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REVIEW ARTICLE

Biomechanical and Neuromuscular Characteristics of Male Athletes: Implications for the Development of Anterior Cruciate Ligament Injury Prevention Programs

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Abstract Prevention of anterior cruciate ligament (ACL) injury is likely the most effective strategy to reduce undesired health consequences including reconstruction surgery, long-term rehabilitation, and premature osteoarthritis occurrence. A thorough understanding of mechanisms and risk factors of ACL injury is crucial to develop effective prevention programs, especially for biomechanical and neuromuscular modifiable risk factors. Historically, the available evidence regarding ACL risk factors has mainly involved female athletes or has compared male and female athletes without an intragroup comparison for male athletes. Therefore, the principal purpose of this article was to review existing evidence regarding the investigation of biomechanical and neuromuscular characteristics that may imply aberrant knee kinematics and kinetics that would place the male athlete at risk of ACL injury. Biomechanical evidence related to knee kinematics and kinetics was reviewed by different planes (sagittal and frontal/coronal), tasks (single-leg landing and cutting), situation (anticipated and unanticipated), foot positioning, playing surface, and fatigued status. Neuromuscular evidence potentially related to ACL injury was reviewed. Recommendations for prevention programs for ACL injuries in male athletes were developed based on the synthesis of the biomechanical and neuromuscular characteristics. The recommendations suggest performing exercises with multi-plane biomechanical components including single-leg maneuvers in dynamic movements, reaction to and decision making in unexpected situations, appropriate foot positioning, and consideration of playing surface condition, as well as enhancing neuromuscular aspects such as fatigue, proprioception, muscle activation, and inter-joint coordination.

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Key Points

Research evidence indicates that specific biomechanical and neuromuscular characteristics may underlie increased risk of anterior cruciate ligament injury in male athletes

In male athletes, differences in lower extremity biomechanics are observed for anticipated versus unanticipated tasks, and these differences are influenced by foot positioning, playing surfaces, and fatigue status

Neuromuscular status including fatigue, proprioception, muscle activation, and inter-joint coordination contribute to different lower extremity biomechanics

1 Introduction

Anterior cruciate ligament (ACL) injury is one of the most frequent and severe injuries in sports with significant undesirable mid- and long-term health-related consequences [44, 49, 60, 61]. In addition, the economic costs for healthcare systems are substantial [64] and the risk of knee osteoarthritis increases in ACL deficiency and reconstructed individuals [24, 60]. Therefore, the development of a prevention program designed to target ACL injury reduction is likely to be a feasible approach for individuals participating in sport. A thorough understanding of injury mechanisms and risk factors is a crucial step towards the development of effective prevention programs. Risk factors for ACL injury have been examined in terms of environmental [72–74, 100], anatomical [71, 81, 88, 89], hormonal [9, 84, 102], genetic [37, 79, 86], and biomechanical/neuromuscular components [47, 48, 70, 108, 109]. However, environmental, anatomical, hormonal, and genetic risk factors are considered non-modifiable from a practical standpoint. Conversely, modifiable risk factors are those that are considered to be subject to change or influence by a human intervention. Thus, the modifiable ACL injury risk factors are variables mainly associated with biomechanics and neuromuscular aspects. Unfortunately, while the investigation of biomechanical and neuromuscular risk factors for ACL injuries has been the scope of numerous studies within the last two decades, available evidence has mainly involved female athletes or has compared male and female athletes without an intra-group comparison for male athletes [3, 4, 22, 23, 45, 78, 82]. Comparing male athletes as "control" subjects to female athletes does not provide adequate evidence to investigate risk factors for ACL injury in male athletes [17, 19, 48].

