Motion Analysis and the Anterior Cruciate Ligament: Classification of Injury Risk

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Abstract

Anterior cruciate ligament (ACL) injuries are common, catastrophic events that incur large expense and lead to degradation of the knee. As such, various motion capture techniques have been applied to identify athletes who are at increased risk for suffering ACL injuries. The objective of this clinical commentary was to synthesize information related to how motion capture analyses contribute to the identification of risk factors that may predict relative injury risk within a population. Individuals employ both active and passive mechanisms to constrain knee joint articulation during motion. There is strong evidence to indicate that athletes who consistently classify as high-risk loaders during landing suffer from combined joint stability deficits in both the active and passive knee restraints. Implementation of prophylactic neuromuscular interventions and biofeedback can effectively compensate for some of the deficiencies that result from poor control of the active knee stabilizers and reduce the incidence of ACL injuries.

Keywords
- ► anterior cruciate ligament injury
- ► injury risk classification
- ► motion capture
- ► motion analysis
- ► neuromuscular training

More than 55% of all athletic injuries are incurred on the lower extremity,[1–4] while damage specific to the knee accounts for approximately 15% of all athletic injuries.[5] Overall, 43% of these knee injuries are classified as strains or sprains, which makes them the third most prevalent form of lower extremity injury with a rate of 102 incidents per 100,000 athletes per year.[6] Of these knee injuries, it is estimated that 45% involve internal knee trauma, and 49% of those entail anterior cruciate ligament (ACL) rupture,[7] as 1 in 3,000 persons are likely to suffer an ACL disruption each year.[8] However, ACL injury is a sex-specific event, as females are 2 to 10 times more likely to suffer ACL disruption than their male counterparts,[9–14] which produces an incidence rate of 1 ACL tear in every 50 to 70 female athletes per year.[15] These high incidence rates of ACL rupture lead to an estimated 250,000 ACL tears and 127,000 ACL reconstructions (ACLR) annually in the United States.[16,17] With conservative repair estimates ranging from $5,000 to $44,000 per ACLR depending on the type of repair and severity of injury,[13,18–20] the annual medical expense of ACL injury treatments in the United States alone may exceed $2 billion. Worldwide, it is estimated that the annual incidence of ACL tears could reach as high as 2 million patients,[21] which would exponentially increase these costs. Unfortunately, despite the expense associated with ACLR, surgical repair has not been found to significantly reduce the long-term outlook of knee osteoarthritis compared with nonoperative rehabilitation.[22,23] As many as 86% of patients demonstrated early onset osteoarthritis following ACLR and 75% report degradation in knee quality of life within 20 years postsurgery.[23–25] For these reasons, the focus on treating ACL injuries may be best served through identification and treatment of modifiable injury risk factors that may prevent ruptures before they happen.

Two- and three-dimensional (2D and 3D) motion analysis systems have been used in vivo to identify, classify, and associate biomechanical risk factors with the likelihood of

