This is a major limitation of the current literature because a majority of ACL injuries occur during a cutting task and is a common aspect of sports such as soccer and basketball.[57] Therefore, it is critical to understand whether injury prevention programs can modify movements during these types of tasks as well as landings.

The principle of exercise specificity, or specific adaptations to imposed demands, is widely accepted with regard to exercise training.[9, 61] This principle may provide some explanations for why more substantial changes in lower extremity biomechanics during the cutting tasks were not observed. During both programs, time was spent focusing on correcting and encouraging proper movement technique during relatively slow and anticipated exercises, such as squats, lunges, and jumps. The traditional program consisted of primarily sagittal plane movements, which may have led to improvements in sagittal plane assessments, such as a drop landing task. Even though the traditional program performed sidestep cutting maneuvers for nine weeks, the cutting was slow and controlled in contrast to the dynamic cutting task used during the testing sessions. The pediatric program included exercises in multiple planes, but the program was progressive and only involved a demanding cutting task during the final three weeks. If more time had been spent on cutting during the programs, it is possible we would have observed greater changes. Since injuries do occur during dynamic activities, such as cutting, more training with this task should be included in future injury prevention programs.

Another possible explanation for failing to see improvements in lower extremity sagittal and frontal plane kinematics and kinetics is the population. To our knowledge, there are only two other studies that have aimed to change lower extremity biomechanics in a population under 13 years old. DiStefano et al.[10] observed improvements in landing technique after an injury prevention program using a clinical motion analysis tool, but reported that the high school aged sample in the study improved to a greater extent than the pre-high school age group (ages 10-13 years). Grandstrand et al.[21] hypothesized that the reason they did not see improvements in knee separation distances with children between the ages of 9-11 years after an injury prevention program was because some of the exercises seemed too difficult for the children, such as the Russian Hamstring exercise.

The conclusions from the three previous studies that have implemented an injury prevention program in young children combined with the findings of literature related to youth resistance training and motor learning led to the development of the pediatric ACL injury prevention program. Kilding et al.[33] recommended more variety with the exercises to prevent boredom and improve compliance, Grandstrand et al.[21] believed exercise difficulty may have prevented improvements from being attained, and DiStefano et al.[10] suggested the need for a specialized program. The youth resistance training literature encourages high repetitions with low weight and decreased frequency to improve strength in preadolescent children. All of the exercises in both programs required only 10-15 minutes and utilized only bodyweight as resistance. The pediatric program also involved higher repetitions of strengthening exercises with a gradual increase in training sessions per week and progressed into demanding plyometric exercises after a foundation of strength training had been achieved. This is in contrast to several other injury prevention programs that have required 30-90 minutes of training several days per week, several plyometric exercises, and included exercises with heavy weights and low resistance.[27, 35, 53]

The motor learning literature suggests the ideal environment for children to acquire new motor skills consists of continuous feedback and instruction, tasks that match their cognitive ability, and are progressive. The pediatric program was designed to teach proper movement patterns by providing constant feedback and cues with an internal focus of attention, such as “bend your knees” and “keep your toes straight ahead”. The first phase included basic exercises, such as a double limb squat and forward lunge, to begin education the participants about proper technique. The second and third phases built on the simplicity of the first phase by incorporating multiplanar movements (“Sideways” and “Transverse Lunge”) and progressed simple skills into more difficult movements (“Single Limb Squat”). We believe the pediatric program’s design enabled the participants to improve the quality of their movement.

While the traditional program did not use heavy weights or extensive time to complete the program, there were no progressions or variety. The traditional program did receive technique instruction and feedback but the verbal cues were for an external focus of attention (“Jump like a spring”, “Land light as a feather”, “Don’t make a sound”). Even though we did not observe any significant improvements with the traditional program, we did observe less hip internal rotation with a moderate effect size similar to the pediatric program. Therefore, it appears some amount of training does result in lower extremity movement improvements. However, anecdotally, the participants in the traditional program complained frequently of boredom. Compliance has been a problem with previous ACL injury prevention programs.[60, 67] Therefore, it is vital that injury prevention programs include variety in order for participants to continue to perform the program over the course of a season or several seasons.

Limitations

We used a cluster-randomized design for this study in order to improve external validity. Injury prevention programs should be designed so that they can be easily adopted by large numbers of people in order for widespread impact. Therefore, we believed the best way to implement and study an injury prevention program was to have an entire team perform the program. A limitation of this study was that we were not able to account for the cluster randomization in the analyses because most methods available would be weak with only 7 units of randomization. Previous research indicates that an individual's baseline technique may influence whether or not an individual responds to a program.[11, 50] Individuals with greater capacity for improvement sustain the greatest changes. The control group's values at pre-test for several variables appeared slightly different than the other two groups, but similar to the traditional and pediatric programs' values at post-test. Therefore, the capacity to improve may have influenced our ability to detect significant changes between programs. We believe the use of change scores eliminated the possible effect of these pre-existing group differences, but recognize these differences may still be influential. We recommend further research analyzing prevention program effects from baseline assessments.

Anticipated and unanticipated cutting tasks were used to assess changes in lower extremity biomechanics because cutting is a frequent component of soccer and basketball and also associated with ACL injury mechanisms.[57] Previous studies have demonstrated differences between the two types of tasks, however, our findings were consistent across the two tasks. While we did not analyze the anticipated and unanticipated cutting tasks, the means do not appear very different. The majority of participants required several additional trials of both cutting tasks and we believe the difficulty of the tasks for this age group may have precluded extensive differences between the anticipatory conditions. Future research should compare lower extremity biomechanics in several dynamic tasks, such as double-limb and single-limb landings and anticipated and unanticipated cutting tasks, with this population.

Conclusion

The pediatric ACL injury prevention program caused children between the ages of 9-11 years old to reduce tibial external rotation, hip internal rotation, and anterior tibial shear force during anticipated and unanticipated sidestep cutting tasks. However, the traditional program did not result in any significant changes supporting the idea that injury prevention programs for children need to be progressive and include more variety, feedback, and time for instruction. These results indicate it may be possible to intervene with children before they reach ages associated with highest ACL injury risk, which may result in improved long-term outcomes.

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Table 1. Subject Demographics

Group	Sample Size	Age	Mass	Height
Pediatric	11 males, 8 females	10 ± 1 years	33.31 ± 5.02 kg	140.43 ± 7.06 cm
Traditional	11 males, 11 females	10 ± 1 years	35.06 ± 5.60 kg	144.41 ± 6.01 cm
Control	14 males, 9 females	10 ± 1 years	33.57 ± 5.39 kg	141.48 ± 5.95 cm

Table 2. Comparison of injury prevention programs

<u>EXERCISES</u>	**Traditional Program**	**Pediatric Program**		
		Phase I	**Phase 2**	**Phase 3**
Time	**12-14 minutes**	**12-14 minutes**	**12-14 minutes**	**12-14 minutes**
Duration	**3 days/week**	**2 days/week**	**3 days/week**	**3 days/week**
	9 weeks	**3 weeks**	**3 weeks**	**3 weeks**
Lower Extremity	Forward Lunge	Forward Lunge	Sideways Lunge	Twisting Lunge
Strengthening	Broad Jump	Double Leg Squat	DL to SL Squat	
	SL Squat	Toe Walk	Broad Jump	
		DL Heel Raise		
Repetitions	**1x5 each leg**	**1x15**	**1x15**	**1x15**
Core Strengthening	Hip Bridge	Hip Bridge	Human Arrow	Sideways Plank
Repetitions	**1x10; hold 3 sec**	**1x10; hold 3 sec**	**1x10; hold 3 sec**	**1x10; hold 3 sec**
Flexibility Type	***Static***	***Dynamic***	***Dynamic***	***Dynamic***
	Calf	Straight Leg March	Straight Leg Skip	Straight Leg Skip
	Hip Flexor	Hand Walk	Walking Calf Stretch	Leg Cradle
	Adductor	Walking Butt Kicks	Hip Flexor Walk	Twisting Hip Flexor Walk
		Walking Quad Stretch	Knee to Chest	Running Butt Kicks
				High Knee Run
Repetitions	**30 sec. each**	**30 sec. each**	**30 sec. each**	**30 sec. each**
Plyometric	Squat Jumps	DL Forward Line Hops	SL Forward Line Hops	SL Sideways Line Hops
	DL Forward Hops (SL)		DL Sideways Line Hops	Squat Jumps
	DL Sideways Hops (SL)		Up and Down Hops	Tuck Jumps
Repetitions	**10 repetitions**	**20 repetitions**	**20 repetitions**	**20 repetitions**
Balance	180° Jump to Balance	180° Jump to Balance	Sideways Hop to Balance	Twisting Hop to Balance
	SL Forward Hop to Bal.	Forward Hop to Balance	Single Leg Ball Toss	SL Balance Perturbations
	SL Ball Toss			
Repetitions	**1x10 each leg**	**1x10**	**1x10**	**1x10**
Agility	Toe-Heel Walk	Forward Skipping	For & Back Skipping	Unanticipated Side Cuts
	High Knee Run	Sideways Shuffle	Side Cuts	
	Sideways Shuffle			
	Z Cuts			
Repetitions	**30 sec. each**	**30 sec. each**	**30 sec. each**	**30 sec. each**

Table 3. Kinematic Variables at Initial ground contact During Anticipated Cutting Task

