Knee Biomechanics during Side-Step Cutting and Performance on Return to Sport Tests: Retrospective Analysis Following Anterior Cruciate Ligament Re-Injury

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Abstract

Objective: Re-injury rates following anterior cruciate ligament reconstruction (ACLR) are elevated compared to rates for initial anterior cruciate ligament (ACL) injury. The purpose of this study was to examine three-dimensional knee mechanics in an individual who had undergone an ACLR and then went on to re-injure that reconstructed ACL.

Methods: The primary subject was a female soccer player, 18 months post-ACLR, who then re-injured her ACL 3 months after biomechanical testing and return to sport (RTS) testing. We conducted 3-dimensional biomechanical testing of her knee mechanics and performance on return to sport (RTS) tests prior to her ACL re-injury. In addition, we compared her knee mechanics prior to re-injury to a control group of healthy female soccer athletes to determine if any biomechanical differences existed that may have indicated risk for ACL re-injury.

Results: Our findings indicate that altered lower extremity biomechanics, previously associated with increased risk of ACL injury, are present following ACLR and return to sports participation despite a lack of marked bilateral differences in performance on return to sport tests.

Conclusion: These findings are consistent with those in the literature suggesting that subjects’ post-ACLR may be adopting a strategy that minimizes loading at the knee joint. While it is not known if this biomechanical pattern increases the risk for a re-injury event, it suggests that there are deficits present following ACLR that may not be addressed with rehabilitation and recognized with RTS testing prior to return to sports participation. These findings point to an important gap in the literature with regards to clinical predictors of ACL re-injury.

Keywords: ACLR, RTS, Kinematics, Kinetics

Introduction

There are approximately 200,000 individuals who suffer anterior cruciate ligament (ACL) tears in the United States annually. The majority of these injuries occur in female athletes, 15 to 25 years of age, and require surgical intervention to reconstruct the ACL [1-5]. ACL reconstruction (ACLR) is considered to be the gold standard treatment following ACL injury, with the goals of reproducing function of the original ligament and restoring knee stability. While this surgery is considered to be successful in restoring joint stability and allowing for return to sports participation, recent studies indicate that the surgery may not be as successful as previously thought. Studies on return to sport following ACLR showed that up to 66% of individuals 1 year post-ACLR were unable to return to their previous level of sports participation [1]. In addition, re-injury rates following ACLR are considerably elevated compared to rates for initial injury. One in 4 individuals post-ACLR experience a re-injury event up to 12 years post-ACLR and the overall incidence rate of a second ACL injury within 24 months after ACLR is nearly 6 times greater. Following ACLR, individuals typically undergo vigorous physical rehabilitation for 6-12 months to address strength and functional performance deficits prior to returning to sports participation. Although athletes are typically permitted to return to sport after 6 months of rehabilitation, the timeline will vary depending upon the athlete and their performance on return to sport (RTS) tests. Rehabilitation professionals commonly utilize RTS tests to assist in the decision making process of when to return an athlete to sport participation after ACLR. RTS tests aim to test a patient’s strength, power, endurance, and overall coordination. Most RTS tests consider a bilateral difference of less than 10-15% indicative of readiness to return to sport. However, more recent guidelines suggest that performance on RTS tests must be at least 90% that of the un-involved extremity. Examples of RTS tests commonly implemented include the 5-jump test, single leg hop for distance, triple hop for distance, single leg 6 meter hop for time, or some combination of these tests [3-21].

While RTS tests capture performance on sports related tasks, recent studies have questioned whether these standard tests truly capture return to sport readiness [19]. In addition, it is unknown if such tests can identify individuals at risk for re-injury upon return to sports.
participation. Risk for initial ACL injury has been determined through studies examining lower extremity biomechanics during sports specific maneuvers, such as landing and cutting, in which non-contact ACL injury most often occurs [2]. While the biomechanics associated with ACL re-injury are unknown, studies on initial ACL injury risk have identified specific lower extremity movement patterns that are associated with increased risk for injury, including increased knee valgus angles and moments [7,9,10,18]. Ideally, performance on RTS tests would relate to lower extremity biomechanics observed during sports specific maneuvers and risk for re-injury, providing clinicians with a rationale for returning their athletes to sports participation while minimizing re-injury risk.

The purpose of this case study is to report on lower extremity mechanics and performance on RTS tests in a female soccer player, 18 months post-ACLR, who then re-injured her ACL 3 months after testing. A secondary purpose is to compare the lower extremity biomechanics of this female soccer athlete to that of a control group of healthy female soccer athletes with similar soccer experience performing the same side-step cutting maneuver to determine if any biomechanical differences existed that may have indicated risk for ACL re-injury.

