Abstract

Although intrinsic and extrinsic risk factors for anterior cruciate ligament (ACL) injury have been explored extensively, the factors surrounding the inciting event and the biomechanical mechanisms underlying ACL injury remain elusive. This systematic review summarizes all the relevant data and
clarifies the strengths and weaknesses of the literature regarding ACL injury mechanisms. The hypothesis is that most ACL injuries do not occur via solely sagittal, frontal or transverse plane mechanisms. Electronic database literature searches of PubMed MEDLINE (1966–2008), CINAHL (1982–2008) and SportDiscus® (1985–2008) were used for the systematic review to identify any studies in the literature that examined ACL injury mechanisms. Methodological approaches that describe and evaluate ACL injury mechanisms included athlete interviews, arthroscopic studies, clinical imaging and physical exam tests, video analysis, cadaveric studies, laboratory tests (motion analysis, electromyography) and mathematical modelling studies. One hundred and ninety-eight studies associated with ACL injury mechanisms were identified and provided evidence regarding plane of injury, with evidence supporting sagittal, frontal and/or transverse plane mechanisms of injury. Collectively, the studies indicate that it is highly probable that ACL injuries are more likely to occur during multi-planar rather than single-planar mechanisms of injury.

1. Introduction

The anterior cruciate ligament (ACL) is one of the most commonly injured ligaments of the knee.[1] An estimated 200,000 injuries occur annually in the US and epidemiological studies demonstrate that female athletes have a 2- to 8-fold greater ACL injury rate compared with male athletes.[2,3] ACL injuries can be devastating to an athlete, with the potential loss of a year or more of sports participation, possible loss of scholarship funding and a significantly greater risk of developing knee osteoarthritis in the long term, regardless of the treatment.[4] Prevention of ACL injury would allow many athletes to receive the health benefits of sports participation and avoid the long-term sequelae of disability associated with knee osteoarthritis.

It is widely recognized that tibiofemoral knee joint motions occur in three planes (sagittal, frontal and transverse) with six degrees of freedom (three rotations, three translations) between the femoral condyles and tibial plateaus.[5] The knee joint can rotate in the sagittal plane by flexion and extension, in the frontal plane by abduction and adduction, and in the transverse plane by internal and external rotation. The knee joint can also translate in the sagittal plane anteriorly and posteriorly, in the frontal plane medi ally and laterally, and in the transverse plane by compression and distraction (figure 1).

While the knee can move in all 12 of these potential directions, most of these motions take place in a relatively limited range with the exception of flexion and extension (tables I and II). The end range of motion (joint laxity) is highly variable in the general population and may vary by age, pubertal status, sex and race.[10-12] Excessive knee joint loading that leads to motion beyond the normal physiological range in the sagittal, frontal or transverse planes could potentially damage the internal knee joint structures. Several studies indicate that individuals with greater knee or general joint laxity have an increased risk for ACL injury.[13]

The planar contributions to the mechanisms of ACL injury is a current debate in recent journal articles, which has led to many letters to the editor, commentaries and symposia at sports medicine conferences.[14-17] Many current ACL prevention programmes only target single plane landing and movement mechanics (hops/jumps in one direction) rather than complex multi-planar movements that incorporate rotational and translational directions.[18-20] Such programmes may minimize risk of injury in the targeted plane but may be ineffective at ameliorating important multi-planar contributions. Likewise, post-injury interventions that neglect to address the multi-planar contributions to ACL injury could seriously hamper ACL injury prevention efforts in athletes returning to sport after a previous ACL injury. This ongoing controversy was the primary motivation...
for examining the multi-planar contributions of ACL injury supported in the literature via a thorough systematic review.

This review summarizes all the relevant data and identifies the strengths and weaknesses in the literature regarding ACL injury mechanisms. The primary research goal attempts to identify and consider any biomechanical and mechanistic knee studies that evaluated the ACL in the literature to determine the most likely underlying mechanisms of ACL injuries. The hypothesis is that ACL injuries do not occur via solely sagittal, frontal or transverse plane mechanisms.

2. Search Strategy

2.1 Electronic Database Literature Search

Electronic database literature searches, including PubMed MEDLINE (1966–2008), CINAHL (1982–2008) and SportDiscus® (1985–2008) with the subject term 'anterior cruciate ligament' were used for the review. The search was supplemented by a review of the bibliographies of retrieved articles, personal correspondence with authors of the retrieved articles and hand searching of pertinent journals to identify any additional studies addressing this topic of interest. These relatively liberal search criteria were used to identify all published relevant studies and to maximize the generalizability of this review.

2.2 Inclusionary and Exclusionary Criteria

Since the quality of a systematic review depends on the quality of studies appraised, reviewing Level I or II studies would provide the best evidence for answering our important clinical question about ACL injury mechanisms. However, it is unethical to attempt to incite ACL injury events in subjects in the laboratory and it is currently not feasible to design randomized
controlled trials that examine ACL injury mechanisms. Hence, this specific research question necessitated the inclusion of lower level evidence and a comprehensive evaluation of both basic and applied research examining probable mechanisms of ACL injury. Assimilation and integration of the results of such studies may provide important preliminary data and may identify areas of concentration for future research on ACL injury mechanisms and prevention methods. Thus, for this review, all levels of evidence for both basic and applied research were included if the studies met the required inclusionary and exclusionary criteria.