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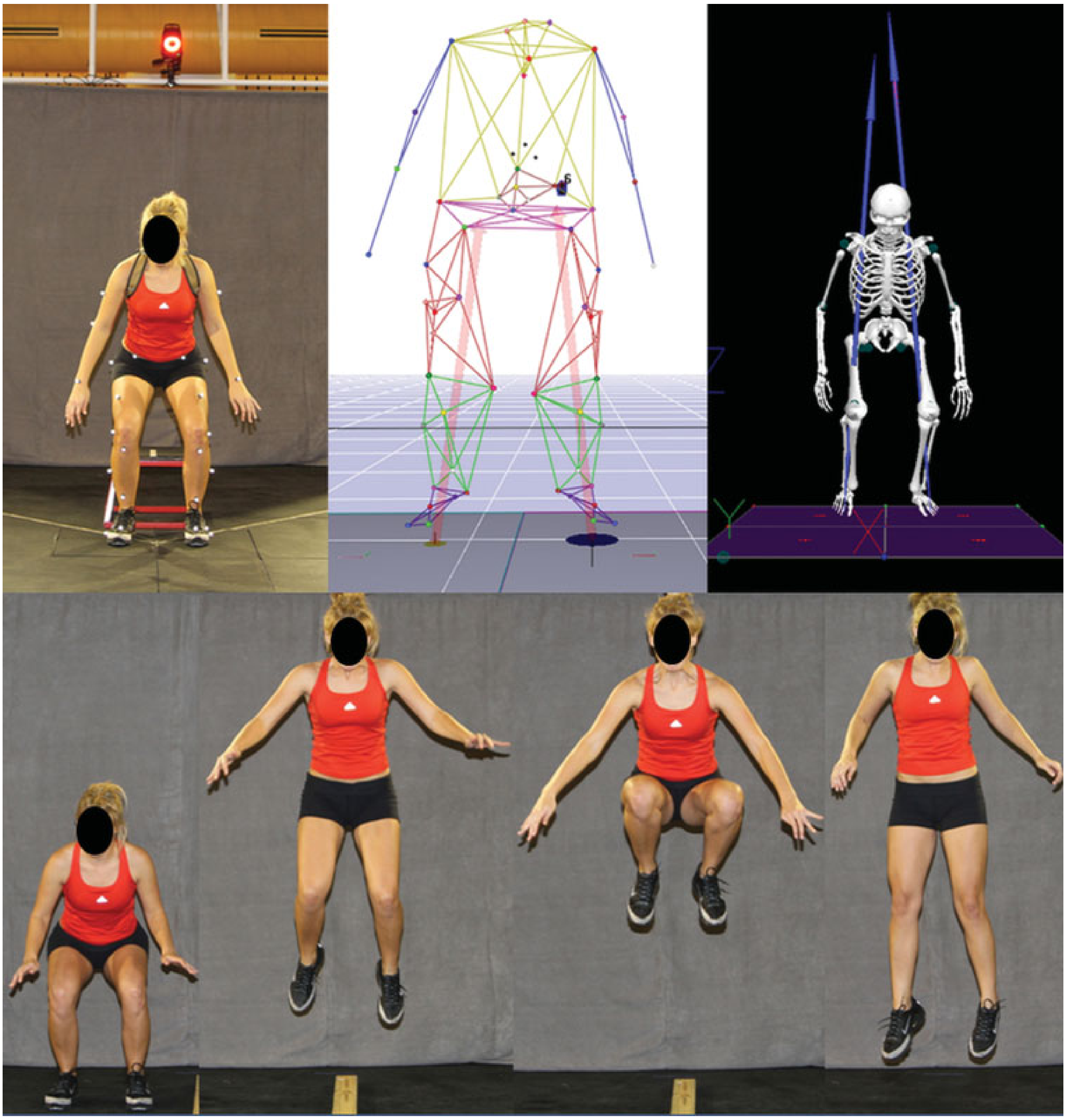

Fig. 1 (Top row) From left to right depicts three-dimensional (3D) motion capture models at the minimum center of gravity for a drop vertical jump performed in vivo within a 3D motion analysis laboratory, within the tracking software used to process 3D positional data from the in vivo markers, and within the musculoskeletal modeling software used to process 3D kinematic and kinetic biomechanics from the positional data and recorded ground reaction forces. Knee abduction torque from a drop vertical jump is commonly used to assess anterior cruciate ligament injury risk in 3D motion analyses.[26,75] (Bottom row) Progression of a tuck jump task during two-dimensional (2D) motion analysis. The tuck jump task has been demonstrated as a clinician friendly, 2D assessment that can be used to identify high-risk mechanics and provide direction for neuromuscular intervention.[44]

future ACL injury within athletic populations (►Fig. 1). Specifically, in a cohort of 205 female athletes, 3D motion analysis prospectively determined that those who went on to ACL injury expressed larger knee abduction moments when landing from a drop vertical jump task than did healthy controls.[26] This association between frontal plane knee torque and increased ligament loading, which was initially defined through motion analysis, has since been affirmed in a multitude of in vitro, in situ, and in sim models.[27–29] In addition, 3D motion analysis has identified that decreased knee flexion,[30] increased hip adduction,[31–33] and greater trunk instability[34–37] when landing from a jump are all related to abnormal loading at the knee and potentially increased ACL injury risk. Many of these specific factors identified in 3D models can be generalized in 2D motion analyses that are more cost-effective to the clinical environment. Relative presence of trunk instability,[38,39] knee valgus angle,[40] and knee flexion angle,[40] and knee excursion in the frontal plane[41] can be assessed in 2D capture. While not as precise as 3D analyses, these 2D generalizations have effectively been used to adapt biomechanical nommograms that identify athletes within an athletic cohort who are predisposed to ACL injury risk.[40–44]