Variable	Group	Pre-test	Post-test	Change Score	95% CI of Change Score	Effect Size	$F_{(2, 63)}$	P-value
Knee flexion	**Pediatric**	11.12 ± 5.74	9.07 ± 7.51	-2.05 ± 7.80	(-5.94, 1.83)	-0.31	0.3	0.74
	Traditional	9.13 ± 5.06	8.41 ± 5.39	-0.72 ± 6.38	(-3.55, 2.11)	-0.14		
	Control	10.29 ± 5.16	8.23 ± 4.44	-2.05 ± 5.41	(-4.39, 0.29)	-0.43		
Knee valgus	**Pediatric**	-0.55 ± 3.41	-1.40 ± 3.33	-0.85 ± 4.22	(-2.38, 0.68)	-0.25	0.36	0.7
	Traditional	-1.15 ± 2.18	-2.66 ± 2.41	-1.51 ± 3.18	(-2.94, -0.09)	-0.65		
	Control	-1.12 ± 2.86	-1.83 ± 2.49	-0.71 ± 2.58	(-2.10, 0.68)	-0.26		
Knee rotation*	**Pediatric**	-11.57± 8.82	-3.84 ± 6.10	7.73 ± 10.71	(3.36, 12.10)	1.02	3.79	0.03
	Traditional	-8.41 ± 9.87	-5.84 ± 6.09	2.57 ± 10.09	(-1.49, 6.63)	0.31		
	Control	-6.57 ± 7.89	-6.92 ± 6.58	-0.35 ± 7.76	(-4.32, 3.62)	-0.05		
Hip flexion	**Pediatric**	-21.53± 7.44	-18.41± 8.43	3.13 ± 9.61	(-0.83, 7.08)	-0.39	1.36	0.26
	Traditional	-20.40± 5.79	-19.40± 7.76	0.99 ± 8.12	(-2.68, 4.67)	-0.14		
	Control	-18.78± 7.37	-20.05± 6.70	-1.27 ± 8.22	(-4.86, 2.33)	0.18		
Hip abduction	**Pediatric**	-18.93± 5.48	-16.36± 5.25	2.57 ± 5.56	(-0.12, 5.02)	0.49	0.9	0.41
	Traditional	-18.07± 5.48	-17.56± 4.37	0.35 ± 4.99	(-1.93, 2.63)	0.07		
	Control	-17.23± 5.67	-15.58± 5.86	1.65 ± 5.49	(-0.58, 3.79)	0.29		
Hip rotation	**Pediatric**	6.85 ±10.12	2.74 ± 8.78	-4.11 ± 13.03	(-9.21, 0.98)	0.43	1.39	0.26
	Traditional	8.24 ± 8.48	3.05 ± 9.21	-4.99 ± 10.41	(-9.73, -0.25)	0.56		
	Control	2.51 ± 8.71	2.70 ± 7.70	0.19 ± 10.01	(-4.45, 4.82)	-0.02		

Table 4. Peak Kinematic Variables During First 40% of Stance Phase of Anticipated Cutting Task

Variable	Group	Pre-test	Post-test	Change Score	95% CI of Change Score	Effect Size	$F_{(2,63)}$	P-value
Knee flexion	**Pediatric**	44.55 ± 7.33	44.98 ± 7.21	0.43 ± 7.49	(-2.99, 3.85)	-0.06	0.02	0.98
	Traditional	44.45 ± 7.00	44.66 ± 6.81	0.20 ± 7.92	(-2.98, 3.38)	-0.03		
	Control	43.90 ± 7.53	43.92 ± 6.56	0.02 ± 6.97	(-3.09, 3.13)	0.00		
Knee valgus	**Pediatric**	-3.18 ± 6.37	-5.18 ± 4.65	-2.00 ± 6.73	(-4.32, 0.32)	-0.36	0.78	0.46
	Traditional	-4.15 ± 3.46	-6.61 ± 3.84	-2.46 ± 3.94	(-4.62, -0.30)	-0.67		
	Control	-4.65 ± 4.36	-5.29 ± 4.20	-0.64 ± 4.38	(-2.75, 1.47)	-0.15		
Knee Internal Rotation*	**Pediatric**	2.35 ± 7.85	8.80 ± 7.06	6.44 ± 9.05	(2.08, 10.81)	-0.86	4.96	0.01
	Traditional	7.38 ± 9.03	6.19 ± 5.88	0.03 ± 9.26	(-4.19, 4.25)	0.00		
	Control	6.71 ± 9.40	4.74 ± 7.33	-1.97 ± 8.38	(-5.60, 1.65)	0.23		
Knee External Rotation	**Pediatric**	-10.19±10.96	-4.67 ± 5.38	5.52 ±13.13	(0.84, 10.20)	0.64	2.01	0.14
	Traditional	-9.00± 9.88	-7.00 ± 5.47	2.00 ± 9.74	(-2.35, 6.35)	0.25		
	Control	-7.35 ± 8.03	-8.17 ± 6.50	-0.81 ± 7.55	(-5.07, 3.44)	-0.11		
Hip Flexion	**Pediatric**	-29.87± 8.25	-26.59± 9.23	3.28 ± 8.90	(-0.85, 7.40)	-0.37	1.53	0.23
	Traditional	-26.87± 7.28	-28.04± 8.67	-1.17 ± 8.07	(-5.00, 2.66)	0.15		
	Control	-25.03± 9.01	-25.90± 6.46	-0.88 ± 9.87	(-4.71, 2.96)	0.11		
Hip Adduction	**Pediatric**	-14.84± 6.40	-11.53± 7.14	3.31 ± 6.28	(0.47, 6.15)	0.49	0.13	0.88
	Traditional	-14.58± 6.60	-11.81± 5.81	2.78 ± 5.62	(0.14, 5.42)	0.45		
	Control	-12.79± 8.08	-10.48± 8.60	2.31 ± 6.64	(-0.33, 4.95)	0.28		
Hip Abduction	**Pediatric**	-21.54± 5.44	-19.14± 5.89	2.41 ± 5.50	(-0.23, 5.04)	0.42	0.25	0.78
	Traditional	-20.95± 6.52	-19.53± 5.21	1.42 ± 6.19	(-1.03, 3.87)	0.24		
	Control	-19.62± 6.40	-18.42± 7.04	1.20 ± 5.47	(-1.25, 3.65)	0.18		
Hip Internal Rotation	**Pediatric**	10.73 ± 7.78	6.74 ± 9.46	-3.99 ±11.64	(-8.55, 0.56)	0.46	2.42	0.1
	Traditional	10.95 ± 7.97	6.86 ± 9.33	-4.09 ± 9.49	(-8.32, 0.14)	0.47		
	Control	5.51 ± 7.65	7.23 ± 5.69	1.72 ± 8.65	(-2.51, 5.95)	-0.26		
Hip External Rotation	**Pediatric**	-0.62 ± 8.48	-5.02 ± 8.55	-4.41 ±10.41	(-8.88, 0.06)	-0.52	0.8	0.45
	Traditional	-2.12 ± 6.62	-4.13 ± 8.34	-2.01 ± 9.46	(-6.17, 2.14)	-0.27		
	Control	-5.30 ± 8.25	-5.87 ± 7.62	-0.56 ± 9.41	(-4.72, 3.59)	-0.07		

Table 5. Peak Kinetic Variables During First 40% of Stance Phase of Anticipated Cutting Task

Variable	Group	Pre-test	Post-test	Change Score	95% CI of Change Score	Effect Size	$F_{(2,63)}$	P-value
VGRF (%BW)	**Pediatric**	3.75 ± 0.67	3.90 ± 0.66	0.15 ± 0.89	(-0.28, 0.58)	-0.22	1.04	0.36
	Traditional	3.68 ± 0.75	3.96 ± 0.65	0.27 ± 0.76	(-0.07, 0.62)	-0.38		
	Control	3.86 ± 0.89	3.77 ± 0.90	-0.09 ± 0.91	(-0.48, 0.30)	0.10		
ATSF (%BW)	**Pediatric**	0.36 ± 0.22	0.32 ± 0.14	-0.03 ± 0.21	(0.13, 0.07)	0.17	0.58	0.56
	Traditional	0.26 ± 0.14	0.29 ± 0.18	0.03 ± 0.20	(-0.06, 0.12)	-0.19		
	Control	0.31 ± 0.15	0.28 ± 0.20	-0.03 ± 0.19	(-0.11, 0.06)	0.17		
Knee Extension	**Pediatric**	-0.10 ± 0.09	-0.13 ± 0.08	-0.03 ± 0.11	(-0.09, 0.02)	-0.33	0.05	0.95
Moment	**Traditional**	-0.16 ± 0.09	-0.20 ± 0.11	-0.04 ± 0.10	(-0.09, 0.01)	-0.36		
(%BW*m)	**Control**	-0.13 ± 0.15	-0.17 ± 0.11	-0.04 ± 0.13	(-0.01, 0.01)	-0.27		
Knee Valgus	**Pediatric**	-0.18 ± 0.15	-0.17 ± 0.12	0.01 ± 0.17	(-0.07, 0.08)	0.00	0.55	0.58
Moment	**Traditional**	-0.18 ± 0.12	-0.17 ± 0.12	0.01 ± 0.15	(-0.06, 0.07)	0.08		
(%BW*m)	**Control**	-0.13 ± 0.12	-0.17 ± 0.14	-0.03 ± 0.16	(-0.10, 0.03)	-0.21		
Knee Internal	**Pediatric**	0.09 ± 0.05	0.08 ± 0.03	-0.01 ± 0.06	(-0.04, 0.02)	0.20	0.23	0.8
Rotation Moment	**Traditional**	0.07 ± 0.04	0.07 ± 0.03	0.00 ± 0.04	(-0.02, 0.02)	0.00		
(%BW*m)	**Control**	0.08 ± 0.06	0.07 ± 0.05	-0.01 ± 0.08	(-0.04, 0.03)	0.17		

Table 6. Kinematic Variables at Initial ground contact During Unanticipated Cutting Task

Variable	Group	Pre-test	Post-test	Change Score	95% CI of Change Score	Effect Size	$F_{(2, 63)}$	P-value
Knee flexion	**Pediatric**	11.72 ± 6.40	10.04 ± 6.14	-1.69 ± 7.82	(-4.58, 1.21)	-0.27	1.31	0.28
	Traditional	8.82 ± 4.68	8.63 ± 4.82	-0.18 ± 5.34	(-2.73, 2.36)	-0.04		
	Control	10.00 ± 4.45	6.94 ± 4.37	-3.07 ± 4.88	(-5.56, -0.58)	-0.70		
Knee valgus	**Pediatric**	-0.23 ± 4.17	-1.70 ± 3.40	-1.47 ± 4.62	(-3.36, 0.42)	-0.39	0.13	0.88
	Traditional	-1.73 ± 2.00	-3.03 ± 2.57	-1.30 ± 3.37	(-3.01, 0.41)	-0.57		
	Control	-1.49 ± 3.25	-2.35 ± 3.08	-0.86 ± 4.06	(-2.53, 0.82)	-0.27		
Knee rotation*	**Pediatric**	-11.76± 9.60	-3.78 ± 6.20	7.98 ± 11.93	(3.58, 12.38)	0.99	6.92	0.002
	Traditional	-7.99 ± 9.15	-9.80 ± 5.74	-2.19 ± 9.56	(-1.79, 6.17)	-0.29		
	Control	-4.62 ± 5.74	-7.68 ± 6.32	-3.06 ± 6.18	(-7.04, 0.93)	-0.51		
Hip flexion	**Pediatric**	-21.30± 7.56	-18.27± 8.12	3.03 ± 10.23	(-0.62, 6.68)	-0.39	1.23	0.3
	Traditional	-19.44± 5.62	-20.26± 7.19	-0.82 ± 6.19	(-4.12, 2.49)	0.13		
	Control	-19.70± 7.25	-19.03± 6.39	0.66 ± 6.73	(-2.64, 3.96)	-0.10		
Hip abduction	**Pediatric**	-19.64± 6.57	-18.50± 5.98	1.14 ± 4.43	(-2.43, 4.71)	0.18	0.02	0.98
	Traditional	-19.58± 5.18	-17.99± 9.09	1.59 ± 10.49	(-1.64, 4.82)	0.21		
	Control	-18.07± 6.07	-16.88± 6.23	1.18 ± 5.92	(-2.05, 4.41)	0.19		
Hip rotation	**Pediatric**	8.47 ± 9.50	4.70 ± 8.60	-3.78 ± 11.48	(-9.25, 1.69)	0.42	0.64	0.53
	Traditional	7.28 ± 6.98	3.15 ±11.19	-4.13 ± 11.99	(-9.08, 0.82)	0.44		
	Control	4.15 ± 9.14	3.66 ± 7.70	-0.49 ± 11.29	(-5.44, 4.46)	0.06		