Investigations were included in the review if the report identified ACL injury mechanisms, risk factors for ACL injury (prospectively or retrospectively) or knee biomechanics associated with ACL loading. However, only studies that were associated with ACL injury and provided evidence regarding a plane of injury were included in the final analysis. A study that directly observed or induced an ACL injury mechanism was defined as a direct ACL injury mechanism study. A study that evaluated the differences between intact and ACL deficient conditions, described lesions or identified risk factors associated with ACL injury was defined as an indirect ACL injury mechanism study. Abstracts, unpublished data and published reports not written in English were excluded. Studies were also excluded from the analysis if the experiment was not conducted in humans or human specimens, did not examine planar loading or motion, did not contain original (i.e. review article) or empirical data, or contained only one specimen or subject (case report). In addition, studies that included subjects that had pathologies that may significantly alter knee biomechanics relative to the native (or deficient) conditions or that examined variables unrelated to ACL injury mechanisms were excluded from the analyses. For example, studies that examined reconstruction techniques, effects of bracing, effects of menstrual cycle or hormones, long-term outcomes of ACL injury, partial ACL tears or injuries resulting from vehicle accidents were excluded. Finally, studies with subject (or specimen) reported knee osteoarthritis or ACL deficiency without intact comparisons were excluded from the analyses.

2.3 Independent Review and Analysis

Two independent reviewers performed first-stage screening of titles and abstracts based on...
the study design and research question to identify all relevant articles. Any study identified by either reviewer was included in the first-stage screen. After the initial screening, a second-stage review was performed to identify which studies met the study criteria and for data extraction and analysis. If there was disagreement regarding study criteria or data extraction, a third reviewer was available to reconcile any differences of opinion. A quality appraisal of the literature was used to determine the strengths and weaknesses of the methodologies used to examine ACL injury mechanisms. Data analysis and results consisted of descriptive evaluations of each study, including the methodology, outcomes and the planar direction (if available) supported by the results for each study.

3. Results

The initial literature search yielded 9861 total references; 639 articles met the minimum inclusion criteria. The articles retrieved varied by level of evidence, methodology, study population and outcomes. As expected, no randomized controlled trials were identified. Common methodological approaches used to study ACL injury mechanisms included athlete interviews or questionnaires, arthroscopic studies, clinical imaging and physical exam testing, video analysis, in vivo laboratory tests (such as motion analysis or EMG) or mathematical modelling studies. The studies utilized either in vivo (human subjects) or in vitro (human cadaver) techniques. However, because of the unique differences between in vivo and in vitro techniques, we categorized cadaveric investigations as using a separate methodology, even though cadaveric studies often utilized similar methods such as imaging, motion analysis or arthroscopy to evaluate knee biomechanics.

While 639 studies met the a priori established criteria, only 34 studies were associated with ‘direct’ ACL injury mechanisms and provided evidence regarding the planar mechanism of injury. The breakdown of studies addressing planar mechanisms of injury consisted of 16 interview/questionnaire studies,[21-36] six video analysis studies[21,37-41] that reported a planar mechanism of injury, six modelling studies[42-47] and six cadaveric studies.[48-53] Twenty-eight of these 34 studies (82%) supported multi-planar mechanisms (table III).

In addition to the studies related to direct ACL injury mechanisms, 164 studies were identified that looked at ACL injury mechanism ‘indirectly’ and provided evidence regarding possible planar injury mechanisms. A total of 80 of these 164 studies (49%) supported multi-planar mechanisms (table IV). Sixty-two of the 132 (47%) diagnostic studies using imaging, arthroscopy, physical exam or instrumented laxity provided evidence to support multi-planar mechanisms (table IV). While 50 of the 132 (38%) diagnostic studies provided evidence to support a sole sagittal plane mechanism, it is important to consider that most of these studies only evaluated anterior tibial translation and did

**Table II.** Range of motion for knee rotations in the frontal and transverse planes

<table>
<thead>
<tr>
<th>Rotation</th>
<th>Direction</th>
<th>Knee flexion (°)</th>
<th>Applied force (Nm)</th>
<th>Laxity (° [mean])</th>
<th>Study type (n)</th>
<th>Comment</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frontal</td>
<td>Adduction and abduction</td>
<td>0</td>
<td>–8</td>
<td>1.9 [± 1.7]</td>
<td>Cadaver (35)</td>
<td>Manual application of force to determine laxity</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10</td>
<td></td>
<td>4.5 [± 1.9]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>20</td>
<td></td>
<td>5.4 [± 2.1]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>45</td>
<td></td>
<td>6.0 [± 2.4]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>90</td>
<td></td>
<td>7.5 [± 2.8]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>135</td>
<td></td>
<td>8.4 [± 3.1]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transverse</td>
<td>Internal and external</td>
<td>0</td>
<td>–8</td>
<td>10.1 [± 4.0]</td>
<td>Cadaver (35)</td>
<td>Manual application of force to determine laxity</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10</td>
<td></td>
<td>19.5 [± 4.9]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>20</td>
<td></td>
<td>24.5 [± 4.9]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>45</td>
<td></td>
<td>26.7 [± 5.6]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>90</td>
<td></td>
<td>24.3 [± 4.7]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>135</td>
<td></td>
<td>26.2 [± 7.2]</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