As previously stated, the intent behind the identification of high-risk biomechanical behaviors and the athletes that display them is to treat and prevent ACL injuries before they occur. It has been repeatedly demonstrated that prophylactic neuromuscular interventions can have a positive influence on the reduction of ACL injuries within an athletic population.[18,45–50] Neuromuscular training (NMT) is effective in reducing the magnitude of knee abduction moments generated by athletes during the performance of athletic tasks.[51–54] As these frontal plane torques are directly associated with ACL injury,[26] it is likely that decreasing their magnitudes is in part responsible for the overall reduction in injury incidence following NMT. Furthermore, NMT has been demonstrated to have a greater biomechanical effect on high-injury risk athletic populations than medium- or low-risk cohorts.[52] Accordingly, the classification of athletes in injury risk levels and definition of the underlying mechanisms that lead to these levels of risk may be vital to maximize the future efficacy of ACL injury prevention.

In this clinical prediction commentary, we synthesize information related to how motion capture analyses contribute to the identification of risk factors that may predict relative injury risk within a population. We argue that an athlete's relative ACL injury risk is dependent on which systems of control an athlete can effectively employ to restrain the knee joint during athletic tasks. In the first section of this commentary, we define the systems of control available at the knee and identify differences in mechanical outcomes between effective and less effective systems. In the second section, we identify the divisions of relative ACL injury risk based on knee abduction moment and justify our stated arguments. In subsequent sections, we address how robust the classifications of injury risk may be and examine the effectiveness of incorporation of biofeedback techniques with motion capture analysis to reduce relative injury risk within an athlete and an athletic population.

Knee Joint Restraints

Motion at the knee is constrained by a series of active and passive restraints that work in conjunction to stabilize the articulating structures when forces and perturbations are applied during an athletic maneuver. Active restraints reference the musculature surrounding the joint and the neuromuscular control mechanisms used to activate this musculature, specifically, the proprioceptive, kinesthetic, visual, vestibular, and motor command systems.[55] With respect to the ACL, it has been hypothesized that ligament injury risk is related to measureable and modifiable deficits within these neuromuscular control mechanisms that influence muscle strength, power, and activation and, ultimately, knee joint and ACL loads.[26,56–58] Relative to muscle mechanics, quadriceps activation has traditionally been seen as antagonist to the ACL, adding strain, whereas, hamstrings activation has been agonist, providing protection.[59] Accordingly, a poor quadriceps-hamstrings activation ratio can lead to increased knee extension during landing and excess anterior tibial translation, both of which increase ACL strain.[60–62] This preferential activation of knee extensors over knee flexors to stabilize the knee during motion tasks is termed quad dominance.[63] Quadriceps-dominant traits can lead to lower flexion angles upon landing that indicate less time and movement to absorb the impulse forces generated from landing and lead to greater joint force generation as a result of this more extended position.[55,62,64] A second deficit within active knee restraints is leg dominance, where the imbalance between muscular strength and recruitment on opposing limbs lead to contralateral asymmetries.[63] Kinetic and kinematic analyses have shown this type of deficit to be especially prevalent in female athletes, as they demonstrate greater limb asymmetries, especially in regard to frontal plane kinematics, than their male counterparts.[57,65] Furthermore, motion analysis investigations have revealed that contralateral asymmetries are greater following ACLR; and therefore, may be related to the increased likelihood of secondary or contralateral ACL rupture that exists within the ACL-injured population following return to sport.[66] The common outcome brought on by the variety of neuromuscular control deficits documented here is that the active knee stabilizers are unable to restrain the joint from articulating into dynamic valgus rapid deceleration tasks, a trait that is able predict ACL injury risk with 78% sensitivity and 73% specificity.[26]

Passive knee restraints reference the ligaments, bony structures, and generalized laxity within the joint that contribute to the mechanical constraint of motion in the absence of a neuromuscular response. Excessive employment of the passive restraints in the knee can be related to insufficient control of the active restraints that results in a ligament dominant condition.[63,67] Ligament dominance refers to decreased medial/lateral muscle control that leads to high valgus torque and vertical ground reaction forces.[63,66,68,69] In this condition, the ground reaction forces dictate joint movement direction rather than the musculature and allow for substantial loading of the ligamentous structures within the knee.[63,67] In addition, increased knee laxity, especially in the anteroposterior degree of freedom, leads to increased tibial translation, which leads to additional loading of the knee ligaments as they mechanically work to resist this excess motion. Morphologic changes that can relate to ACL injury risk include tibial plateau slope[70] and femoral notch width.[71] As posterior tibial slope increases, the femur is more likely to slide posteriorly on the tibial plateau, which places mechanical demand on the ACL as the ligament resists up to 85% of anterior tibial translational force in the knee.[70,72,73] As the femoral notch width decreases, the likelihood of ACL impingement increases, which adds strain to the ligament.[74] Unlike active restraints, these passive knee restraints cannot be altered by intervention training and are thus referred to as nonmodifiable risk factors as changes require invasive surgical intervention.