Table 7. Peak Kinematic Variables During First 40% of Stance Phase of Unanticipated Cutting Task

Variable	Group	Pre-test	Post-test	Change Score	95% CI of Change Score	Effect Size	$F_{(2,62)}$	P-value
Knee flexion	**Pediatric**	47.37 ± 6.84	46.27 ± 7.08	-1.09 ± 5.77	(-4.15, 1.97)	-0.16	1.44	0.25
	Traditional	45.63 ± 6.54	47.83 ± 5.87	2.21 ± 6.89	(-0.56, 4.97)	0.35		
	Control	46.18 ± 8.43	45.94 ± 6.67	-0.24 ± 6.61	(-2.95, 2.47)	-0.03		
Knee valgus	**Pediatric**	-3.34 ± 7.12	-5.93 ± 4.62	-2.60 ± 7.07	(-5.10, -0.10)	-0.43	0.92	0.4
	Traditional	-4.82 ± 3.55	-6.91 ± 4.20	-2.09 ± 4.77	(-4.35, 0.18)	-0.54		
	Control	-5.26 ± 4.35	-5.74 ± 4.27	-0.48 ± 4.05	(-2.69, 1.73)	-0.11		
Knee Internal Rotation*	**Pediatric**	2.74 ± 8.65	9.90 ± 7.17	7.15 ± 9.72	(2.80, 11.51)	-0.90	6.49	0.003
	Traditional	8.17 ± 8.12	6.38 ± 5.43	-1.80 ± 9.55	(-5.73, 2.14)	0.26		
	Control	8.05 ± 8.50	5.65 ± 6.98	-2.40 ± 8.49	(-6.25, 1.45)	0.31		
Knee External Rotation*	**Pediatric**	-12.32± 9.33	-4.40 ± 5.75	7.92 ± 11.40	(3.59, 12.24)	1.02	5.73	0.005
	Traditional	-8.65 ± 9.09	-6.65 ± 5.00	2.00 ± 9.24	(-1.91, 5.91)	0.27		
	Control	-6.47 ± 6.80	-8.30 ± 6.11	-1.84 ± 6.87	(-5.66, 1.99)	0.28		
Hip Flexion	**Pediatric**	-32.44± 9.01	-29.16± 9.16	3.27 ± 10.38	(-1.25, 7.79)	-0.36	2.5	0.09
	Traditional	-28.60± 8.66	-32.08± 8.35	-3.48 ± 7.94	(-7.57, 0.61)	0.41		
	Control	-30.04± 8.38	-29.69± 8.05	-0.35 ± 10.38	(-3.74, 4.44)	-0.04		
Hip Adduction	**Pediatric**	-14.78± 7.87	-14.30± 7.81	0.48 ± 5.09	(-3.11, 4.07)	0.06	0.5	0.61
	Traditional	-15.51± 6.31	-12.72± 9.39	2.79 ± 10.08	(-0.45, 6.04)	0.35		
	Control	-13.02± 7.83	-11.83± 7.60	1.20 ± 6.32	(-2.05, 4.44)	0.16		
Hip Abduction	**Pediatric**	-21.53± 6.85	-20.91± 6.63	0.62 ± 5.01	(-2.87, 4.10)	0.09	0.49	0.62
	Traditional	-22.30± 5.46	-19.62± 9.25	2.67 ± 9.89	(-0.48, 5.82)	0.35		
	Control	-19.91± 6.45	-19.06± 6.76	0.85 ± 5.93	(-2.30, 4.00)	0.13		
Hip Internal Rotation	**Pediatric**	13.27 ± 7.63	8.56 ± 8.64	-4.72 ± 9.97	(-9.67, 0.24)	0.58	0.4	0.67
	Traditional	10.05 ± 5.78	7.40 ± 9.54	-2.65 ± 9.87	(-7.13, 1.83)	0.34		
	Control	9.44 ± 9.62	7.67 ± 7.41	-1.77 ± 11.47	(-6.25, 2.71)	0.21		
Hip External Rotation	**Pediatric**	1.23 ± 8.39	-2.05 ± 8.34	-3.28 ± 10.72	(-8.04, 1.47)	-0.39	0.24	0.79
	Traditional	-1.61 ± 4.52	-3.01 ± 9.06	-1.41 ± 9.74	(-5.71, 2.89)	-0.20		
	Control	-2.42 ± 8.46	-3.71 ± 7.77	-1.29 ± 9.88	(-5.59, 3.01)	-0.16		

Table 8. Peak Kinetic Variables During First 40% of Stance Phase of Unanticipated Cutting Task

Variable	Group	Pre-test	Post-test	Change Score	95% CI of Change Score	Effect Size	$F_{(2,63)}$	P-value
VGRF (%BW)	**Pediatric**	3.86 ± 0.77	4.10 ± 0.91	0.25 ± 0.92	(-0.16, 0.65)	-0.30	1	0.37
	Traditional	3.85 ± 0.90	4.10 ± 0.71	0.25 ± 0.68	(-0.12, 0.61)	-0.31		
	Control	3.94 ± 1.03	3.87 ± 1.18	-0.07 ± 0.95	(-0.43, 0.29)	0.06		
ATSF (%BW)	**Pediatric**	0.40 ± 0.27	0.26 ± 0.13	-0.14 ± 0.32	(-0.26,-0.02)	0.67	1.01	0.37
	Traditional	0.30 ± 0.14	0.25 ± 0.17	-0.05 ± 0.23	(-0.16, 0.07)	0.31		
	Control	0.29 ± 0.16	0.26 ± 0.22	-0.03 ± 0.24	(-0.14, 0.08)	0.16		
Knee Extension Moment (%BW*m)	**Pediatric**	-0.11 ± 0.11	-0.17 ± 0.10	-0.06 ± 0.12	(-0.13, 0.01)	-0.55	0.13	0.88
	Traditional	-0.20 ± 0.16	-0.24 ± 0.11	-0.04 ± 0.15	(-0.10, 0.04)	-0.16		
	Control	-0.16 ± 0.13	-0.20 ± 0.13	-0.04 ± 0.18	(-0.11, 0.02)	-0.31		
Knee Valgus Moment (%BW*m)	**Pediatric**	-0.25 ± 0.15	-0.25 ± 0.17	0.00 ± 0.20	(-0.10, 0.08)	0.00	0.78	0.47
	Traditional	-0.32 ± 0.16	-0.30 ± 0.17	0.02 ± 0.22	(-0.06, 0.11)	0.12		
	Control	-0.23 ± 0.13	-0.28 ± 0.13	-0.05 ± 0.18	(-0.13, 0.03)	-0.38		
Knee Rotation Moment (%BW*m)	**Pediatric**	0.11 ± 0.04	0.12 ± 0.07	0.001± 0.08	(-0.03, 0.03)	-0.01	0.01	0.99
	Traditional	0.11 ± 0.05	0.11 ± 0.05	0.003± 0.08	(-0.03, 0.04)	0.06		
	Control	0.11 ± 0.04	0.11 ± 0.05	0.003± 0.05	(-0.03, 0.03)	0.06		

Figure 1. Starting position for all cutting tasks

Figure 2. Sidestep cutting task

Figure 3. Tibial rotation at initial ground contact during ***anticipated cutting task*** (*p<0.05)

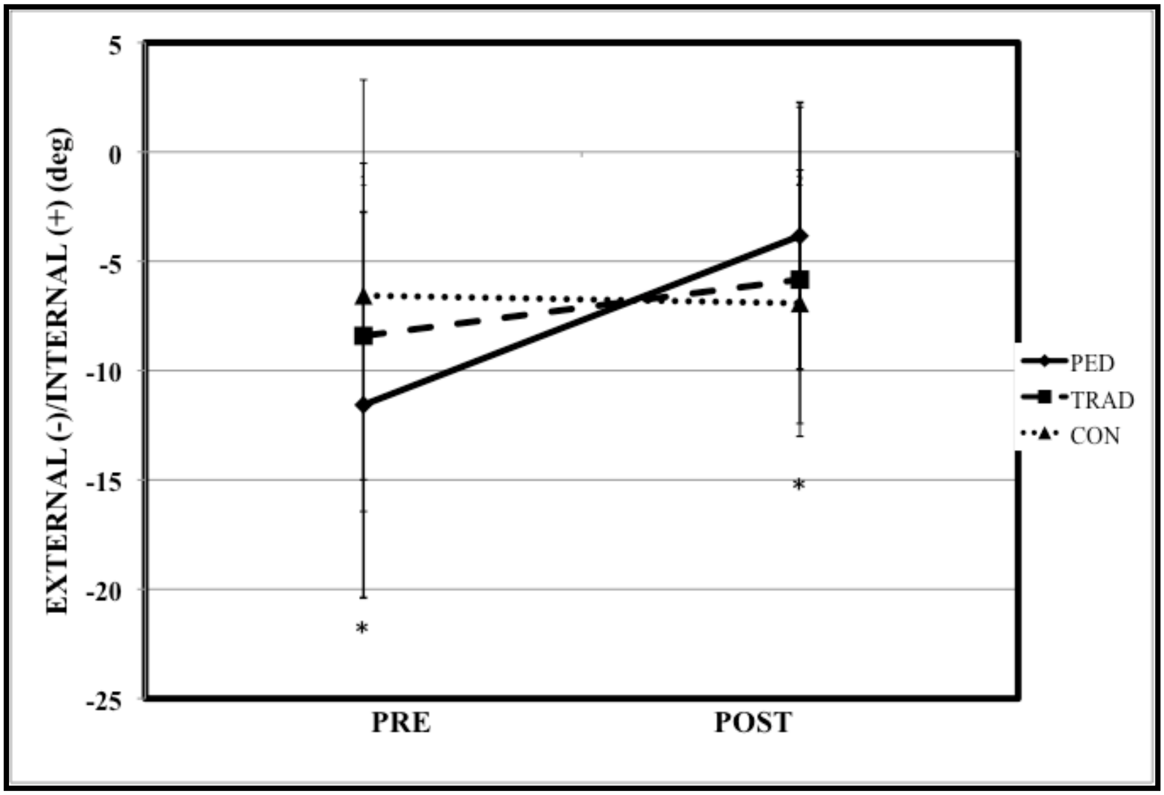

Figure 4. Peak tibial internal rotation during ***anticipated cutting task*** (*p<0.05)