Recent studies that systematically reviewed ACL injury in male athletes concluded that there is limited evidence in terms of biomechanical and neuromuscular risk factors and prevention programs for ACL injury in the male athletes [3, 4]. Only five studies were found to investigate these risk factors in the male population [43, 83, 95, 108, 109], and only three of them were prospective cohort studies [95, 108, 109]. There are studies investigating biomechanical and/or neuromuscular characteristics in male athletes, but most of them do not claim to assess these characteristics as risk factors for ACL injuries, but to show the kinematics and kinetics of the lower extremity of male athletes while performing sports actions. Some studies have evaluated biomechanical and/or neuromuscular characteristics and associated them with knee laxity or strain on the ACL [35, 36, 68, 77]. Other studies have applied training programs aimed to modify biomechanical and neuromuscular characteristics in male athletes, but have not evaluated the modification of ACL injury rates [10, 20, 26, 29, 53]. Except for the very few studies investigating biomechanical and neuromuscular risk factors for ACL injuries in male athletes [43, 83, 95, 108, 109], the remaining biomechanical and neuromuscular studies for male athletes did not compare these characteristics between ACL-injured and ACL-intact male athletes, thus no conclusions can be made concerning risk factors for an ACL injury. An adequate understanding of the existing evidence for both factors may help generate ideas for future research in this field and elaborate prevention programs in the male population.

The purpose of this project was to review the existing evidence regarding the investigation of biomechanical and neuromuscular characteristics that may imply aberrant knee kinematics and kinetics that would place the male athlete at risk of ACL injury.

2 Methodological Aspects

2.1 Literature Search

A literature search was performed using the PubMed (MEDLINE), EMBASE, and Cochrane library databases from 1980 to September 2012. Then, an updated literature search was executed using the PubMed and EMBASE databases until September 2014. Free terms (title, and abstract for PubMed; and title, abstract and keywords for EMBASE) and MeSH terms (for PubMed and Cochrane) were used. A combination of the following words was used: [(neuromuscular OR control OR coordination OR anticipated OR unanticipated OR surface OR activation OR muscle OR muscular OR muscles OR fatigue OR maneuver OR maneuvers OR action OR actions OR landing OR land OR position OR positioning OR cutting OR cut OR jumping OR jump OR running OR run OR kinematics OR kinematic OR kinetics OR kinetic OR biomechanical OR biomechanics OR biomechanic OR sagittal OR coronal OR axial) AND (anterior cruciate ligament OR ACL OR injury OR injuries OR prevention OR sports OR sport OR athlete OR athletes OR players OR player)]. In addition, the output of the literature search employed in a previous systematic review (involving 1,827 references) was also scrutinized after duplicates were identified [3, 4]. Furthermore, a manual search was performed in the reference list of reviewed studies. The search was limited to human studies written in English.

2.2 Inclusion Criteria

All original studies related to any biomechanical and neuromuscular characteristic in male athletes, whether or not directly related to ACL injury, were included for the current review. Studies involving female athletes were only included in the present article if a specific intra-group comparison for male athletes was reported. Review articles were included to help avoid the omission of any reference and assure a good overall picture of each of the areas covered. Furthermore, studies dealing with women athletes, editorial letters, case reports, comments, abstracts, posters, and unpublished data were excluded.

2.3 Data Extraction and Synthesis

Basic information on the type of study, type of sport/activity involved (sport, level of sport, whether training or games), type of subjects involved (ACL injured, healthy athletes, non-athletes), type of comparison (i.e., injured vs healthy), outcomes collected, results, and conclusions were extracted from each reviewed study. The information extracted from all the studies was then divided into biomechanical and neuromuscular evidence. The information on each section was then summarized according to several subcategories. The subcategories of biomechanical evidence were: plane of study (sagittal and frontal), type of movement (single-leg landing and cutting), type of activity (game vs practice, anticipated vs unanticipated), foot positioning in dynamic motion, biomechanical effects of playing surface, and biomechanical effects of fatigue. The subcategories of neuromuscular evidence were: trained vs untrained, muscle action, inter-joint muscular coordination, and prophylactic bracing/taping. The most important findings depending on the type of sport were also summarized in Table 1.

3 Results

3.1 Biomechanical Evidence

The number of references related to biomechanical aspects potentially related to ACL injury in male athletes was considerable. For this reason, information on biomechanical aspects was classified under several subcategories based on the principal purpose of the study. The investigation of biomechanical characteristics in male athletes can be first classified into joint kinetics and kinematics. There is more information available for the causes of movement rather than the movement itself. In this section, the most commonly investigated joint is the knee. The sports involved include soccer, basketball, hockey, American Football, Australian Rules Football, and rugby. Table 1 summarizes the available evidence with regard to biomechanical characteristics related to knee mechanics in male athletes.