Methods

Subject

A 23 year old female (59 kg/162.5 cm) recreational soccer player 18 months post-ACLR was recruited to participate in a larger study. The subject previously played soccer at the club level and was on a high school varsity team. At the time of participation in our study, she had been actively playing recreational soccer for 5 months after being cleared by her physician for return to sports participation. Following participation in our study, she had a second non-contact ACL injury sustained while playing soccer, thereby injuring her reconstructed ACL.

History of initial ACL injury, rehabilitation, and return to sport

The subject sustained the initial non-contact ACL injury to her left knee while she was performing a cutting maneuver during a soccer game. She reported immediate pain and instability in her left knee. Four days after her injury, a complete ACL tear was confirmed on magnetic resonance imaging (MRI). The examining orthopedic surgeon reported the following physical examination findings: 1+) joint effusion in the left knee, 10 degrees short of full knee extension range of motion, and 100 degrees of knee flexion range of motion (ROM), tenderness present across her proximal tibia, absence of joint line tenderness, a 2+ anterior drawer test, a positive Lachman test, and a negative posterior drawer test. The surgeon recommended reconstructive surgery to the subject once her ROM returned to normal.

Prior to reconstructive surgery, the subject completed 4 weeks of physical therapy to decrease swelling, increase ROM, and improve strength. The pre-surgical physical therapy was successful in decreasing pain levels and restoring full knee ROM, however the patient continued to report left knee instability. Seven weeks after injury, she underwent an allograft ACL reconstructive surgery using a tibialis anterior tendon, as well as a partial lateral meniscectomy. Four days after surgery, she was able to demonstrate full extension and 80 degrees of knee flexion ROM at her orthopaedic surgeon’s office.

The subject initiated physical therapy six days post-surgery, which consisted of manual treatments including joint mobilizations, soft tissue mobilizations, ROM, therapeutic exercises, and modalities as needed. Four months following surgery her active range of motion was at 153 degrees of knee flexion and 3 degrees of knee hyper-extension. Manual muscle testing for key lower extremity musculature was as follows on her ACLR extremity: quadriceps: 5/5, hamstrings 5/5, hip abductors 4+/5, hip flexors 4+/5, hip extensors 4+/5. A jogging program was introduced into her rehabilitation program at four months post-surgery, and was then progressed over the next 2 months as appropriate to include agility, balance, and strength training for return to sport specific tasks.

The subject was cleared by her physician and returned to playing soccer at 9 months post-ACLR. Although she had completed physical therapy, she continued to have decreased confidence on the field and soreness after playing. Given her symptoms, she opted to play goalie, instead of her usual position as outside defender, and/or 10 to 15 min intervals of her usual position over the 90 min soccer games. At that time, the subject felt that she needed more sport specific strength training to improve her agility and balance. At 10 months post reconstruction, she hired a personal trainer to focus on improving her strength, balance, and soccer skills in an effort to boost her confidence and make a smooth transition back to full soccer participation. After working with her personal trainer for 3 months, she was able to return to full participation in her recreational soccer leagues.

Procedures

All testing took place at a biomechanics research laboratory. Prior to participation, all procedures were explained to the subject and an informed consent was obtained as approved by the Institutional Review Board for the University.

Prior to kinematic and kinetic data collection, height and mass were measured. To control for the potential influence of varying footwear, the subject was fitted with the same style of cross-training shoe used previously for biomechanics studies involving side-step cutting maneuvers (New Balance Inc., Boston, MA, USA). Reflective markers (14 mm spheres) were placed bilaterally over the following anatomical landmarks: the 1st and 5th metatarsals heads, medial and lateral malleoli, medial and lateral femoral epicondyles, greater trochanter, iliac crests, and a single marker on the joint space between the fifth lumbar and the first sacral spinous processes. In addition, triads of rigid reflective tracking markers were securely placed bilaterally on the lateral surfaces of the subject's thigh, leg and heel counter of the shoe.

For the side-step cutting task, the subject was instructed to run five meters at a speed of 5.3-7.0 m/s before contacting her foot on the force plate and then changing direction to the either the right or the left. For a right-sided side-step cutting maneuver, the subject planted her right foot on the force plate and completed a cutting maneuver to the right side. Cones placed at 35° and 55° from the original direction of progression were used to direct the subject to cut at an angle of 45°. Approach speed was calculated with the use of a photoelectric switch and force plate contact. The subject completed four successful trials; a trial being deemed successful if: a) the subject's foot came into contact with the force platform, b) the subject remained within the pathway.
designated by the cones, and c) the required approach speed was maintained. The subjects were allowed 3-5 practice trials in order to become familiar with the procedures and instrumentation.