n = no. of subjects; Nm = Newton metres; – indicates approximate; ° indicates degrees.
not consider other planes in the diagnostic evaluation. Four of eight (50%) modelling studies and 13 of 23 (57%) cadaveric studies supported multi-planar mechanisms for ACL injury (table IV). Although many in vivo laboratory studies evaluated the effects of ACL deficiency on dynamic knee biomechanics, the complex neuromuscular compensation patterns that may occur as a result of injury made it difficult to interpret the planar consequences of ACL deficiency. However, one prospective in vivo biomechanical/epidemiological laboratory study supported a multi-planar mechanism, as abnormal mechanics in all three planes during landing predicted ACL injury risk (table IV).

4. Discussion

4.1 Planar Biomechanics Surrounding the Inciting Anterior Cruciate Ligament Injury Event

The various methods used to study ACL injury mechanisms indicate that the ACL may be subject to high forces when under varying loading conditions. Based on this systematic analysis, we accepted the hypothesis that ACL injuries do not occur via solely a sagittal, frontal or transverse plane mechanism. Table V summarizes the types, advantages and limitations of research methods used to study ACL injury mechanisms found in the studies identified through this review.\textsuperscript{[54]} It is important to note that since it is well established that females have increased rates of ACL injury in similar sports compared with males, the ACL injury studies identified often focused on the determination of differences between the sexes that may increase the risk for injury in females. Sections 4.2–4.8 highlight some of the support and limitations for solely sagittal, frontal and transverse mechanisms of ACL injury compared with a multi-planar mechanistic view of ACL injury.

4.2 Evidence that Supports a Sagittal Plane Mechanism Theory

Many conventional and current theories support a sagittal plane mechanism of injury. A total of 32% of the studies identified supported a sole sagittal plane mechanism of injury. The knee has the largest range of motion in the sagittal plane compared with the frontal or transverse planes and more erect knee postures during landing are theorized to increase risk for ACL injury. Females have been reported to have less knee flexion during landing, jumping and cutting tasks compared with males. In addition, interview and video observational studies indicate that the knee is at low (0–30°) knee flexion angles during injury events.\textsuperscript{[21,25,29,37,39,41]}

Table III. Planar evidence for studies directly associated with anterior cruciate ligament injury

<table>
<thead>
<tr>
<th>Study type</th>
<th>No. of studies with planar mechanism evidence</th>
<th>No. of studies that support multi-planar mechanisms</th>
<th>Other support</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cadaver</td>
<td>6</td>
<td>4</td>
<td>Sagittal = 1; frontal = 1</td>
</tr>
<tr>
<td>Modelling</td>
<td>6</td>
<td>3</td>
<td>Sagittal = 2; frontal = 1</td>
</tr>
<tr>
<td>Video</td>
<td>6</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Interview/questionnaire</td>
<td>16</td>
<td>15</td>
<td>Sagittal = 1</td>
</tr>
<tr>
<td>Total</td>
<td>34</td>
<td>28</td>
<td>Sagittal = 4; frontal = 2</td>
</tr>
</tbody>
</table>

Table IV. Planar evidence for studies indirectly associated with anterior cruciate ligament injury

<table>
<thead>
<tr>
<th>Study type</th>
<th>No. of studies with planar mechanism evidence</th>
<th>No. of studies that support multi-planar mechanisms</th>
<th>Other support</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cadaver</td>
<td>23</td>
<td>13</td>
<td>Sagittal = 6; frontal = 4</td>
</tr>
<tr>
<td>Modelling</td>
<td>8</td>
<td>4</td>
<td>Sagittal = 4</td>
</tr>
<tr>
<td>Diagnostic</td>
<td>132</td>
<td>62</td>
<td>Sagittal = 50; frontal = 11; transverse = 9</td>
</tr>
<tr>
<td>In vivo laboratory</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>164</td>
<td>80</td>
<td>Sagittal = 60; frontal = 17; transverse = 9</td>
</tr>
</tbody>
</table>

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Table V. Summary of research methods used to study anterior cruciate ligament (ACL) injury mechanisms (reproduced from Quatman et al.\textsuperscript{54} with permission from BMJ publishing group)