3.1.1 Biomechanics: Sagittal Plane

The ACL is obliquely tilted approximately at $26.6 \pm 6°$ vertically and runs from the posterior part of the medial side of the lateral condyle to the anterior intercondylar area between a transverse meniscal ligament and medial side of medial meniscus [75]. The ACL consists of three functional bundles: antero-medial bundle (AMB), intermediate bundle, and postero-lateral bundle (PLB) [7, 31–33, 90]. In knee flexion motion, the AMB tightens, and the PLB loosens [107]. In knee extension motion, the AMB moderately loosens, and PLB is tight [107]. However, both AMB and PLB elongate in the final 30° of knee extension [7]. Utturkar et al. [99] found that the ACL length of healthy male athletes shortened from extension to 30° of knee flexion to knee valgus collapse; therefore, the authors concluded that landing with an extended knee would be a more significant risk factor for ACL rupture than knee valgus collapse owing to greater elongation of the ACL.

To find an association between ACL elongation and knee flexion and extension mechanism, Ali et al. [5] evaluated the effects of varying height and horizontal distance on landing kinematic and kinetics in young male recreational athletes. The authors found that increased vertical height produced higher knee flexion angle, trunk flexion angle, and knee power and work at landing [5]. Additionally, the authors observed that an increase in vertical height produced a significant increase in peak vertical and posterior ground reaction force (GRF). The increase in horizontal height produced an increase in posterior GRF, ankle plantar flexion, hip flexion angle, and trunk flexion angle. At increasing vertical height, the authors found a positive correlation with peak posterior GRF. At increasing horizontal height, the authors found a

Table 1 Summary of biomechanical and neuromuscular evidence potentially related to aberrant knee mechanics in male athletes

Sport	Findings
Joint kinetics	
Soccer	Cutting maneuvers higher varus-valgus and internal-external knee moments than running (no differences in flexion-extension knee moments) [13]
	Side-step cutting elicited knee flexion, valgus, and IR loads, and crossover cutting elicits knee flexion, varus, and ER loads [13]
	Cutting maneuvers elicited higher foot loading in the medial aspect, and sprinting higher loading in the first and second ray [34]
Basketball	During side-step cutting, higher peak stance knee valgus moment was associated with higher initial contact hip flexion and IR, and knee valgus position [66]
Soccer and basketball	No longitudinal changes in peak knee abduction moments at landing in pubertal and post-pubertal athletes [40]
Basketball and hockey	Players wearing knee braces landed with lower peak vertical GRF compared with subjects without knee brace [80]
American football	Artificial turf higher peak pressures within central forefoot and lesser toes than natural grass, but the latter higher relative load within medial forefoot and lateral mid- foot [38]
Australian football	Ankle taping reduced knee IR and varus moments during running and side-step cutting in planned and unplanned situations [87]
Combination	Foot wide and torso towards the opposite direction of the side-step cut (technique modification) increased knee valgus and IR moment [27]
	Foot internally rotated during side-step cutting elicited lower flexion/extension moments compared with foot wide technique [27]
	Increased knee valgus at landing if the ball to catch is moving towards the preferred landing leg [25]
	Landing with foot and knee ER, hip abduction and IR, and lateral flexion of the trunk is associated with higher knee valgus and IR loads [25]
	Single-leg landing or increasing landing height produced higher peak GRF [5, 105]
	Increasing landing height produced greater knee power and work [5]
	In single-leg landing, hip and ankle were the main energy dissipaters in sagittal plane, and knee the main energy dissipater in the frontal plane [106]
	In double-leg landing, hip and knee were the main energy dissipaters in sagittal plane, and hip the main energy dissipater in the frontal plane [106]
	In the frontal plane, single-leg landing had greater knee range of motion, moment, and energy dissipation compared with double-leg landing [106]
	Peak vertical and posterior GRF increased with greater vertical height at landing. The peak posterior GRF also increased with greater horizontal distance at landing [5]
Joint kinematics	
Soccer and rugby	Side-step cutting produced larger maximum knee flexion, abduction, and external rotation during foot contact compared with straight running [67]
Soccer and basketball	No longitudinal changes in peak knee abduction angles at landing in pubertal and post-pubertal athletes [40]
Combination	Side-step cutting produced some degree of tibial IR during the stance phase, but likely submaximal compared with swing phase with knee flexion [21]
	Male athletes from pivoting sports had less knee IR during maximal muscle activation than male athletes from non-pivoting sports [103]
	Increasing knee flexion angle at landing elicited greater peak knee extensor moment, and lower peak vertical and posterior GRF and H moments [76]
	Anterior-sloped knee brace decreased knee range of motion and angular velocity compared with unbraced conditions but had no effect on peak vertical and anterior GRF [104]
	Single-leg landing elicited greater frontal plane knee range of motion compared with double-leg landing [106]
	Peak anterior tibial translation occurred early in the landing phase [92]
	The anterior tibial translation was positively correlated with knee valgus angle, and lateral tibial translation with knee flexion and IR angles, at landing [92]
	Increasing vertical height at landing produced increased knee flexion angle and trunk flexion angle [5]
	Increasing horizontal distance at landing produced increased ankle plantar flexion angle, hip flexion angle, and trunk flexion angle [5]
	Peak vertical GRF was negatively correlated with ankle plantar flexion and knee flexion angles at increasing vertical heights at landing [5]
	Peak posterior GRF was negatively correlated with ankle plantar flexion angles at increasing horizontal distance at landing [5]
Inter-joint coordination	
NR	Chronic ACL-deficient subjects have different inter-joint coordination than controls [85]