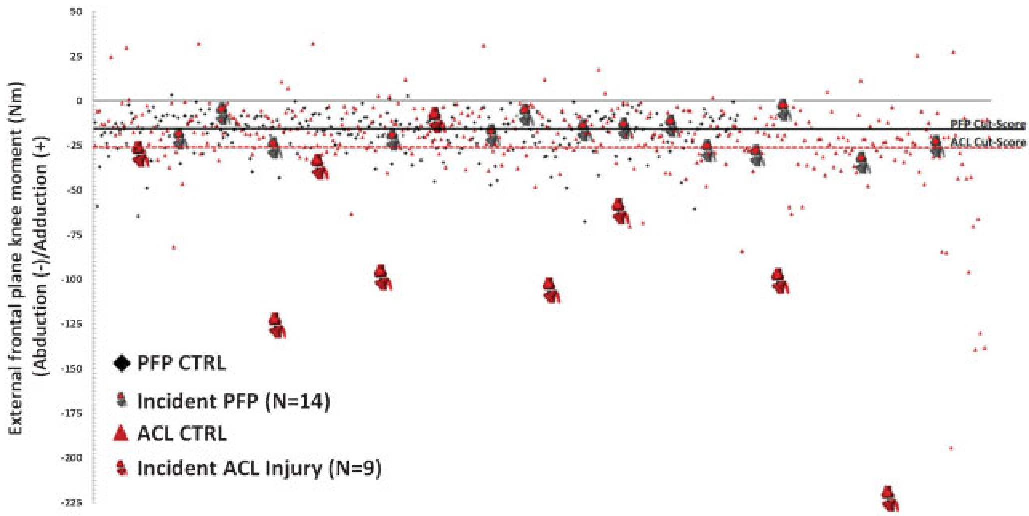

Fig. 2 Peak knee abduction moments generated by two prospectively analyzed cohorts of adolescent female athletes during a DVJ task. The first cohort (red) was used to determine the magnitude of knee abduction torque that would predict ACL injury risk,[26] while the second cohort (black) was used to determine the magnitude of knee abduction torque that would predict patellofemoral pain risk.[75,77,78] The horizontal lines designate relative injury risk divisions for the medium (solid line) and high (dashed line) risk groups. (Reprinted with permission from Myer et al[75]). ACL, anterior cruciate ligament; CTRL, Control; PFP, patellofemoral pain.

Relative Injury Risk

Traditionally, the relative level of ACL injury risk displayed by an athlete has been determined by the magnitude of knee abduction moment he or she generates during drop landing (►**Fig. 2**).[26,40] In a cohort of 205 female athletes who underwent 3D motion analysis and were prospectively monitored for subsequent ACL injury, it was discovered that those athletes who went on to injury exhibited greater knee abduction moments than did healthy controls.[26] The mean peak knee abduction torque for injury patients was 21.74 N*m. Within this population, it was later assessed that peak knee abduction moments above 25.3 N*m increased risk for subsequent ACL injury from 0.4 to 6.8%; thus, this was established as the cutoff threshold for the classification of high injury risk athletes.[75] Similarly, during 3D motion analysis of the same drop vertical jump task, a separate patient population with patellofemoral pain was found to generate greater peak knee abduction moments on their uninvolved limb than did healthy controls.[76] Within these two population cohorts that were examined separately for ACL injury and patellofemoral pain, the incidence of patellofemoral pain was found to be 2.2 times greater than ACL injury when normalized for athlete seasons.[75] This discrepancy in incidence indicated that a tertiary level of injury risk may be present. Indeed, a second investigation based on the same 3D motion analysis techniques that defined high injury risk athletes found that probability of patellofemoral pain occurrence increased dramatically in athletes with peak knee abduction moments greater than 15.4 N*m.[75,77] This threshold predicted knee abduction load associated with increased patellofemoral pain risk with 92% sensitivity and 74% specificity and, as such, was determined to represent a medium injury risk classification among athletes.[75,77]