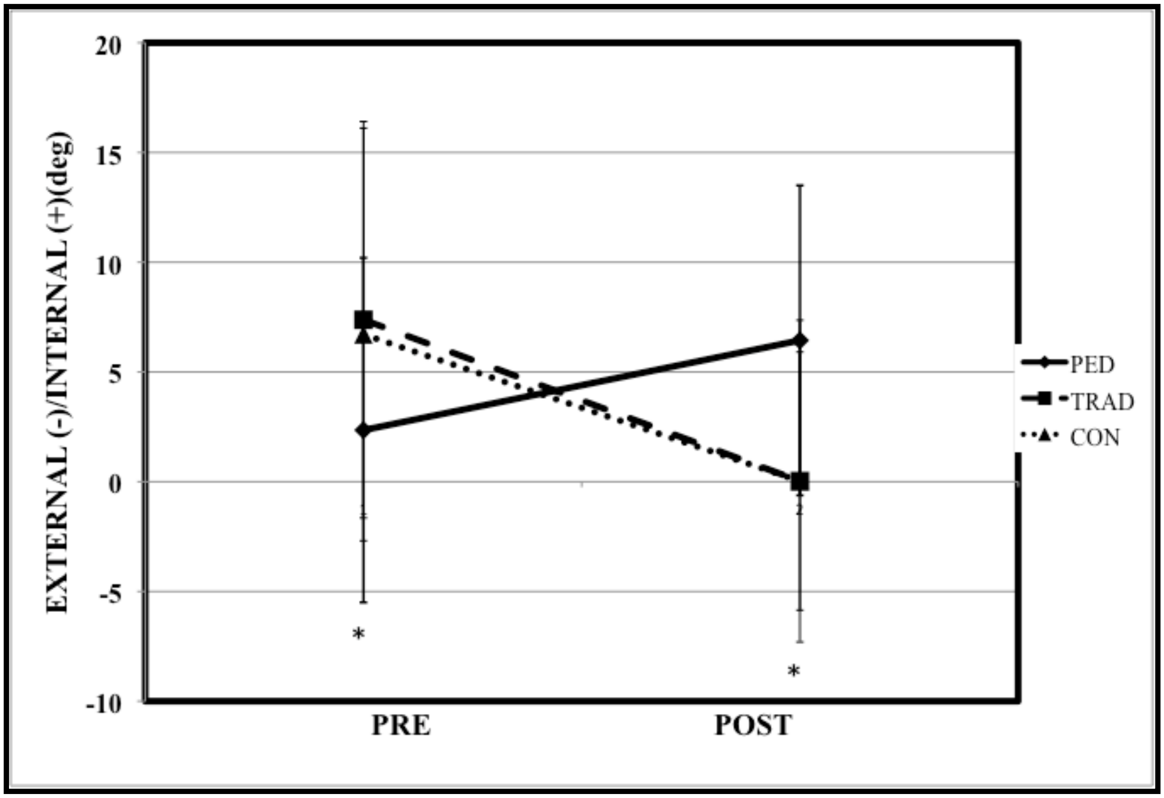

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Figure 5. Tibial rotation at initial ground contact during ***unanticipated cutting task*** (*p<0.05)

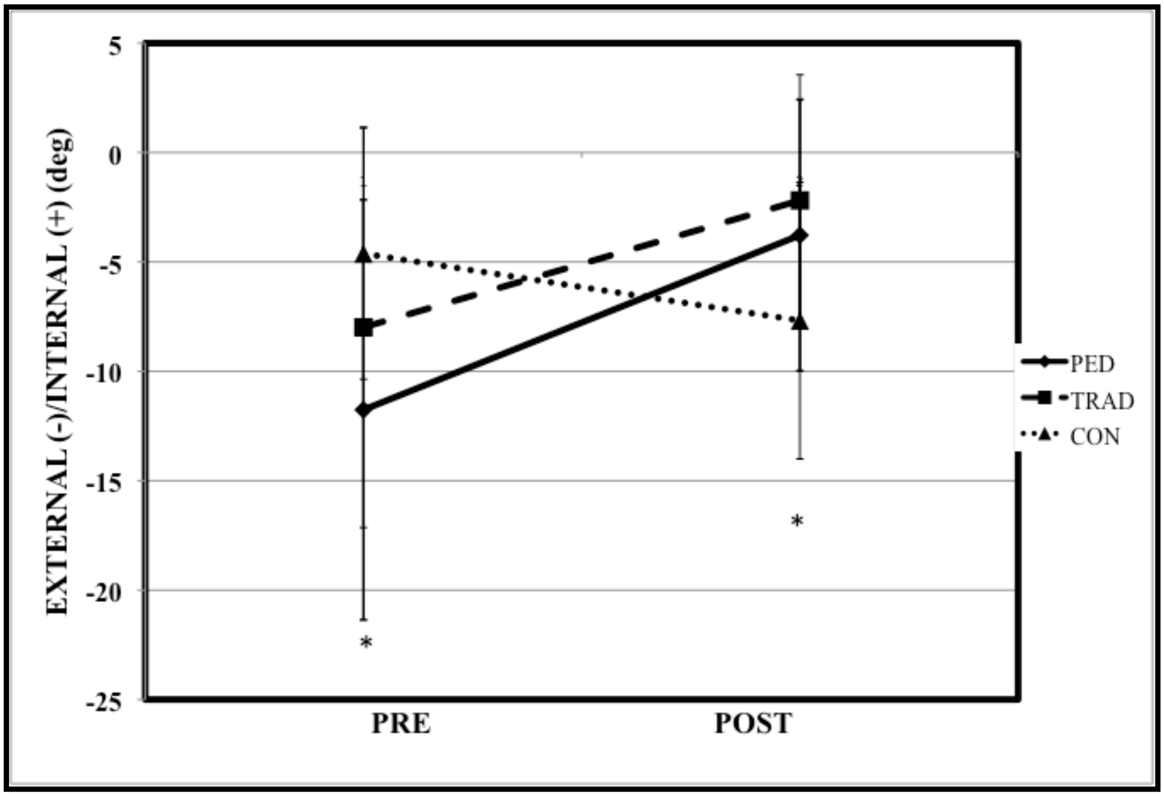


Figure 6. Peak tibial internal rotation during first 40% of stance phase during ***unanticipated cutting task*** (*p<0.05)

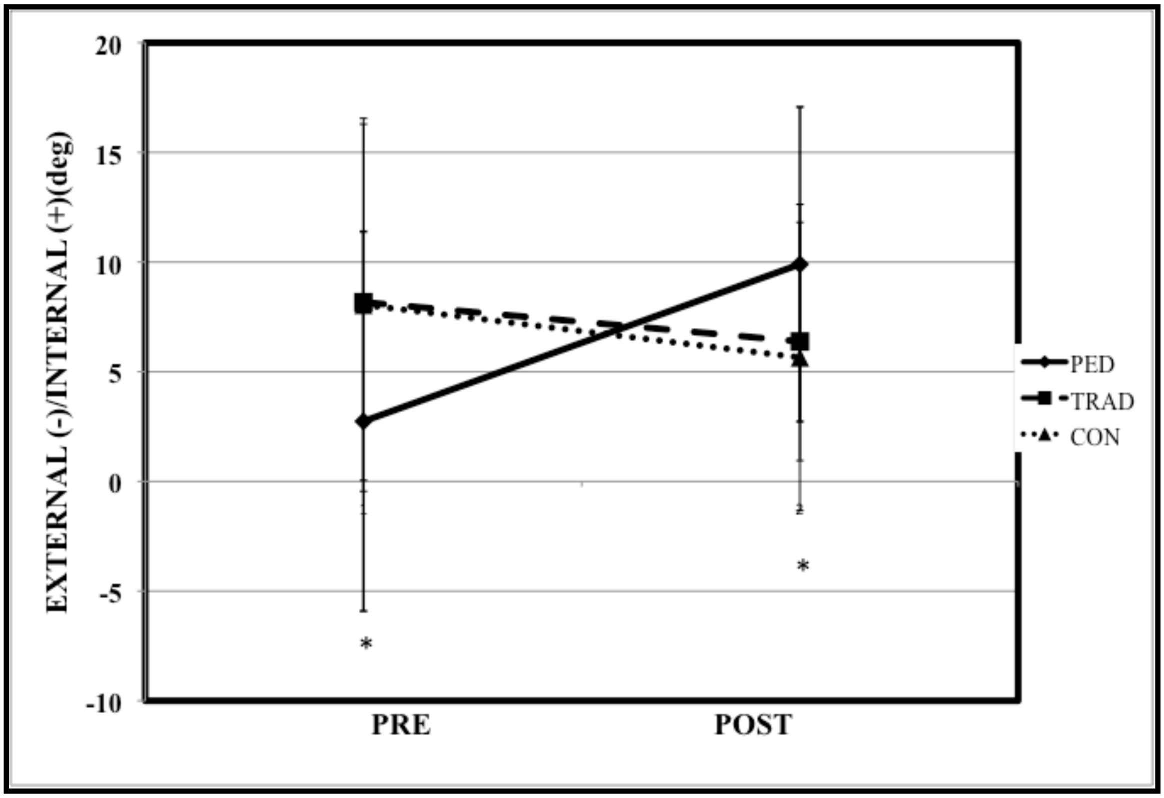
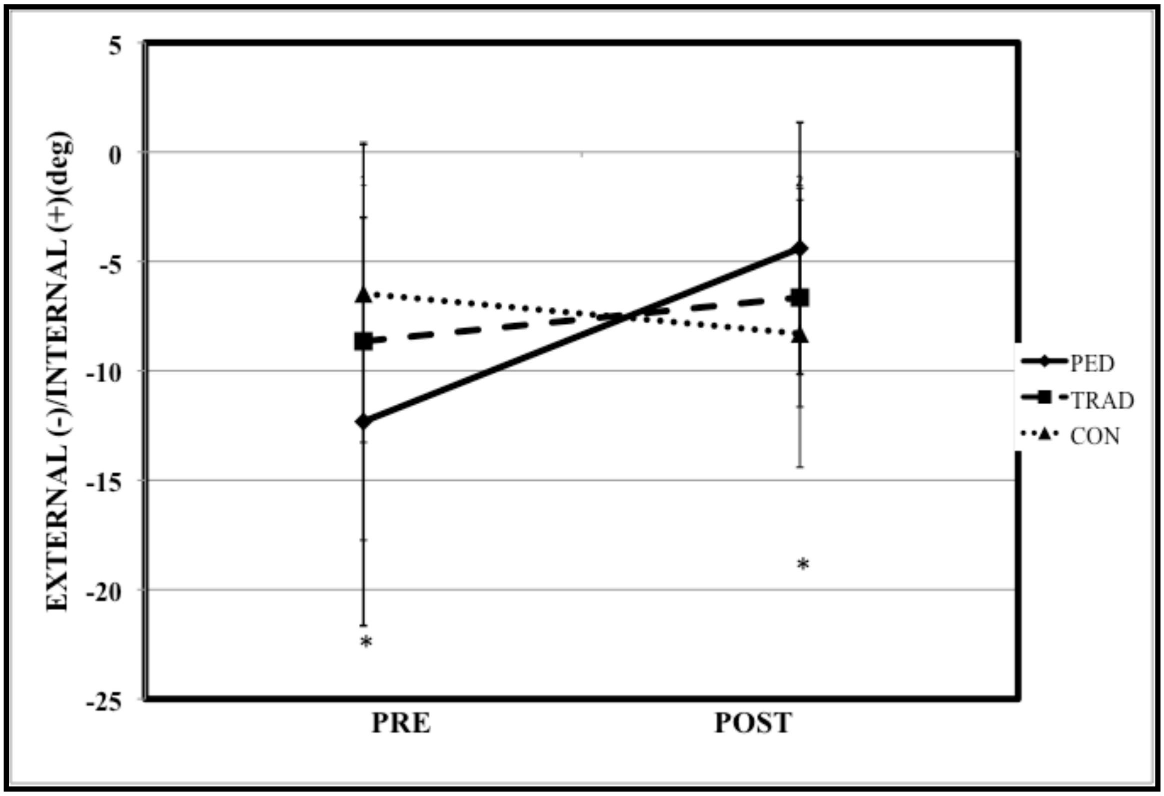