Instrumentation

Kinematic data were collected using a Vicon eight-camera, three dimensional motion analysis system (Oxford Metrics LTD. Oxford, England) at a sampling frequency of 250 Hz. The cameras were interfaced to a microcomputer and placed around a force platform embedded within the floor (Advanced Mechanical Technologies, Inc., Newton, MA, USA). The force platform (1500 Hz) was interfaced to the same microcomputer that was used for kinematic data collection via an analog to digital converter. This interface allowed for synchronization of kinematic and kinetic data.

RTS testing

The subject was instructed to perform the following RTS tests: 1) single leg hop 2) triple hop and 3) crossover hop for distance; 4) maximal isometric knee flexor/extensor strength. For each test, the distance covered (cm) was recorded for both the ACLR and uninjured limb. Limb symmetry was calculated for each test as follows: ACLR/ uninjured limb*100.

Data analysis

Coordinate data were digitized in Vicon Workstation software (Workstation, Oxford Metrics LTD, Oxford, England). Consistent with previous studies evaluating dynamic tasks, kinematic and kinetic data were filtered using a fourth-order zero-lag Butterworth 10-Hz low-pass filter. Visual3D™ software (C-Motion, Inc., Rockville, MD, USA) was used to quantify three dimensional knee and hip kinematics. Joint kinematics was calculated using a joint coordinate system approach and were reported relative to a static standing trial.

Kinematics, ground reaction forces and anthropometrics were used to calculate joint moments at the knee and hip using inverse dynamics equations in Visual3DTM software. Kinetic data were normalized to body mass. The joint moments referred to in this investigation are the internal resultant moments. Data was analysed over the landing cycle, which was identified as the period from foot contact to toe-off, as determined by the force plate recordings. The dependent variables of interest included the peak knee abduction angle, peak knee adductor moment, peak knee flexion angles, and peak knee and hip extensor moments.

Results

RTS testing

Results from RTS testing are displayed in Tables 1 and 2. Performance on the ACLR leg was within 92-97% of the unininvolved (UI) leg for the single leg hop (ACLR: 125.8 cm, UI: 136.5 cm), triple hop (ACLR: 378.5 cm, UI: 405.7 cm), and crossover hops for distance (ACLR: 386.3 cm, UI: 399.0 cm). Isometric strength testing indicated that the ACLR leg was within 93-94% that of the UI leg for the knee flexors (ACLR: 68 Nm, UI: 72 Nm) and knee extensors (ACLR: 186 Nm, UI: 200 Nm) strength.

Biomechanics testing

Lower extremity biomechanics during the side-step cutting task for the subject and activity matched controls can be found in Tables 3 and 4.

<table>
<thead>
<tr>
<th>Test</th>
<th>ACLR</th>
<th>UI</th>
<th>% difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single leg hop for distance</td>
<td>125.8 cm</td>
<td>136.5 cm</td>
<td>92%</td>
</tr>
<tr>
<td>Triple hop for distance</td>
<td>378.5 cm</td>
<td>405.7 cm</td>
<td>93%</td>
</tr>
<tr>
<td>Crossover hops for distance</td>
<td>386.3 cm</td>
<td>399.0 cm</td>
<td>97%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Isometric Strength Test</th>
<th>ACLR</th>
<th>UI</th>
<th>% difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knee flexors</td>
<td>68 Nm</td>
<td>72 Nm</td>
<td>94%</td>
</tr>
<tr>
<td>Knee extensors</td>
<td>186 Nm</td>
<td>200 Nm</td>
<td>93%</td>
</tr>
</tbody>
</table>

Table 1: Performance on specific hop tests for the case report subject on the injured (ACLR) and un-injured (UI) extremities.