As noted previously, the data from these 3D motion analyses were disseminated into algorithms that could predict both ACL injury[40–42,78] and patellofemoral pain.[77] The purpose of these 2D injury risk nommograms was to create clinically relevant tools that could quickly, accurately, and cost-efficiently categorize athletes into relative injury risk groups based on these peak knee abduction moment divisions. While 3D motion analysis is an effective laboratory tool, these systems are cost prohibitive and involve intensive data analysis, which makes them inaccessible to most clinical environments.[40,79] To this effect, the selected clinically based nomograms involve minimal investment (two video cameras and laptop),[40,79] can be quickly and reliably assessed by a trained clinician,[80] and exhibit high sensitivity and moderate specificity in the classification of relative risk for ACL injury (84 and 67%, respectively) or patellofemoral pain (92 and 46%, respectively).[77,81]

Despite having equivalent fall heights, 3D motion capture analysis of the first and second landings of a drop vertical jump (DVJ) has revealed several differences in kinetic and kinematic performance.[82] Because of these differences, the first landing may be more predisposed to exhibit larger frontal plane moments than the second. As such the two landing phases exhibit a potential shift in injury risk classification. A population of 239 adolescent female athletes underwent 3D motion analysis as they completed both the first and second landings of a DVJ, as was described previously in the literature.[82–84] Of these athletes, both landings were successfully captured on 206 subjects. Peak knee abduction moments calculated from the motion capture model were used to classify these athletes into relative injury risk groups as specified earlier. It was found that during the first landing 57.2% were classified as low ACL injury risk, 21.8% were medium risk, and 20.9% were high risk; while during the second landing 66.5% were low risk, 21.4% were medium risk, and 12.1% were high risk (►**Fig. 3**). This cohort of athletes was

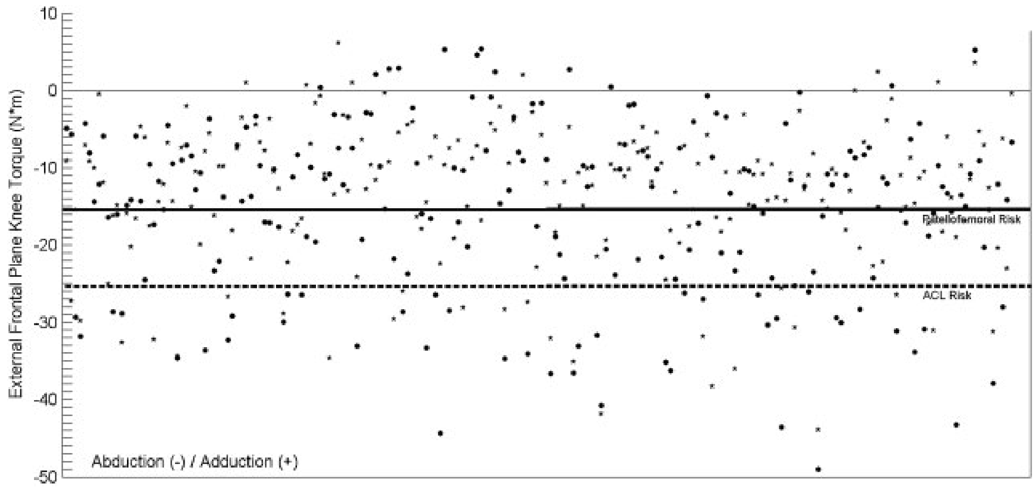

Fig. 3 Depiction of risk category divisions during the first (circles) and second (stars) landing of a DVJ within the 206 adolescent female athletes examined in this article. Peak abduction torques below the patellofemoral risk line designate the medium injury risk classification, while values below the anterior cruciate ligament risk line designate the high injury risk classification.