Figure 7. Peak tibial external rotation during first 40% of stance phase during ***unanticipated cutting task*** (*p<0.05)



APPENDIX B. MANUSCRIPT II

Manuscript II
Integrated Injury Prevention Program Improves Balance and Vertical Jump Height in Children
(Journal of Athletic Training)

ABSTRACT
Context: Implementing an injury prevention program to youth athletes may lead to reduced injury rates. However, there is limited knowledge regarding whether this population will be able to modify dynamic balance ability and vertical jump measures.

Objective: To compare the effects of a pediatric and a traditional injury prevention program to no program at all in the ability to change balance and performance measures in athletes under twelve years of age.

Design: Cluster-randomized controlled trial

Setting: Research laboratory and soccer field

Patients or Other Participants: 65 youth soccer athletes (Males: n=38, mass=34.16±5.36 kg, height=143.07±6.27 cm, age=10±1 years; Females: n=27, mass=33.82±5.37 kg, height=141.02±6.59 cm) volunteered to participate. Teams were cluster-randomized to either a pediatric or traditional injury prevention program, or a control group.

Main Outcome Measure(s): Change scores for anterior-posterior and medial-lateral time-to-stabilization measures and maximum vertical jump height and power were calculated from the pre-test and post-test sessions.

Results: Anterior-posterior time-to-stabilization decreased after the traditional program (Change Mean±SD=-0.92±0.49) compared to the control group (-0.49±0.59) ($F_{(2,60)}$=6.34, p=0.003). The traditional program (1.70±2.80) increased vertical jump height compared to the control group (0.20±0.20)($F_{(2,61)}$=3.45, p=0.04)

Conclusions: Youth athletes under the age of 12 can improve dynamic balance ability and vertical jump height after completing a traditional injury prevention program, but no improvements were seen after the completion of the age-specific injury prevention program.

Key Words: balance, performance, injury prevention

INTRODUCTION

Injuries to the anterior cruciate ligament (ACL) are associated with early development of osteoarthritis[18] and are most common among individuals between the ages of 16-18 years.[43] However, the frequency of ACL injury increases steadily around ages 11and 12 years old.[43] Sex differences in ACL injury rates and neuromuscular risk factors for injury also appear to emerge after children encounter puberty.[38, 50] Therefore, there is reason to believe intervening with children at a young age may result in better long-term outcomes for ACL injury prevention. While it appears intervening with children at a young age may be critical, it is unclear on whether this age group will respond to an ACL injury prevention program.

Only two previous studies have evaluated the potential to change neuromuscular risk factors with an ACL injury prevention program in athletes under 12 years old with mixed results.[11, 16] Both Grandstrand et al.[11] and Kilding et al.[16] had children perform an injury prevention program that had been shown previously to be effective with older populations. Grandstrand et al. failed to see changes in knee separation distances (knee valgus) and vertical jump height, and hypothesized that these results occurred because the children were unable to perform some of the exercises. Kilding et al. observed improvements in several performance variables including vertical jump height. Despite these positive changes, Kilding et al. recommended more variety to be added to the injury prevention program to decrease boredom and improve compliance in the young population.

The findings of Grandstrand et al. and Kilding et al. suggest children may require age-specific injury prevention programs designed for their age group. While children can achieve strength gains, the mechanism for these changes appears to be due primarily to neural adaptations compared to muscle hypertrophy in adults.[12, 33] Skeletally immature children are also prone to overuse injuries.[9, 20] Therefore, children do not need intense strengthening programs and any type of training program needs to be gradual and include time for recovery. Unfortunately, several ACL injury prevention programs that have been implemented require longer than 30 minutes of training and/or involve heavy resistance.[13, 17, 30] Young children also have been shown to require more feedback when learning a task,[47] and utilize attention differently than adults.[6] While feedback and instruction are frequently components of ACL injury prevention programs, it appears young pre-pubertal children may benefit from this type of intervention more than their older peers. Based on these findings, injury prevention programs for children should be implemented with lower frequency, basic progressions, more instruction, and feedback opportunities. Addressing these differences between children and adults may improve the ability to change neuromuscular risk factors for injury in a young population.

There is moderate evidence that supports the use of neuromuscular ACL injury prevention programs to reduce ACL injury rates,[3, 14, 19, 31, 32, 35, 49] but it is also necessary to understand how these programs affect potential neuromuscular risk factors for injury. An inability to maintain proper balance or postural control has been proposed as a neuromuscular risk factor for several lower extremity injuries.[2, 21, 22, 41] Isolated balance training improves balance measures in healthy adult individuals.[1, 7, 15, 24, 42] However, knowledge regarding the effectiveness of balance training during an integrated ACL injury prevention program is scarce despite the fact that balance exercises are a frequent component of these programs. In addition, no one has investigated the effects of any type of training on balance ability in children under 14 years old.

A common limitation of research investigating ACL injury prevention programs is poor compliance.[37, 46] Therefore, future research should determine how to improve athlete, coach, and parent support for these programs, which hopefully will result in improved compliance. While the primary purpose of ACL injury prevention programs is to change possible neuromuscular risk factors for injury, it is reasonable to assume positive changes in performance variables, such as vertical jump height, will accompany improvements in strength, balance, and movement. Athletes and coaches may improve their compliance with these programs if provided with evidence the programs improve athletic performance as well as reduce injury rates. Unfortunately, this information is lacking in much of the previous literature on ACL injury prevention programs.

The purpose of this study was to evaluate the effects of integrated (many types of exercises) ACL injury prevention programs on balance and vertical jump ability in young children. A second purpose was to determine whether or not a program designed specifically for a pediatric population would result in greater balance and vertical jump improvements. We hypothesized an integrated ACL injury prevention program consisting of basic progressions, more instruction and feedback, lower frequency, and higher repetitions would result in greater balance ability and improvements in vertical jump height and power compared to a program that was not age-specific.

METHODS

Research Design

A cluster-randomized controlled trial was used to evaluate changes in balance ability, and vertical jump height and power before and after an intervention period. Six teams from the Under-10 (9 years old) and Under-11 (10 years old) age levels were recruited from a local soccer association that agreed to participate in this study. Following an initial testing session (pre-test), the six teams were stratified by sex and cluster randomized into one of three injury prevention programs: pediatric (PED), traditional (TRAD), or control (CON). As a result, one boys' and one girls' team were assigned to each program. A seventh team, which was a boys' team, was added due to a small roster size with the boys' control team, and was consequently assigned to the control program to ensure sufficient sample size. All players on these teams performed their respective injury prevention program as part of their normal warm-up, but only players who volunteered to participate in the study completed the two testing sessions (pre-test and post-test).

Participants

Sixty-five youth soccer players (Males: n=38, age= 10 ± 1 years, mass= 34.16 ± 5.36 kg, height= 143.07 ± 6.27 cm; females: n=27, age= 10 ± 1 years, mass= 33.82 ± 5.37 kg, height= 141.02 ± 6.59 cm) from seven teams volunteered to participate in this study (Table 1). All participants were free from any injury or illness that prohibited soccer activity at the time of initial testing. Prior to the first testing session, all parents and players read and completed informed consent and assent forms, respectively, which were approved by the university's Institutional Review Board.

Instrumentation

Ground reaction force data were collected from a non-conductive force plate (Model #4060-NC Bertec Corporation, Columbus, OH). Time-to-stabilization test data were collected with a sampling frequency of 180 Hz.[39] Data were collected during the time-to-stabilization test for ten seconds following initial ground contact, which occurred when the vertical ground reaction force exceeded 10 N. Data during a maximum vertical jump were sampled at 1,000 Hz and used to calculate power and vertical jump height. All ground reaction force data were collected through Motion Monitor software (Innovative Sports Training Inc, Chicago, IL).

Procedures

All participants attended two identical testing sessions that lasted approximately one hour in a sports medicine research laboratory. The second session (post-test) occurred within one week after completion of the intervention period. All participants wore their own running shoes. The same shoes were worn for both testing sessions. Participants' height and weight were measured and recorded upon arrival to the laboratory. Participants performed a maximal vertical jump test and a dynamic balance assessment in a randomized order. All testing occurred on participants' dominant limbs, which were the legs preferred to kick a ball for maximal distance.