During the side-step cutting task, the subject’s peak knee flexion angle was 40% lower on the ACLR extremity, as compared to the UI extremity (ACLR: 47.5 degrees, UI: 66.4 degrees). In addition, her peak knee extensor moment was 122% lower on the ACLR extremity, as compared to the UI side (ACLR: 1.80 Nm/kg, UI: 4.04 Nm/kg). However, this pattern was reversed for hip flexion, with a 15% greater peak hip flexion angle (ACLR: 49.9 degrees, UI: 43.4 degrees) and a 66% higher peak hip extensor moment observed on the ACLR side, as compared to the UI extremity (ACLR: 4.19 Nm/kg, UI: 2.52 Nm/kg). The subject’s peak knee valgus angle was 15% higher on the ACLR extremity, as compared to the UI side (ACLR: 5.2 degrees, UI: 4.5 degrees). There was only a minimal difference (<3%) in the peak knee valgus moment (ACLR: 0.77 Nm/kg, UI: 0.75 Nm/kg) between the subject’s ACLR limb and UI limb.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>ACLR</th>
<th>UI</th>
<th>Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak knee flexion angle</td>
<td>47.5°</td>
<td>66.4°</td>
<td>45.9°</td>
</tr>
<tr>
<td>Peak knee extension moment</td>
<td>1.80 Nm/kg</td>
<td>4.04 Nm/kg</td>
<td>2.34 Nm/kg</td>
</tr>
<tr>
<td>Peak hip flexion angle</td>
<td>49.9°</td>
<td>43.4°</td>
<td>40.06°</td>
</tr>
<tr>
<td>Peak hip extensor moment</td>
<td>4.19 Nm/kg</td>
<td>2.52 Nm/kg</td>
<td>2.17 Nm/kg</td>
</tr>
<tr>
<td>Peak knee valgus angle</td>
<td>5.2°</td>
<td>4.5°</td>
<td>3.6°</td>
</tr>
<tr>
<td>Peak knee valgus moment</td>
<td>0.77 Nm/kg</td>
<td>0.75 Nm/kg</td>
<td>0.37 Nm/kg</td>
</tr>
</tbody>
</table>

Table 3: Lower extremity biomechanics during a side-step cutting task. Data is shown for the case report subject (ACLR and UI) and the preferred limb of our activity matched controls (control).

A control group of 6 activity matched female soccer players was used to compare the lower extremity biomechanics of the subject during the side-step cutting maneuver. As compared to the control subjects, the ACLR subject had a 46% higher knee valgus angle (ACLR: 5.2 degrees, control: 3.6 degrees), and a 108% higher peak knee valgus...
moment on her ACLR extremity (ACLR: 0.77 Nm/kg, control: 0.37 Nm/kg).

Peak hip flexion angle on her ACLR extremity was 23% higher than that of control subjects (ACLR: 49.9 degrees, control: 40.6 degrees), and the peak hip extensor moment was 93% higher than that of control subjects (ACLR: 4.19 Nm/kg, control: 2.17 Nm/kg). The peak knee extensor moment on her ACLR extremity was 31% lower than that of controls (ACLR: 1.80 Nm/kg, control: 2.34 Nm/kg).

There was only a minimal difference in the peak flexion angle between her ACLR extremity and that of the control group (ACLR: 47.5 degrees, control: 45.9 degrees).

**Discussion**

Our findings indicate that altered lower extremity biomechanics are present following ACLR and return to sports participation, despite a lack of marked bilateral differences in performance on RTS tests. It is important to keep in mind that all reported findings are descriptive in nature since a case report does not lend itself to statistical analyses. As RTS tests are the current metric used to determine return to sport readiness, these differences in lower extremity biomechanics are not detected with these current screening tools. In particular, given the increased risk for re-injury following ACLR and return to sport, this case points to some potentially important shortcomings of current return to sport guidelines in capturing re-injury risk. This study is unique in the literature in that it not only quantifies lower extremity biomechanics during a sport specific activity, but also additionally captures performance on RTS tests in an individual known to re-injury her ACL.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>% difference ACLR vs. UI</th>
<th>% difference ACLR vs. Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak knee flexion angle</td>
<td>40%</td>
<td>&lt;3%</td>
</tr>
<tr>
<td>Peak knee extension moment</td>
<td>122%</td>
<td>31%</td>
</tr>
<tr>
<td>Peak hip flexion angle</td>
<td>15%</td>
<td>23%</td>
</tr>
<tr>
<td>Peak hip extensor moment</td>
<td>66%</td>
<td>93%</td>
</tr>
<tr>
<td>Peak knee valgus angle</td>
<td>15%</td>
<td>46%</td>
</tr>
<tr>
<td>Peak knee valgus moment</td>
<td>&lt;3%</td>
<td>108%</td>
</tr>
</tbody>
</table>

**Table 4**: Differences in lower extremity biomechanics during the side-step cutting task both between extremities for the case report subject (ACLR vs. UI) and between the case report subject’s affected limb and that of the matched controls (ACLR vs. control).