<table>
<thead>
<tr>
<th>Data collection method</th>
<th>Examples</th>
<th>Advantages</th>
<th>Limitations</th>
<th>Applications in ACL research</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>In vivo</td>
<td>Observational: questionnaires, videos, interviews</td>
<td>Direct observation or description of injury mechanism</td>
<td>Cannot determine internal structure stresses/strains Questionnaire/interview: subjective and dependent on athlete’s ability to recall event Video: limited by quality of video, camera angles available and observer’s ability to describe event</td>
<td>Description of inciting event (contact or non-contact, type of sporting activity), gross position of knee, trunk, lower extremity during injury</td>
<td>2,21,25,27,55,56</td>
</tr>
<tr>
<td></td>
<td>Clinical: arthroscopic, imaging, physical exam</td>
<td>Identify lesions associated with injury, strain gauges on internal joint structures, analyze anatomic restraints Functional-dynamic imaging such as MRI or roentgen stereogrammetric analysis techniques offer enhanced ability to visualize internal structures during dynamic weight-bearing activities Accuracy, precision, reliability of data acquisition continues to improve</td>
<td>Do not directly analyse injury mechanism Post-injury pathology and associated biomechanical effects may not be reliable indicators of actual injury mechanisms Arthroscopic: not ethical for healthy subjects, may affect proprioception or cause joint impingement, expensive Imaging: possible radiation exposure, expensive Physical exam: often subjective and highly variable differences between subjects</td>
<td>Strain gauges placed on ACL during arthroscopy provide information about ACL strains during external loads Bone bruise locations may provide evidence for injury mechanisms Posterior tibial slope calculated from images may be associated with ACL injury Lachman’s, pivot shift, knee arthrometer data provide evidence of biomechanical effects of ACL deficiency Functional dynamic images help identify osteokinematics and ACL changes that occur during weight-bearing tasks</td>
<td>57,58</td>
</tr>
<tr>
<td>Laboratory: motion analysis, electromyography</td>
<td>Mimic specific movements that occur during injury Estimate both kinematics and net kinetics at joint during high risk movements Coupled</td>
<td>Do not replicate actual injury, rather estimate total joint biomechanics during high risk movements Difficult to reproduce or even approximate the strains and stresses that occur in internal joint structures</td>
<td>Identify sex differences in landing/cutting mechanics that may be associated with ACL injury Identify biomechanical/neuromuscular variables</td>
<td>9,59-63</td>
<td></td>
</tr>
</tbody>
</table>

Continued next page
<table>
<thead>
<tr>
<th>Data collection method</th>
<th>Examples</th>
<th>Advantages</th>
<th>Limitations</th>
<th>Applications in ACL research</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>In vitro</strong></td>
<td>Robotic, quasi-static, dynamic</td>
<td>Identify passive biomechanical characteristics of joint motions Direct injury studies possible Quantify multiple degree of freedom kinematics of joints Measure ligament and joint articulation contact forces</td>
<td>Age of specimens (may differ significantly from the population of interest) Difficult to reproduce dynamic joint motions and neuromuscular contributions to motion during injury conditions Expensive and injury studies often require a large number of specimens to reproduce injury mechanisms Orientation of loading, rate of loading and age of specimen may have significant effects on musculoskeletal failure loads</td>
<td>ACL strains and biomechanical parameters during different external loading parameters provide evidence of how ACL injuries may occur Cadaveric ACL injury may occur during anterior tibial shear, abduction, knee hyperextension and many combined loads Biomechanical consequences of ACL deficiency</td>
<td>48-53, 64-71</td>
</tr>
<tr>
<td><strong>In silico</strong></td>
<td>Phenomenological, anatomic, rigid, finite element, quasi-static, dynamic, stochastic, inverse simulation, forward simulation</td>
<td>Estimate internal joint biomechanics in vivo biomechanical data can be used as input for geometric models to analyse movements Can be used to extend motion analysis data to relate ground reaction forces and kinematics to ligament, cartilage and bone forces Can be used to simulate injury mechanisms Parametric sensitivity studies possible Relatively inexpensive if equipment is readily available Accuracy, precision, reliability of data acquisition continues to improve</td>
<td>Due to complexity of joints, models are simplified Certain assumptions are necessary about material properties, boundary conditions and anatomy Models must be validated (ideally by in vivo and in vitro data), which can be difficult without adequate material property characteristics available for the population of interest Not currently possible to validate high loading rate injury simulations</td>
<td>ACL injury simulations for various tasks Identification of possible strategies to lower ACL injury risk Extension of coupled biomechanical epidemiological motion analysis data to relate ground reaction forces and external loading conditions to ACL strains</td>
<td>44,45,72-80</td>
</tr>
</tbody>
</table>
Sagittal plane translation movements are also important to consider, since the ACL is a major stabilizing ligament of the knee that provides approximately 85% of the total restraint in the knee joint to the anterior tibial translation. Many cadaveric, imaging and physical exam studies demonstrate that ACL-deficient knees have significantly more anterior tibial translation compared with ACL-intact conditions. Both in vivo and in vitro studies demonstrate that the total range for anterior/posterior tibial displacement is greater at 30° than 90° of knee flexion, which indicates that the knee joint has the potential to translate further anteriorly at shallow knee flexion angles.

During sagittal plane movements at the knee joint, the quadriceps muscle contractions produce anterior shear force at the proximal end of the tibia through the patellar tendon. Proximal tibia anterior shear is the most direct ACL loading mechanism and decreasing knee flexion angles increases the anterior shear force at the tibia. Since video studies indicate that ACL injuries usually occur at low flexion angles, it is theorized that a powerful quadriceps force at low knee flexion angles could produce enough anterior shear force at the tibia to cause ACL rupture.