Maximal Vertical Jump Test

Participants completed three trials of a double leg countermovement maximal vertical jump test so that power and jump height could be assessed. This task has been shown to demonstrate good intersession reliability.[26] The participants began with their feet shoulder width apart while standing with their dominant foot on a force plate (Bertec Corporation, Columbus, OH). An overhead goal was used to encourage maximal performance.[8] The participants were instructed to jump for maximal vertical height and try to touch the overhead goal. They performed two practice trials and the overhead goal was placed slightly above the participant's highest practice jump. Thirty seconds of rest were allowed between each trial.

Time-to-Stabilization Test

Participants performed a dynamic balance assessment using time-to-stabilization measures (TTS), which have been used before to evaluate training effects.[40] Participants stood on a 30 cm high box placed a distance equal to half of their body height away from a force plate with their hands on their hips. Participants jumped forward from the box with their non-dominant foot and landed with their dominant foot in the center of the force plate while keeping their hands on their hips and their non-dominant foot off of the ground. Participants were instructed to balance as quickly as possible without putting their non-dominant foot down. Participants practiced the task until they indicated they felt comfortable with the task and performed it correctly. Three trials were performed, but were repeated if the participant was unable to maintain this single-limb landing position with their hands on their hips or if a subsequent hop occurred after landing. Participants repeated 4 trials during the pre-test and 1 trial during the post-test on average. The number of repeated trials did not differ between groups (p=0.94).

Implementation of Injury Prevention Programs

The four intervention teams performed their respective program as part of their normal practice warm-up during the nine-week intervention period while teams assigned to the control programs completed a warm-up designated by their coaches. The principal investigator or a research assistant taught the teams the program within one week of completing the pre-test session, supervised the program implementation at every practice to provide feedback and technique instruction, and monitored compliance. Proper technique was continually stressed to all of the participants while they performd the exercises. The teams assigned to the control program were supervised once every other week to ensure contamination of the programs did not occur.

Traditional ACL Injury Prevention Program

The traditional program was modified from previous ACL injury prevention programs that have been shown to be effective with participants in high school or college.[13, 19, 29] This program consisted of static flexibility, balance, strengthening, agility, and plyometric exercises on both limbs. Participants ran forward a distance of 10 m after completing each exercise to make it a dynamic warm-up. The speed of this run gradually increased as the participants progressed through the warm-up. All exercises were performed on both legs and the program required approximately 10-15 minutes to complete. Table 1 provides a detailed description of the traditional ACL injury prevention program.

The static flexibility exercises involved stretching of the gastrocnemius, adductor, hip flexor, and quadriceps muscles. Participants also performed three balance exercises. The first balance exercise was a double limb jump with a 180 degree twist in the air followed by a double limb landing and stabilized hold for one second (“180° Jump”). The second balance exercise required participants to maintain a single limb stance with their knee slightly flexed as they threw a soccer ball back and forth with a teammate (“Single Limb Ball Toss”). The third balance exercise involved a hop forward from one limb to a single limb landing and balance (“Forward Hop to Balance”).

Strengthening, agility, and plyometric exercises composed the remainder of the traditional ACL injury prevention program. One strengthening exercise targeted the core musculature (“Hip Bridge”), while the remaining two strengthening exercises focused on the muscles of the lower extremity, specifically the quadriceps and hamstrings (“Walking Lunges”, “Single Leg Squat”). The agility exercises required lateral movement (“Sideways Shuffle), dynamic direction changes (“Z-cuts”), and forward propulsion (“Bounding”). Finally, four plyometric exercises were incorporated into the traditional program. Two plyometric exercises required primarily either horizontal or vertical motion, coordination, and strength (“Broad Jump”, “Squat Jumps”) while the remaining two plyometric exercises focused on changing either sagittal or frontal plane directions while hopping back and forth over a line (“Forward Line Hops”, “Sideways Line Hops”).

Pediatric ACL Injury Prevention Program

The pediatric program consisted of three phases. The first phase was performed twice per week and the final two phases were performed three times per week. The three progressive phases in the pediatric program were further delineated. The first week of each phase was an introductory phase with time spent emphasizing proper form, verbal and visual feedback, and scaled down repetitions of each exercise. The remaining weeks of each phase included the addition of one or two exercises and added movement between all exercises. Table 2 provides a list of the pediatric ACL injury prevention program. All three phases required 10-15 minutes to complete.

Similar to the traditional program, the pediatric program incorporated several of the exercises into a dynamic warm-up protocol. The two programs were very similar during the first phase by requiring participants to run at progressively increasing speeds following the exercise movement (Figure 1a). However, participants completing the pediatric program performed a “timing” run after the exercise movements instead of the speed forward run during the second phase. The “timing” run involved two participants finishing the exercise movements at the same time, running at a diagonal, and crossing in front of or behind the opposite player. This movement required the participants to control their body and use visual information about another moving player to direct their motion to avoid a collision (Figure 1b). During the third phase, a sidestep cut was performed at the end of the diagonal run (Figure 1c).

Instead of static flexibility exercises, the pediatric program consisted of dynamic flexibility exercises. The dynamic flexibility exercises targeted the gastrocnemius (“Walking Calf”, “Hand Walk”), hamstrings (“Straight Limb March/Skip”, “Walking Hamstring”, “Hand Walk”), quadriceps (“Walk/run Butt Kicks”, “Walking Quadriceps”), hip flexor (“Hip Flexor Walk”, “Twisting Hip Flexor Walk”), and gluteal (“Knee to Chest”, “Leg Cradle”) muscles. The pediatric program consisted of some of the same balance exercises as the traditional program, such as the “Single Limb Ball Toss”, the “180 Degree Jump to Balance”, and the “Forward Hop to Balance”. However, the “Single Limb Ball Toss” and the “180 Degree Jump to Balance” were each only completed during one three-week phase. The “Forward Hop to Balance” exercise progressed during the second and third phases to include movement in the frontal and transverse plane (“Sideways Hop to Balance”, “Twisting Hop too Balance”). Finally, the pediatric program also performed a single limb balance exercise while a partner pushed the other partner in different directions (“Single Limb Balance with Perturbations”) during the last phase.

The pediatric program began with primarily strengthening exercises and minimal plyometric exercises and transitioned by gradually changing these proportions. As a result, the final phase included only one strengthening exercise and several plyometric exercises. Strengthening exercises for the pediatric program included lunges in three planes (“Forward/ Sideways/Transverse Lunge”), a squat progression (“Double Limb Squat”, “Single Limb Squat”), progressive core exercises (“Hip Bridge”, “Human Arrow”, “Side Plank”), and lower leg strengthening exercises (“Toe Walk”, “Double/Single Heel Raises”). The plyometric exercises emphasized rapid changes of direction with double to single leg progressions (“Forward/sideways Line Hops”), vertical jumps (“Squat Jumps”, “Tuck Jumps”), and consecutive jumps for distance (“Broad Jumps”). Finally, the pediatric program incorporated several agility exercises (“Side Shuffle”, “Z-cuts”, “High Knee Run”, “Skipping”, “Quick Cuts”).

Data Reduction

Data from the vertical jump test and the time-to-stabilization test were exported into a customized software program (MatLab version 7; MathWorks, Natick, MA) for reduction. The time spent in the air, which was determined as the time between toe-off (VGRF<10N) and initial contact (VGRF>10N), was used to calculate vertical height with the following formula (g represents constant acceleration due to gravity):

$$\text{Height} = 0.5(g(t/2)^2)$$ [16]

Power was computed using the following equation:

$$\text{Power (W)} = 61.9 \times \text{jump height (cm)} + 36.0 \times \text{mass(kg)} - 1822.$$ [25]

The three trials were averaged for all analyses.

The time-to-stabilization data were reduced using a method described by Ross et al.[41] The absolute ground reaction force ranges for both the anterior-posterior (A/P) and medial-lateral (M/L) between the eighth and ninth seconds of single limb stance were divided by the participants' body weight. These values were used to determine a mean range-of-variation value for each component and across all 3 trials. Standard deviations (SDs) were also calculated for each component and three SDs were added to each mean range of variation. The A/P and M/L components of the ground reaction force were analyzed separately for each participant. The components were rectified and a decay curve was determined by fitting the data with an unbounded third-order polynomial. A horizontal line was inserted over the top of the data for each component, which was equal to the component's mean range of variation plus three SDs. The time-to-stabilization for each component and each participant's trial was the point the unbounded third-order polynomial transected the mean range of variation value. The average time-to-stabilization value from the three trials for each component were used for analyses.

3.7 Statistical Analyses

Seven possible covariates were evaluated for a significant relationship with the treatment effects for all dependent variables. These covariates included variables regarding anthropometrics (Pre-test BMI, Change in BMI between testing sessions, % Predicted Adult Height), demographic information (sex, age in months), memory and learning ability (Learning and Total scores from BVMT), and the initial value of each dependent variable. Change scores were calculated for all dependent variables by subtracting the pre-test value from the post-test value.

Separate analyses of covariance were conducted for each dependent variable and covariates were included in the model if they had a statistically significant effect on the change score. Significant group effects were evaluated with a Bonferroni post hoc correction. All data analyses were performed using SPSS version 16.0 (SPSS, Inc., Chicago, IL) with an *a priori* alpha level of 0.05.

Results

All subjects in the intervention groups (Traditional and Pediatric programs) completed at least 80% of all training sessions and both testing sessions and no one sustained any injuries requiring lost time from activity during the intervention period. One control subject did not complete the post-test session due to scheduling conflicts. The time to stabilization data from one testing session was not usable for 2 intervention subjects. No statistically significant differences between groups existed for height ($F_{(2,63)}=2.24$, $P=0.12$) or weight ($F_{(2,63)}=0.66$, $P=0.52$) at the time of the pre-test. Complete means and measures of variability are provided in Table 4.

Our findings indicate that the subjects' pre-test score and sex significantly influenced the ability to improve time-to-stabilization in the anterior-posterior direction. The adjusted group change scores (Sex=1.43, Pre-test A/P score=2.71s) revealed a significant group main effect ($F_{(2,60)}=6.34$, $P=0.003$, Effect size=0.17). Post-hoc testing demonstrated that the traditional group improved their anterior-posterior time-to-stabilization greater than the control group ($P<0.001$, Effect size=0.82)(Figure 1). However, the pediatric program was not significantly different from the control program ($P>0.016$). We did not observe any difference between the three groups ($F_{(2,61)}=0.59$, $P=0.56$, Effect size=0.02) for medial-lateral time-to-stabilization.