previously shown to generate a slightly larger mean peak frontal plane knee torque during the first landing of a drop vertical jump than during the second.[82] The frequency of high-risk classifications between landings presented here corresponded with that finding; however, the relative infrequency of high-risk kinetics during the second landing may indicate that it is more selective in diagnosis. Of the athletes who expressed high-risk knee abduction torque during the first landing, 37.2% continued to demonstrate torque magnitudes indicative of high-risk biomechanics during the second landing, while 30.2 and 32.6% exhibited medium and low risk, respectively (►**Fig. 4**). Conversely, 64.0% of athletes who exhibited "high-risk" torques in the second landing were also classified as high risk in the first landing. Kinematic and kinetic variability within the performance of an athletic task, as captured by motion analysis systems, has been previously documented.[80,85] For peak knee abduction moments within a session, the interclass correlation coefficient was 0.931, which represents excellent reliability and consistent results.[85] Accordingly, it would be expected that subjects would steadily demonstrate the same level of ACL injury risk when landing from a jump. However, the classification consistency of this data did not match the reported reliability. It is possible to generate high-risk knee abduction torques with poor control over either the dynamic or passive knee restraints, but perhaps athletes who consistently exhibit high-risk frontal plane torques between landings represent subjects who express poor control over both mechanisms of knee restraint.

The authors propose that athletes who continually express relatively high levels of injury risk during rapid deceleration tasks have poor control over both their active and passive mechanisms of knee restraint. Those athletes who express medium injury risk, or fluctuate between groups, may only express poor control over one set of knee restraints, either the active or passive systems. During the performance of athletic tasks, athletes generate large impulse forces at the knee that

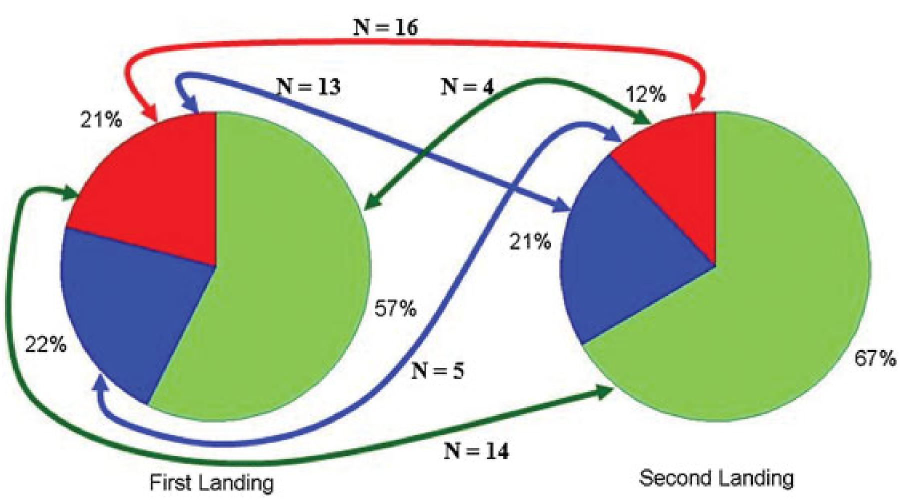

Fig. 4 Pie chart depiction of anterior cruciate ligament injury risk classifications for 206 adolescent female athletes during the first and second landing of a DVJ. Lines demonstrate the number of high-risk athletes that changed injury risk classifications between landings. Only 16 athletes (7.8%) were classified as high risk in both landings based on their peak knee abduction moment.

are primarily absorbed over time as the musculature flexes the joint through a range of motion.[30,55] When muscular strength or activation proves insufficient to properly flex the joint and restrain these impulse forces, the knee is forced into frontal and transverse plane rotations.[57,86] As the musculature at the knee primarily functions in the sagittal plane, such perturbations may require passive structures to restrain the joint from collapse.[57,86–88] Therefore, as relative injury risk levels are classified by peak knee abduction torque generated during landing,[26] athletes who exhibit high knee abduction torques during drop vertical jumps have, by definition, identified themselves to have poor neuromuscular control. This is because their musculature failed to constrain the resultant ground reaction forces within the sagittal plane of the knee.[57,86] However, not all athletes who express weak musculature or poor hamstrings to quadriceps strength ratios generate high knee abduction moments during landing.