Correspondingly, several studies support anterior tibial shear as a mechanism for ACL injury. MRI studies after ACL injury demonstrate that tibial bone bruises are located more posteriorly than femoral condylar bone bruises and it has been speculated that this is a result of the tibia shifting anteriorly relative to the femur during the injury. In vivo arthroscopic studies demonstrate that the ACL is a primary restraint to anterior shear loading and abnormal anterior tibial translation relative to the femur is a clinical measure used to determine ACL deficiency. The relationships between high ACL strains, low knee flexion angles and quadriceps muscle forces have been extensively examined. The landing phase of many sports movements are associated with large quadriceps forces at relatively small knee flexion angles, which induce anterior force on the tibia. Cadaveric investigations have demonstrated that isolated quadriceps contractions increase ACL strain and force during low knee flexion angles. Studies by DeMorat et al. and Pandy and Shelburne indicated that aggressive quadriceps loading in slight knee flexion produce significant anterior tibial translation sufficiently large enough to injure the ACL. Withrow et al. showed that during a high impact load, ACL strain is proportional to increased quadriceps forces. In an arthroscopic study, Fleming et al. found that quadriceps contractions produced ACL strains between 0° and 30° of knee flexion. At the same time, several motion analysis and EMG studies showed that females have more knee extension during landing compared with males, and that females have significant neuromuscular imbalances between quadriceps and hamstrings recruitment levels, making it more difficult to decelerate from a landing and control anterior tibial translation.

4.3 Evidence Against a Sole Sagittal Plane Mechanism Theory

Although, theoretically, many of the studies identified support a sagittal plane mechanism, several limitations to these studies should be considered. In combination, these limitations provide a strong argument against single plane mechanisms of injury and subsequently underscore the likelihood of a more multi-planar mechanism of injury. For example, theoretically, if the mechanism was solely an anterior shear, the bone bruise patterns on MRI after ACL injury would most likely be located along the medial tibial plateau as well as the tibial plateau. Since the bone bruises are usually located laterally, lateral compression or internal/external tibial rotation of the joint also likely occurred during these injuries. Moreover, while some motion analysis studies suggest that females show greater knee extension during landing, other studies show no sex difference or even greater knee flexion in females during athletic tasks. Video analyses of ACL injuries indicate that females may actually have a higher knee flexion angle compared with males during the injury event. Furthermore, knee flexion angle does not appear to predict ACL injury risk.

Cadaveric studies also indicate that hamstrings co-contraction with quadriceps contraction is
effective in reducing excessive forces in the ACL, specifically between 15° and 60° of knee flexion.\[87\] At the same time, during landing, ACL strains are higher under multi-planar loading conditions compared with isolated anterior tibial loading situations, making it easier to damage the ACL under combined planar situations.\[85\] DeMorat et al. found that a quadriceps contraction appeared to affect ACL loading in more than one plane of motion, as knee internal rotation and valgus moments to the tibia occurred coincident with anterior tibial translation.\[48\]

Mathematical models indicate that large ground reaction forces posteriorly directed with respect to the proximal tibia help protect the ACL during landing and posterior deceleration forces and reduce ACL strain during a run-to-stop simulation.\[103\] Moreover, hamstrings co-contraction can lead to joint compression and decreased anterior tibial translation.\[104,105\] Several mathematical models have demonstrated that sagittal plane mechanisms alone cannot account for ACL forces high enough to rupture the ACL.\[45,106,107\] Therefore, it is highly unlikely that ACL injuries result exclusively from a sagittal plane mechanism.

4.4 Evidence that Supports a Frontal Plane Mechanism Theory

The frontal plane theory mechanism has become a recent topic of debate as a contributing factor to ACL injuries. Approximately 10% of the studies identified supported a sole frontal plane mechanism and over 80% of the studies identified supported frontal plane mechanisms (specifically abduction motions) as a contributor to a multi-planar mechanism of injury. Based upon the studies identified, frontal plane motions are often associated with ACL injuries and excessive movements in the frontal plane outside normal ranges may be catastrophic to the knee joint.

Ligament restraints and knee joint articulation limit the passive range of knee motion in the frontal plane, which results in a smaller range of motion in the frontal plane compared with the sagittal plane. It is difficult to accurately measure medial-lateral translations of the knee since the translations that can occur in a healthy knee are limited. Cada-veric studies and in vivo studies have demonstrated that the frontal plane rotational range of motion is also relatively limited.\[60\] Shultz et al. demonstrated in vivo that a 10 Newton (N) metres (abduction/adduction) load at 20° of knee flexion produced approximately 10° total knee rotation in the frontal plane (abduction ~5.5°; adduction ~4.5°).\[7\]

Markolf et al. and Miyaska et al. demonstrated that cadaveric specimens subjected to abduction torque show increases in ACL tension throughout a range of knee flexion angles (0°–90°) with the highest between 0° and 30° of knee flexion.\[66,85\] Similarly, Wascher et al. and Markolf et al. demonstrated that adduction moments lead to high ACL forces particularly near full knee extension.\[67,108\] Arthroscopic studies indicate that the ACL strain increases under adduction moments during weight-bearing conditions.\[99\] While adduction motions of the knee do appear to increase the tension and strain in the ACL, few observational studies attribute this type of motion to ACL injuries.\[21,39\]