Table 1 continued

Sport	Findings
Proprioception	
Soccer	Soccer players demonstrated better knee rotatory proprioception than controls [69]
Muscle strength and activation	
Lifters	Squat greater Q and H co-contraction and more posteriorly directed tibial forces than leg press [36]
Soccer	Players showed higher knee extensor and flexor peak torque and H/Q ratio than controls35
	Selective lower extremity muscle activation patterns in anticipated conditions but not in unanticipated conditions [11]
	Post-pubertal boys demonstrated greater Q and H strength than pubertal or pre-pubertal boys [2]
	Greater lateral vs medial H activation for run and side-cut (lower for crosscut) [57, 58]
	Isometric knee rotatory strength greater in soccer players compared with controls [69]
Basketball	Post-pubertal boys had greater Q strength than pubertal or pre-pubertal boys [15]
Soccer and basketball	Ankle, knee, and hip stiffness, and external knee flexion moment increased with maturation [39]
	Hip abduction torque increased with age in both dominant and non-dominant sides [14]
Runners	No differences in peak knee flexor and extensor torque and H/Q ratio with knee laxity [77]
Combination	Pivoting sports had greater joint stiffness with muscle contraction and larger knee flexor and extensor peak torque compared with non-pivoting sports [103]
	Decreased muscle co-contraction with increasing degrees of knee flexion at landing [76]
	In pre-landing phase, rectus abdominis, external oblique, and medial gastrocnemius were highly activated [51]
	Activity of vastus medialis and gluteus maximus before ground contact from landing correlated positively with peak vertical GRF in absorption phase [51]
	In landing tasks, at ground contact hip and knee were flexed and ankle was plantar flexed [51]
	In landing, after ground contact peak timings of muscle activities and lower limb joint rotations followed a distal-to-proximal sequential pattern [51]
	At peak GRF of single-leg landing, soleus exerted a posterior force on the tibia in conjunction with H, whereas this effect was not observed in the gastrocnemius [68]
Anticipated compared with unanticipated conditions	
Soccer	Unanticipated side step and crossover performed with more varus-valgus and internal-external knee moments than anticipated tasks, with no differences for flexion-extension knee moments [12]
	Unplanned side step performed with low hip external rotation, high hip abduction, and high peak knee valgus moment compared with planned conditions [59]
Combination	Unplanned drop jump at initial contact with lower hip and knee flexion, knee abduction, and higher ankle plantar flexion angles compared with planned conditions [63]
	Unplanned drop landing at initial contact with lower hip abduction and higher ankle plantar flexion angles compared with planned conditions [63]
	Unplanned drop jump during landing with lower knee abduction and ankle inversion, and higher knee external rotation and ankle dorsiflexion angles than planned [63]
	Unplanned drop landing during landing with lower hip adduction and knee internal rotation and higher knee external rotation and ankle dorsiflexion and eversion angles than planned [63]
	Unplanned drop jump during landing with lower knee extension, knee external rotation, and ankle plantar flexion, and higher hip adduction moments than planned [63]
	Unplanned drop landing during landing with lower hip extension, hip adduction, and knee extension moments compared with planned conditions [63]
Muscular fatigue	
American football	Players had better muscle endurance in knee flexors and extensors compared with controls [50]
Combination	Fatigue produced increased peak proximal tibia anterior shear force and valgus moments, and decreased knee flexion angles during landing of the stop-jump task [18]
	Fatigue produced greater knee abduction and internal rotation displacement and moments during the stance phase of jump landing tasks [65]
	Fatigue produced increased hip flexion, knee flexion, ankle dorsiflexion angles, and ankle dorsiflexion moment, and decreased hip compression, anterior shear force, and hip extensor moments, and decreased peak knee compression, knee extensor moment, knee valgus moment, and shear forces during landing [54]
NR	Fatigue caused no effects on reflex responses of Q and H and anterior tibial translation [8]