We observed a similar effect of pre-test score on the ability to improve vertical jump height. After accounting for this finding (Pre-test vertical jump height=25 cm), we found significant differences in vertical jump height between the three groups ($F_{(2,61)}$=3.45, *P*=0.04, Effect size=0.10). The traditional program resulted in greater improvements in vertical jump height ability compared with the control program (*P*=0.15, Effect size=0.71)(Figure 2). We did not detect any significant difference between groups in power ($F_{(2,61)}$=2.79, *P*=0.07, Effect size=0.08). In summary, the traditional program improved anterior-posterior time-to-stabilization and vertical jump height greater than the control program, but the pediatric program did not change.

Discussion

Contrary to our original hypotheses, the traditional program resulted in positive changes while the pediatric program, which was designed specifically for the young participants, did not cause any improvements. These findings were surprising because we believed the pediatric program would be more effective because it accounted for differences between children and adults in motor learning, strength development, and cognitive level. However, the results of this study demonstrate that children as young as nine or ten years old do not need age-specific training to effectively improve their balance ability and performance on a maximal vertical jump after completing a traditional injury prevention program. The program was brief requiring only ten to fifteen minutes of time, three days per week for nine weeks and easily substituted a team warm-up activity.

Poor balance ability has been associated with an increased risk of falls and sustaining several lower extremity injuries or conditions.[2, 10, 21, 22, 41, 49] In addition, improving balance through training exercises has reduced the rate of ankle sprains,[23, 49] and overall lower extremity injury rates.[32] Padua and DiStefano[34] recently demonstrated that the addition of balance training exercises to either plyometric or resistance exercises in an ACL injury prevention program influences the ability to change lower extremity biomechanics. Therefore, it is reasonable to believe that improving balance ability may reduce the risk of lower extremity injury in children.

Several studies have demonstrated enhanced balance ability after isolated balance training exercise programs.[1, 7, 15, 24, 42] Despite this evidence and the frequent incorporation of balance exercises within integrated injury prevention programs, only a few studies have actually assessed balance ability after integrated programs.[27, 36] In agreement with our findings, both Myer et al.[27] and Paterno et al.[36] reported positive improvements in balance ability after high school females completed an integrated ACL injury prevention program. Myer et al. observed improved medial-lateral stability in center of pressure excursions without concurrent changes in anterior-posterior stability. Similar to our results, Paterno et al. demonstrated anterior-posterior stability improvements but no improvements in the medial-lateral direction. The reason medial-lateral stability did not change along with anterior-posterior stability is not completely understood. We hypothesize our results occurred because the balance test demanded sagittal plane stability but may not have been difficult in the frontal plane, as evidenced by faster stabilization times during the pre-test. Therefore, there was more room for improvement in the anterior-posterior direction.

Our results agree with these previous studies and further demonstrate that balance exercises as part of an integrated injury prevention program can successfully improve dynamic balance ability. Our findings also reveal that an intense balance training program is not necessary to observe improvements, as balance exercises were only a small component of the injury prevention programs. Despite similar findings, our investigation is the only one that compared the results to a control group, required significantly less time than either of the two previous studies, used a different population and did not include balance exercises on an unstable surface. Therefore, the results of our study should support the use of simple balance exercises to improve balance ability in a youth population.

To our knowledge, no one has evaluated balance training in a young population consisting of nine and ten year old athletes. Grandstrand et al.[11] investigated the effects of an integrated injury prevention program in children between 9-11 years old on landing technique and reported no improvements. DiStefano et al.[5] compared responses to an injury prevention program between two age groups and found that the older population, which included high school aged children, improved their landing technique to a greater extent than the younger population of pre-high school aged athletes. Both of these studies hypothesized that children under 12 years old may require specialized training and basic exercises in order to improve movement. Although Kilding et al.[16] observed positive improvements in performance measures with this population, the authors recommended that programs be modified and varied for this young population.

Therefore, we developed and studied the effects of a pediatric program that incorporated additional exercise progressions, more continuous feedback, more variety, and reduced initial frequency. In contrast to our hypotheses that this program would result in greater changes compared to the traditional program, the traditional program was the only program to cause balance improvements compared to the control group.

However, the pediatric program does appear to cause improvements that may be clinically significant as suggested by the within-group strong effect size and the medium effect size when the results are compared to the control program.

We believe these results occurred because the programs differed with regards to the type of balance training exercises. The traditional program required thirty seconds of continuous single limb balance three times per week for nine weeks and performed the forward hop to balance task for the entire duration of the program. In contrast, the pediatric program consisted of thirty continuous seconds of static single limb balance for only three weeks and completed progressive versions of the forward hop to balance exercise by incorporating the frontal and transverse plane. The combination of more time spent in a static single limb balance position (Traditional program=1800 s, Pediatric program= 270 s) and performing the assessment task appears to lead to greater balance improvements.

The forward hop to balance assessment appears to be unintentionally designed to illustrate improvements from the traditional program. The principle of exercise specificity states that human bodies will respond to the demands placed upon it, which means that training a task should result in improvements with that specific task. The traditional program practiced the forward hop to balance exercise repetitively for nine weeks and improved in their ability to stabilize during that task. While this finding is not surprising, it is important to show that young children can respond to training. However, our ability to conclude the pediatric program did not cause clinically significant changes in balance ability that may lead to reduced injury risk is limited. Future research should assess a different type of dynamic balance ability to see if improvements transfer to additional tasks.

Over the past several years, while there have been several studies that have been successful with changing injury rates and possible injury risk factors, there have also been a couple of studies that have not found any significant changes.[37, 46] Both of these studies reported poor compliance with the injury prevention programs. In order to see improvements with research studies and with widespread dissemination, athletes, parents, and coaches must support the use of these programs. There is reason to believe support may be enhanced if these integrated programs can improve athletic performance measures in addition to risk factors associated with injury.

Villarreal et al.[48] demonstrated in a recent meta-analysis that plyometric training results in strong effects on vertical jump height (Effect size=0.84) with greater than 7% improvements. Our results agree with the findings of this meta-analysis as we observed similar effect sizes with the traditional program and slightly lower effect sizes for the pediatric program. The traditional program improved their vertical jump height by 7% while the pediatric program sustained 5% improvements. While the studies included in the meta-analysis discussed previously mainly included studies that used isolated plyometric training, a few studies have evaluated vertical jump changes after an integrated training program with mixed results. Our results agree with Myer et al.[27] who observed improvements in vertical jump height ability after high school female athletes completed an integrated injury prevention program. Similarly, Kilding et al. also reported increases in power during a vertical jump test in males between the ages of 9-11 years old after completing an integrated injury prevention program.

In contrast to the two previous studies, Steffen et al.[45] did not observe similar changes with adolescent females and hypothesized the intensity of their 15 minute program may not have been sufficient to result in performance changes. Villarreal et al.[48] supported this hypothesis by concluding that the training protocol intensity influences the ability to change vertical jump ability. We hypothesize this intensity factor may have contributed to our findings that the traditional program was the only program to sustain significant improvements in vertical jump height compared to the control program. The traditional program included nine weeks of plyometric exercises while the pediatric program slowly progressed the strengthening exercises to include plyometric exercises. The rationale for the pediatric program's gradual incorporation of plyometrics was that young or physically immature individuals are at a greater risk for overuse injury compared to older individuals.[9, 44] Therefore, we designed the pediatric program to gradually build strength and proper technique before the children began strenuous jumping activities. While the traditional program achieved greater improvements in vertical jump height, it is possible the pediatric program moved with better technique. Future research should simultaneously evaluate jump height or other performance measures with lower extremity biomechanics. Similar to the balance data, the principle of exercise specificity provides explanation for these findings because the traditional program practiced maximum vertical jumps for nine weeks and gained improvements in vertical jump height.

Villarreal et al.[48] also found that men have a greater ability to sustain improvements than women. This sex effect may explain the contrasting findings of the studies that used integrated injury prevntion programs as Kilding et al.[16] studied only males while Steffen et al.[45] included only females in their study. Unfortunately, a limitation of the current study is insufficient power to examine a program and sex interaction to evaluate whether sex affected our results. Future research should further evaluate the ability of young females compared to males to improve performance measures following an integrated injury prevention program.

The baseline values of the balance and vertical jump data influenced whether or not a positive change occurred. Our results showed that individuals with greater capacity for improvement sustained the greatest changes, which agrees with Myer et al.[28] and DiStefano et al.[4] Both of these studies observed that baseline values of lower extremity biomechanics affected the ability to modify these variables. These findings suggest injury prevention programs may be the most beneficial for individuals who have the most room for improvement and future research may benefit from targeting these individuals. In addition, future research should account for this factor in analyses to prevent significant findings from being obscured by individuals who do not have room for improvement. By using change scores and including the pre-test value as a covariate, the influence of the pre-test value may be able to be accounted for in analyses.

Limitations

A limitation of this study is the cluster-randomized nature of the study design. In order to protect external validity, we used this type of design versus a pure randomized controlled design. The injury prevention programs were designed to be included as a team warm-up activity, which would be difficult to implement if athletes on the same team performed a different set of exercises or none at all. Due to the small number of clusters, we were unable to directly account for the cluster-randomization effect in the statistical analyses but believe the use of change scores and covariates address the possible influence of pre-test group differences.

Conclusion

The results of this study demonstrate that a young population of athletes can improve their dynamic balance ability and maximum vertical jump height by performing a traditional injury prevention program. The findings suggest children will improve the task that they practice over time. Although improvements were only observed with the traditional program, it is possible the pediatric program caused improvements in different types of tasks. Progressive and variable exercises may enhance participants' enjoyment of the injury prevention program and lead to improved compliance. Therefore, future research should explore slight modifications of the pediatric program.