Video analyses of ACL injuries during sports indicate a common body posture during injury in which the knee is near full extension (between 0° and 30°), the tibia is externally rotated, the foot is planted and a deceleration followed by an abduction collapse of the knee joint occurs.\[21,39\] Olsen et al. found that dynamic abduction collapse was the most common mechanism for ACL injury in handball.\[41\] Similarly, Krosshaug et al. found that dynamic abduction collapse was a common ACL injury mechanism with female basketball players demonstrating a 5.3-fold higher relative risk of abduction collapse during ACL injury compared with male basketball players.\[39\] At the same time, motion analysis studies indicate that high knee abduction motion and torque are both common sex differences during athletic movements and predictors of future ACL injury risk.\[96,99,102,109\]

Clinical imaging and arthroscopic studies also indicate that frontal plane mechanisms play a role in ACL injury. Bone bruises of the lateral femoral condyle or posterolateral portions of the tibial plateau are found to occur 80% of the time in MRI studies after acute ACL injury.\[88,89,110,111\] It is theorized that these bone bruise locations

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indicate that ACL injury occurs from an abduction mechanism, because bone bruising on the lateral part of the knee joint indicates that compression occurs laterally while the medial aspect of the joint opens up. In addition, arthroscopic studies indicate that abduction knee moments applied during weight-bearing conditions significantly increase relative ACL strain.\(^{90}\)

Several cadaveric studies have demonstrated that the ACL may have increased force during abduction loads.\(^{67,85,108}\) Markolf et al. demonstrated that a quadriceps force (200 N) applied in combination with an abduction load increased the ACL force up to 100% compared with abduction loads without a quadriceps force.\(^{85}\) Withrow et al. demonstrated that cadavers subjected to impulsive compression loads with the knee joint in an abduction alignment led to 30% higher ACL strains compared with knees in neutral alignment.\(^{68}\)

Modelling studies have also shown support for an abduction injury mechanism. McLean et al. utilized motion analysis and mathematical modelling to simulate injury and showed that external abduction loads reach values high enough to rupture the ACL during cutting manoeuvres and these abduction loads occurred more frequently in females than males.\(^{145}\) Another forward dynamics model that was used to simulate ACL injuries during an abduction mechanism demonstrated that perturbations to the lower extremity during a side-step cutting manoeuvre can lead to external abduction loads that are capable of rupturing the ACL.\(^{44}\)

4.5 Evidence Against a Sole Frontal Plane Mechanism Theory

Although increased lower extremity abduction loads and movements in the frontal plane may be associated with increased ACL strain and risk of injury, controversy surrounds this theory. The ACL is considered the primary restraint to anterior tibial translation during passive physical exam testing, while the medial collateral ligament (MCL) is considered the primary restraint against abduction stress in the knee joint. Therefore, the abduction motion and torque at the knee joint associated with increased ACL injury risk is surprising to clinicians, since it is estimated that combined ACL/MCL injuries make up only 4–27% of all ACL injuries.\(^{1,112}\) If ACL injuries occur due to movements solely in the frontal plane, higher combined ACL/MCL injury patterns would be expected.

Cadaveric studies indicate that the ACL and MCL may both provide restraint to external abduction, albeit via different mechanisms. The ACL appears to prevent knee abduction by limitation of axial tibial rotation, while the MCL restrains knee abduction by limiting medial joint space opening. Thus, both the MCL and ACL are important structures for restraint of abduction loads and either one may potentially be injured during high knee abduction loading.\(^{69}\) Cadaveric ACL failure loads are reported to range from approximately 640–2100 N, depending on the age of the specimen, rate and orientation of loading.\(^{70}\) Cadaveric MCL failure loads have been reported to be around 2300 N for complete MCL disruption.\(^{113}\) While higher reported MCL failure loads compared with the ACL may help explain how and why the ACL may fail earlier than the MCL during external abduction loading, there are currently no reported studies to support or refute this theory. Few studies have examined ACL and MCL loading simultaneously during an abduction load. Because of the variability in laxity between specimens and different testing conditions and setups, cross referencing of studies to determine how the ACL and MCL simultaneously behave during abduction is difficult.

Another limitation to the frontal plane theory is the non-descript term of ‘valgus’ used in previous studies to describe what occurs during an ACL injury. The medical definition of valgus refers to the outward angulation of the distal segment of a bone or joint. However, at the knee joint, valgus may occur from a direct abduction motion of the knee joint or from transverse-plane knee rotation motions (femoral/tibial internal and external rotations). Thus, describing an injury mechanism as a valgus collapse does not necessarily indicate that the injury occurred solely in the frontal plane.
4.6 Evidence in Support of a Transverse Plane Mechanism Theory

Although only 5% of the studies supported a sole transverse plane mechanism, many of the studies neglected to assess the transverse rotations during experimental procedures. Thus, the transverse plane contributions to ACL injury mechanisms may be significantly underestimated. Similar to the frontal plane, transverse plane ranges of motion (rotational and translational) are not as large as sagittal plane motions and difficult to assess experimentally. Compression is the most common translation that occurs during cutting and landing activities, and could be a direct result of impact (ground reaction) forces, an indirect result from muscular stabilization or, most likely, a combination of both effects. As evidenced by the common association of bone bruises accompanying ACL injuries, compression is a likely component of the ACL injury event.