In this case, our subject demonstrated bilateral differences in lower extremity biomechanics during a side-step cutting task, despite minimal differences in performance on RTS tests. In particular, the subject demonstrated a tendency toward increased sagittal plane angles and moments at the hip joint, and decreased sagittal plane angles and moments at the knee joint. These findings are consistent with those in the literature suggesting that subject’s post-ACLR may be adopting a strategy that minimizes loading at the knee joint. While it is not currently known if this biomechanical pattern increases the risk for a re-injury event, it suggests that there are deficits present following ACLR that may not be addressed with rehabilitation and recognized with RTS testing prior to return to sports participation.

In addition to bilateral differences in sagittal plane lower extremity biomechanics, the subject also demonstrated altered knee biomechanics during side-step cutting consistent with an increased risk for ACLR injury. Specifically, she exhibited higher peak knee valgus moments and peak knee valgus angles as compared to healthy controls. A previous study demonstrated that such increases in frontal plane knee joint angles and moments during sports specific activities are predictive of ACL injury [7]. In addition, a recent study found that an increase in the 2-dimensional frontal plane knee angle during a drop vertical jump was predictive of a second ACL injury [13]. Therefore, it is plausible that biomechanical risk factors for primary ACL injury may also contribute to re-injury.

While previous studies have reported similar differences in lower extremity biomechanics in individuals who have undergone ACLR and returned to sports participation, this is the first study to report on such biomechanical differences in an individual known to go on and incur a re-injury event. Paterno et al. evaluated lower extremity biomechanics during a drop vertical jump in individuals who were cleared to return to sport following ACLR and tracked their incidence of second ACL injury over 12 months [13]. While they found that a specific biomechanical profile, including increased frontal plane knee motion and increased hip transverse plane moments, predicted a second ACL injury, there was no information provided as to performance on specific RTS tests. Another study by Orishimo and colleagues (2010) reported that individuals who had been cleared for return to sport following ACLR demonstrated altered lower extremity biomechanics during both the take-off and landing of a single leg hop for distance, despite a clinically acceptable performance on the test, however the incidence of re-injury following return to sport participation was not reported [12]. Future studies are needed that evaluate both performance on RTS tests, lower extremity biomechanics, and re-injury events.

Based on current guidelines for return to sports participation, the subject demonstrated no deficits in performance on RTS tests that would have indicated the need to delay return to sports participation. These findings point to an important gap in the literature with regards to clinical predictors of ACL re-injury. While recent studies have demonstrated the need for more stringent clinical criteria prior to return to sport, and others have identified altered biomechanics, future studies are needed to improve screening tools and return to sport criteria. In addition, there may be other important factors to consider, such as fear-avoidance and neuromuscular activation, which may provide additional insight into re-injury risk.

While our findings provide important insights into the utility of certain RTS tests in evaluating ACL re-injury risk, there are inherent limitations of any single subject study should be approached with caution. This case represents only the performance of a single subject and does not allow for a statistical comparison to the healthy control group. In addition, there are gaps in the data due to the retrospective nature of the case. Furthermore, while we did examine lower extremity biomechanics during a sports specific activity, this task was performed in a controlled laboratory environment and may not translate to performance during sports participation. In addition, we were only able to evaluate her biomechanics during a side-step cutting task. Evaluation of her lower extremity biomechanics during the specific hop tests utilized in this study would have provided additional information and may have helped explain some of the differences observed between RTS testing and the side-step cutting task. We also compared our subject’s performance during a side-step cutting task to...
a group of female athletes who had a similar activity level; however we did not have data on their performance on the same RTS that the ACLR subject performed. As RTS tests allow only for side to side comparisons, it would have been useful to compare performance of the ACLR subject to that of the healthy controls, as it is possible that our subject, despite a lack of bilateral differences, may have demonstrated overall deficits compared to a control group.

While this study has its limitations, it is the first study to report on both lower extremity biomechanics during a sports specific task and performance on RTS tests in an individual known to have gone on to re-injure her ACLR limb. This study highlights the fact that altered biomechanics may continue to be present well after an individual has been cleared for return to sport, but that these deficits may not be captured using traditional RTS criteria. Even with stricter guidelines for RTS tests (>90% that of the un-injured extremity), this subject would still have been cleared for return to sports participation. While it is not feasible to evaluate the lower extremity biomechanics of all individuals prior to return to sport, this case points to the need for development of improved testing and criteria to capture re-injury risk. Future studies should not only investigate the relationship between RTS tests, lower extremity biomechanics, and re-injury rates, but should include the inclusion of additional criteria and measures that may be better able to capture re-injury risk.

References