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Table 1. Subject Demographics

Group	Sample Size	Age	Mass	Height
Pediatric	11 males, 8 females	10 ± 1 years	33.31 ± 5.02 kg	140.43 ± 7.06 cm
Traditional	11 males, 11 females	10 ± 1 years	35.06 ± 5.60 kg	144.41 ± 6.01 cm
Control	14 males, 9 females	10 ± 1 years	33.57 ± 5.39 kg	141.48 ± 5.95 cm

Table 2. Comparison of Programs

		PROGRAM		
EXERCISES	**Traditional Program**	**Pediatric Program**		
		Phase I	**Phase 2**	**Phase 3**
Time	**12-14 minutes**	**12-14 minutes**	**12-14 minutes**	**12-14 minutes**
Duration	**3 days/week**	**2 days/week**	**3 days/week**	**3 days/week**
	9 weeks	**3 weeks**	**3 weeks**	**3 weeks**
Lower Extremity	Forward Lunge	Forward Lunge	Sideways Lunge	Twisting Lunge
Strengthening	Broad Jump	Double Leg Squat	DL to SL Squat	
	SL Squat	Toe Walk	Broad Jump	
		DL Heel Raise		
Repetitions	**1x5 each leg**	**1x15**	**1x15**	**1x15**
Core Strengthening	Hip Bridge	Hip Bridge	Human Arrow	Sideways Plank
Repetitions	**1x10; hold 3 sec**	**1x10; hold 3 sec**	**1x10; hold 3 sec**	**1x10; hold 3 sec**
Flexibility Type	***Static***	***Dynamic***	***Dynamic***	***Dynamic***
	Calf	Straight Leg March	Straight Leg Skip	Straight Leg Skip
	Hip Flexor	Hand Walk	Walking Calf Stretch	Leg Cradle
	Adductor	Walking Butt Kicks	Hip Flexor Walk	Twisting Hip Flexor Walk
		Walking Quad Stretch	Knee to Chest	Running Butt Kicks
				High Knee Run
Repetitions	**30 sec. each**	**30 sec. each**	**30 sec. each**	**30 sec. each**
Plyometric	Squat Jumps	DL Forward Line Hops	SL Forward Line Hops	SL Sideways Line Hops
	DL Forward Hops (SL)		DL Sideways Line Hops	Squat Jumps
	DL Sideways Hops (SL)		Up and Down Hops	Tuck Jumps
Repetitions	**10 repetitions**	**20 repetitions**	**20 repetitions**	**20 repetitions**
Balance	180° Jump to Balance	180° Jump to Balance	Sideways Hop to Balance	Twisting Hop to Balance
	SL Forward Hop to Bal.	Forward Hop to Balance	Single Leg Ball Toss	SL Balance Perturbations
	SL Ball Toss			
Repetitions	**1x10 each leg**	**1x10**	**1x10**	**1x10**
Agility	Toe-Heel Walk	Forward Skipping	For & Back Skipping	Unanticipated Side Cuts
	High Knee Run	Sideways Shuffle	Side Cuts	
	Sideways Shuffle			
	Z Cuts			
Repetitions	**30 sec. each**	**30 sec. each**	**30 sec. each**	**30 sec. each**

Table 3. Means and Measures of Variability

Variable	Group	Pre-test	Post-test	Change Score	95% CI of Change Score	Effect Size
A/P TTS (s)*	**Pediatric**	2.73 ± 0.42	2.11 ± 0.52	-0.62 ± 0.56	(-0.81, -0.42)	1.32
	Traditional	2.87 ± 0.49	1.82 ± 0.27	-0.92 ± 0.49	(-1.11, -0.73)	2.30
	Control	2.59 ± 0.43	2.22 ± 0.54	-0.49 ± 0.59	(-0.67, -0.31)	1.00
M/L TTS (s)	**Pediatric**	1.40 ± 0.16	1.47 ± 0.18	0.06 ± 0.14	(-0.05, 0.18)	0.29
	Traditional	1.45 ± 0.17	1.42 ± 0.38	-0.03 ± 0.39	(-0.14, 0.08)	0.03
	Control	1.41 ± 0.18	1.39 ± 0.13	-0.02 ± 0.14	(-0.12, 0.09)	0.13
VJ Height (cm)*	**Pediatric**	24.62 ± 2.92	25.90 ± 3.85	1.28 ± 2.70	(0.20, 2.30)	0.37
	Traditional	25.46 ± 3.99	26.97 ± 2.98	1.70 ± 2.80	(0.70, 2.70)	0.48
	Control	25.53 ± 3.95	23.77 ± 3.60	0.20 ± 0.20	(-1.00, 0.90)	0.05
Power (W)	**Pediatric**	874.74 ± 281.48	997.66 ± 296.84	122.91 ± 206.77	(23.25, 222.57)	0.38
	Traditional	1025.01 ± 274.53	1125.55 ± 241.78	100.53 ± 182.40	(19.66, 181.41)	0.37
	Control	847.33 ± 234.81	894.56 ± 184.87	47.23 ± 133.99	(-9.35, 103.81)	0.13
Change scores represent adjusted change scores for A/P TTS and VJ height						

Figure 1. Anterior-posterior time-to-stabilization across time between groups (*p<0.05)

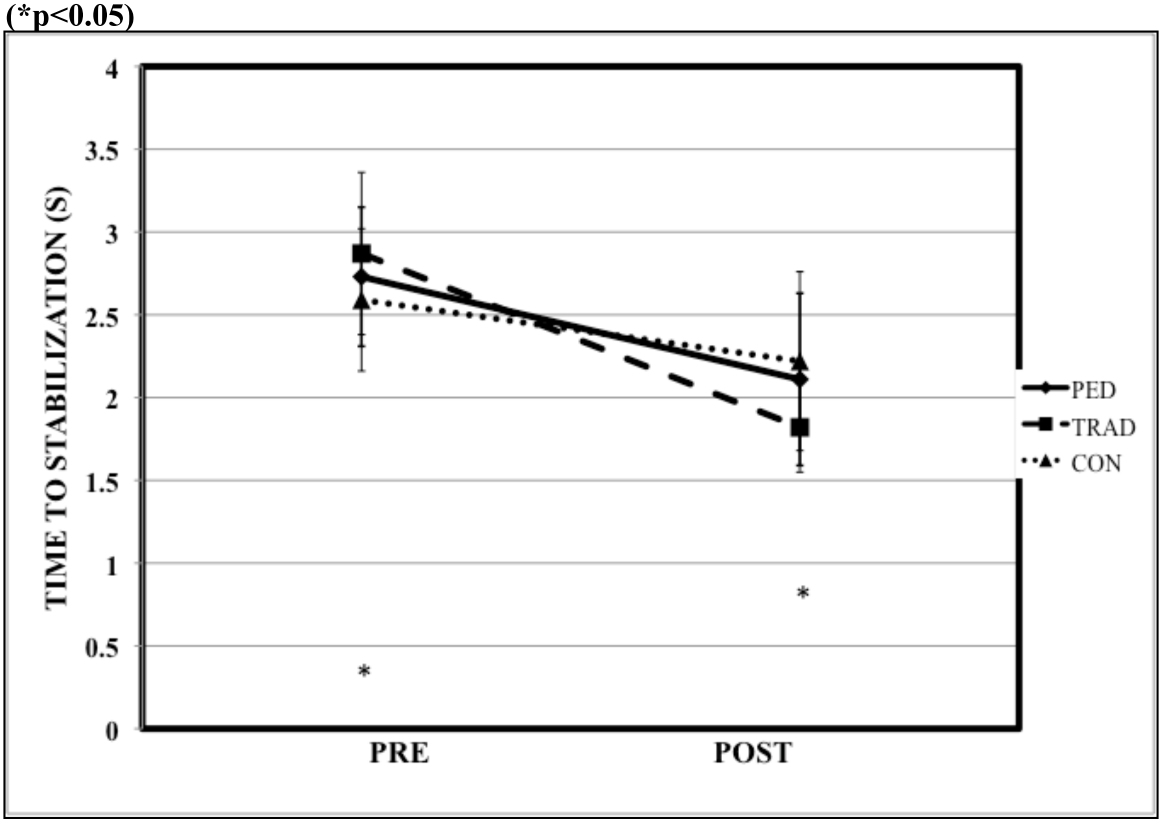
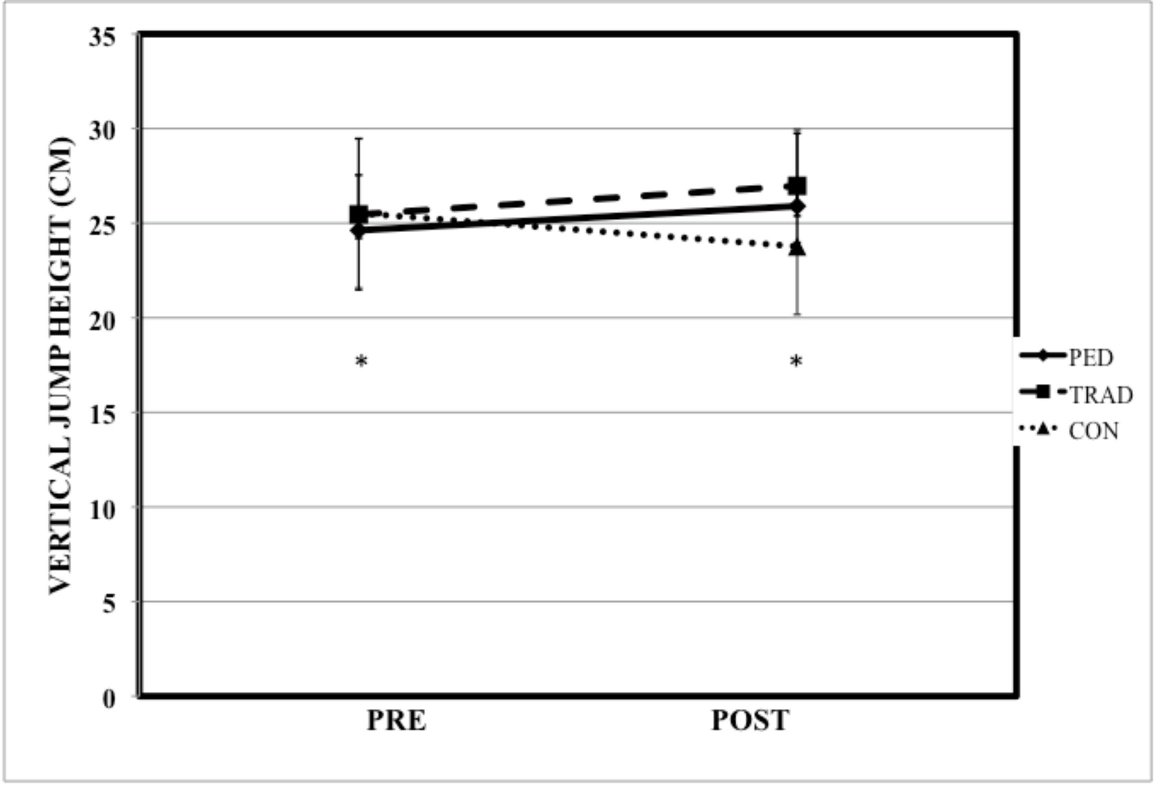


Figure 2. Vertical jump height across time between groups (*p<0.05)



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