The total passive range of rotation (internal and external) in the transverse plane is approximately 25°, depending on the knee flexion angle. Numerous studies have reported that the ACL experiences higher strains during internal tibial rotation, while only minimal increases in strains during external rotation have been noted. Cadaveric studies by Meyer et al. demonstrated that high compressive or internal torsional tibial loads can cause ACL damage with limited damage to other knee ligaments. Similarly, Markolf et al. demonstrated that an internal tibial torque generates significantly higher ACL forces than application of a 100 N anterior tibial force during shallow knee flexion angles. In contrast, external tibial torques applied to cadaveric knees demonstrated little differences in ACL strain and tension over a wide range of flexion angles.

Snow skiing results in a high rate of ACL injury. A common mechanism described during snow skiing ACL injuries is internal tibial rotation or a combination of high axial loading with transverse plane rotations. However, comparisons between ACL injuries that result from snow skiing and ACL injuries that occur during sports that involve cutting, jumping and landing activities are questionable. Skiers have different movement mechanics, since their feet are fixed in ski bindings and they have the added extensions of the skis, which may increase the surface area for applying external multi-planar loads to the distal end of the lower extremity.

A recent imaging study by Stijak et al. found that ACL-injured patients have greater posterior lateral tibial plateau slopes compared with controls. In addition, the lateral femoral condyle has greater translation on the tibia compared with the medial condyle as the flexion angle increases. As the knee goes into deeper flexion, the lateral femoral condyle internally rotates relative to the tibial plateau, while the medial femoral condyle remains relatively stable. Therefore, a greater posterior tibial slope may lead to greater external rotation of the femur or internal rotation of the tibia during activities and may increase an individual’s risk for ACL injury.

4.7 Evidence Against of a Sole Transverse Plane Mechanism Theory

Theoretically, the cushioning provided by the menisci and articular cartilage aids in reduction of the compressive forces and minimization of the compression that occurs during landing and cutting activities. Moreover, it is unlikely that compression without movements in other degrees of freedom could cause injury to the ACL, since ligaments are minimally stressed in compression. It is possible to rupture the ACL in vitro in distraction. However, the intra-articular orientation of the ACL and its variable fibre lengths makes uniform loading of the ACL during tension difficult. Thus, the likelihood of a complete mid-substance ACL rupture is low with pure distractive loads applied along the axis of the tibia. In addition, the compressive knee joint forces resulting from muscle activation during weight-bearing activities would counter any distractive forces that may occur during landing and cutting activities.

In addition, given the strong support for internal tibial rotations being more likely to injure the ACL than external rotations, observational studies that described an external tibial rotation during injury seem counterintuitive and...
contradictory. Arthroscopic data indicate that during non-weight-bearing conditions, internal tibial torque significantly increases ACL strain while external tibial torques produce minimal strain in the ACL. However, arthroscopic data show that weight-bearing conditions can significantly increase the ACL strain during both internal and external torques. In particular, external torques (0–10 nm) increased the ACL strain during weight-bearing conditions by 2–4% compared with non-weight-bearing conditions. Since most ACL injuries occur during weight-bearing conditions, it may be feasible that an external rotation torque could potentially damage the ACL. However, an alternative combined multi-planar loading mechanism may include an externally rotated foot or ski, coupled with foot hyper-pronation and tibial internal rotation and knee abduction, which would lead to high loads on the ligament.

4.8 Multi-Planar Mechanism

Many studies indicate that the knee may experience high loading conditions in any plane. In particular, high loading conditions can occur in sporting manoeuvres, such as landing, jumping and cutting, all of which require movements in multiple planes. Thus, it is unlikely that an ACL injury occurs in a single isolated plane. In support of this concept, 82% of the direct ACL injury mechanism studies identified supported a multi-planar mechanism of injury. This is in corrobororation with Shimokochi and Shultz, who systematically reviewed the retrospective and observational studies available in the literature that assessed ACL injury mechanisms and found that the primary mechanism of ACL injury appears to be a result of multi-planar knee loading conditions.

Physical examination techniques are forensic in that they may reproduce the increased laxations that occurred during the inciting injury. The pivot shift test is one such clinical exam, which is performed by a valgus (knee abduction) stress coupled with flexion and tibial rotation. As such, it is likely reproducing the original mechanism of injury. The pivot shift is a highly sensitive test for ACL insufficiency. Benjaminse and Gokeler reported the pivot shift exam to be the most specific clinical test for ACL rupture, demonstrating a 98% specificity (95% CI 96, 99). It is also a sensitive predictor of future poor conservative outcomes following injury. Cumulatively, these data demonstrate that knee abduction motion may be an important component of the ACL injury mechanism.