The previously described 206 athletes who were successfully evaluated via 3D motion analysis during the first and second landing of a drop vertical jump were also assessed for hamstrings and quadriceps strength on a dynamometer using previously published methods.[89] Of 206 athletes, 117 were found to have poor hamstrings-to-quadriceps strength ratios (below 0.60 hamstrings-to-quadriceps peak strength at 300 degree/second)[90]; yet, within this subset, only 29 and 15 of these athletes generated knee abduction torques greater than 25.3 N*m in the first and second landing, respectively. Furthermore, as landing from a drop vertical jump generates ground reaction force magnitudes up to 4.5 $\times$ bodyweight,[84] if active knee restraints were the sole contributor to injury risk classification, athletes with the lowest peak strength to body mass ratio would be expected to almost entirely comprise the high injury risk group. However, of the 43 athletes classified as high risk in the first landing, only 17 came from athletes who were in the bottom half of strength to body mass ratios. This behavior indicated that well-developed passive restraints within the knee may be able to compensate for active restraint deficiencies. Furthermore, this implicated that consistent high-risk torque generation may require poor control in both active and passive knee restraint mechanisms. In addition to motion capture and strength measures, the same cohort of adolescent female athletes underwent arthrometry evaluations for joint laxity using previously published methods.[91] Again, increased knee laxity alone was not sufficient to predict knee injury risk as only 21 of 43 high-risk subjects exhibited relatively high knee laxity values (greater than 10.22 mm anterior translation under 134 N of anterior force as this was the mean laxity value reported in the contralateral limbs of patients with ACL injury).[87,88] Of the 206 subjects, 43 exhibited each poor hamstrings-to-quadriceps ratio, lower peak-strength-to-body-mass ratio, and high joint laxity.[91,92] Between both landings, 11 of 43 (25.6%) subjects in this subset also exhibited high knee abduction moments during landing. While, far from precise in their indication of risk, the presence of high peak knee abduction torques in these athletes with poor active and passive knee restraints was greater than it was in the overall cohort. These data support that underdeveloped passive restraints contribute to overall injury risk and that a consistent high injury risk classification may be indicative of poor coordination over both systems of knee stabilization.

Neuromuscular Interventions

Prophylactic neuromuscular interventions have been shown to effectively reduce ACL injury incidence over time through successful alteration of negative biomechanical tendencies that contribute to injury risk.[18,45–50] Specifically, a review of interventions discovered that NMT produces a relative risk reduction of 73.4% for noncontact ACL injury in female athletes and that these interventions prevent approximately one injury per every 108 individuals that participate in training.[47] It was also found that those neuromuscular interventions that incorporated multiple types of training, each strengthening, plyometric, and balance exercises, were more effective in the reduction of injury rates than interventions focused on a single training type.[47] An additional mechanism investigators have recently begun to incorporate into intervention training is biofeedback. Biofeedback utilizes motion analysis techniques to assess deficiencies in dynamic task performance and immediately reinforces them with visual or audible cues that indicate directly to the patient how he or she might optimize movement patterns. In clinical settings, biofeedback has primarily been used to treat gait abnormalities in both pediatric and adult populations.[93] Furthermore, investigation has found that biofeedback can instantly reduce relative injury risk for those athletes that exhibit high-risk mechanics.[52] Motion analysis investigations have demonstrated that feedback will correct for pain and deficits in gait with moderate-to-large treatment effect on adult patients.[93] During jump landing, feedback has been shown to effectively reduce jump landing forces,[94] reduce trunk sway,[95] and reduce knee hyperextension.[96] Furthermore, real-time kinetic-focused biofeedback implemented in conjunction with 3D motion analysis during a squat activity has been found to immediately reduce peak knee abduction moment during a drop vertical jump, the primary indicator of ACL injury risk, by 32.8% in adolescent female athletes.[97] As previously noted, increased magnitudes of each of these factors has been associated with ACL injury risk; therefore, reduction through biofeedback exemplifies the potential of this tool to further limit the incidence of ACL rupture. Future implementations of biofeedback could be applied in conjunction with the previously documented injury risk nomograms based on 2D motion analysis as a clinically relevant mechanism for the diagnosis and immediate initiation of corrective treatment for athletes who exhibit high-risk tendencies.

Summary

Motion-capture analyses have made significant contributions to the identification of factors that contribute to ACL injury risk. The classification of relative injury risk via 2D and 3D motion analysis techniques plays an essential role for both researchers and clinicians who wish to intervene and prevent ACL in athletic populations. There is strong evidence to indicate that athletes who consistently classify as high-risk loaders during landing suffer from combined joint stability deficits in both their active and passive restraints at the knee joint. Implementation of prophylactic neuromuscular interventions has been shown to effectively compensate for some of the deficiencies that results from poor control of the active knee stabilizers and, in turn, reduce the incidence of ACL injuries. With continued development of these interventions, such as through the incorporation of motion analysis–based biofeedback, researchers, and clinicians can continue to improve the efficacy of ACL injury prevention initiatives.

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