In retrospective interview studies, individuals often reported that their knee moved in multiple planes during the injury event. Specifically, a ‘valgus’ rotation combined with either an internal or external tibial rotation at low knee flexion angles was reported by injured individuals. Similarly, video studies indicate that ACL injuries occur with minimal knee flexion and are often combined with knee ‘valgus’ or transverse knee rotation movements. This is supported by the bone bruise patterns associated with ACL injuries on imaging studies, with the bone bruises located on the lateral femoral condyles and posterolateral tibial plateaus of patients with acute ACL injured knees. This bruise pattern indicates that internal tibial rotation, femoral external rotation, abduction and/or anterior tibial translation would lead to these specific bone bruise locations.

While few in vivo arthroscopic studies have examined combined planar loading, Fleming et al. noted that weight bearing, which resulted in compressive forces across the joint, altered the strain results in the ACL for various loading conditions. ACL strains were higher when an anterior shear force was applied to the tibia during weight-bearing conditions compared with non-weight bearing, and the weight-bearing effect was shear-load dependent. Strains in the ACL were torque dependent for internal and external rotation torques, with weight bearing leading to significantly higher strains than non-weight-bearing conditions. Similarly, weight bearing led to significantly higher strains in the ACL during abduction/adduction loading compared with non-weight-bearing conditions. While all of these outcomes indicate the ACL can be subjected to high loading strains in all planes in weight bearing, combined loading of anterior shear, abduction/adduction and internal/external torques were not examined. Consequently, it is...
difficult to surmise the combined effects of multi-planar loading on ACL strain from the study.

Cadaveric investigations show that valgus or varus moments, combined with a quadriiceps contraction or anterior shear force, increases ACL strain. Markolf et al. and Berns et al. demonstrated that coupled loading of an abduction moment to an anterior tibial force (at a knee flexion greater than 10°) or coupled loading of an anterior tibial force with an internal tibial torque (at knee flexion less than 20°) leads to additive generation of ACL force and strain compared with an isolated anterior tibial force.\(^{71,85}\) In contrast, coupled external tibial torque and anterior tibial force appears to lower the ACL tensile force after 20° of knee flexion. As such, the ACL may be less vulnerable to injury, since the MCL could be shielding the ACL from stress in this knee position.\(^{85}\)

Motion analysis studies have indicated that various multi-planar motions may increase risk for ACL injury in female athletes. Hewett et al. showed that subjects who subsequently went on to ACL injury after biomechanical testing had larger abduction angles at initial contact and at peak abduction in the frontal plane and significantly lower knee flexion at peak contact in the sagittal plane.\(^{102}\) In addition, various sex differences in landing mechanics have been identified in multiple planes and have been speculated as possible risk factors for ACL injury.

Modelling studies have provided some unique perspectives on the effects of multi-planar loading. Fung and Zhang developed 3-dimensional models of knees to examine factors that could lead to ACL impingement on the intercondylar notch of the femur.\(^{118}\) Simulation of the physical interaction between the ACL and the notch during six-degrees of freedom tibiofemoral motions showed that abduction and external tibial rotation can lead to ACL impingement. McLean et al. reported that neuromuscular control perturbation produced peak stance phase knee abduction loads large enough to cause ACL injury, and landing in a more extended knee flexion angle increased this risk for injury.\(^{44}\) Although the current literature is limited for the evaluation of multi-planar loading effects on knee biomechanics and, specifically, ACL stresses and strains, future modelling work may provide the opportunity to extend motion analysis data to predict stresses and strains in the internal joint structures, simulate injury scenarios, and conduct parametric studies evaluating the effects of isolated and multi-planar loading scenarios without inter-subject variability that occurs during cadaveric and in vivo investigations.

### 4.9 Kinetic Chain Involvement

Finally, while the ACL injury is a direct result of what occurs at the knee joint, it is important to consider the contribution of the entire kinetic chain to knee joint loading. Motion and forces at any segment of the kinetic chain (foot, ankle, hip, trunk and upper extremities) may influence knee joint mechanics. There is increasing evidence that poor or abnormal neuromuscular control of the lower limb during athletic movements, especially at the knee joint, contributes to ACL injury risk. Future work should establish the effects of proximal and distal structures on knee joint biomechanics and how they relate to ACL injury.

### 5. Conclusions

The methodological approaches that have been utilized to investigate ACL injury mechanisms include athlete interviews, arthroscopic studies, clinical visits, video analysis, cadaveric studies, in vivo laboratory studies and mathematical modelling studies. Although none of these methodologies alone can provide strong answers to the question of what the underlying mechanisms are for ACL injuries, all of these data considered together provide important clues to ACL injury mechanisms. When the data from the published literature that relates to mechanisms of ACL injury are summarized and considered in toto, ACL injuries are more likely to occur during multi-planar rather than single-planar mechanisms of injury. Therefore, based on this systematic analysis, we accepted the hypothesis that ACL injuries likely do not occur solely via a sagittal, frontal or transverse plane mechanism.

One important clinical implication for the acceptance of this hypothesis is that ACL prevention
programmes that neglect multi-planar mechanisms, such as combined frontal, sagittal and transverse plane mechanisms, could seriously hamper ACL injury prevention efforts in healthy athletes and athletes returning to sport after a previous ACL injury. Future studies should focus on the examination of the precise mechanisms of combined knee joint loading scenarios to determine at-risk knee postures that may be addressed with neuromuscular training programmes targeted for ACL injury prevention.

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