ACL anterior cruciate ligament, *ER* external rotation, *GRF* ground reaction forces, *H* hamstrings, *IR* internal rotation, *NR* not reported, *Q* quadriceps positive correlation with peak vertical GRF, and knee power and work, and a negative correlation with ankle plantar flexion. These results suggest that sports with higher and longer jumps may have greater risk of ACL injury.

The effects of knee flexion angle on muscle co-contraction in lower extremity muscles during a deceleration phase of landing was quantified in another study [76]. This study reported that the lower extremity muscle co-contraction significantly differs with different knee flexion angles during landing. More precisely, increasing the knee flexion angle at landing elicited a lower peak vertical and peak posterior shear GRF. In contrast, landing with greater knee flexion angle induced greater peak quadriceps moments, and the hamstring moments decreased [76]. These findings suggest that the ability of muscles to act as dynamic stabilizers changes with joint position. In short, landing with an extended knee may increase the risk of non-contact ACL injury because increased GRF and quadriceps moments may promote knee extension mechanism, which elongates the ACL.

3.1.2 Biomechanics: Frontal/Coronal Plane

To further understand ACL injury risk, knee abduction moments and landing mechanics of pubertal and post-pubertal female and male basketball and soccer players were compared [40]. Although increased knee abduction moment was observed in post-pubertal female athletes compared with pubertal female athletes, no change in peak knee abduction moments was noted in either pubertal or post-pubertal male athletes during drop-jump maneuver. One study evaluated the effects of maturation on stiffness, kinematics, and kinetics of ankle, knee, and hip joints by examining pubertal and post-pubertal male and female basketball and soccer players [39]. Unlike female athletes, male athletes demonstrated increased stiffness in ankle, knee, and hip joints with maturation. Authors of this study discussed that joint stiffness and biomechanical changes may be related to hormonal and neuromuscular changes during growth spurt differences between sexes [39].

To examine the effect of sex on neuromuscular development during maturation, a relationship between sex and maturation through isokinetic hip abductor strength in adolescent soccer and basketball players was investigated [14]. The researchers found that, in male athletes, hip abductor torque increased with age; however, this was not observed in female athletes. This study highlights the potential association of hip strength and ACL injury. Other studies report an association between decreased hip abductor strength and increased knee valgus/abductor angles [28, 46]. The knee valgus/abductor moment was considered as the most sensitive and specific risk factor for the female population [47]. To examine the connection between knee frontal and sagittal planes, knee kinematics during drop landing in male recreational athletes was assessed [92]. This study reported that knee valgus angles are directly associated with anterior and lateral tibial translations as well as knee internal rotation angles in male athletes at landing. In addition, the study found that the peak anterior tibial translation occurred within 50 ms of initial ground contact at landing. This study suggests how knee kinematics may be interrelated and potentially important contributors to ACL injury risk; specifically, increased knee valgus could contribute to increased risk in male athletes.

3.1.3 Biomechanics: Single-Leg Landing Movement

Because many athletic movements such as kicking a soccer ball occur with a single leg, knee joint kinematics and energetics in response to different landing techniques was assessed in 10 healthy male recreational athletes [105]. Landing with both legs would be more protective against a non-contact ACL injury because of a better energy dissipation mechanism, compared with higher peak GRF during single-leg landing. The same research group published an investigation on the lower extremity energy dissipation strategies during landing with one or two legs based on sagittal and frontal plane knee kinematics and kinetics [106]. Ten healthy male recreational athletes performed a single-leg or double-leg landing task from a height of 60 cm. The authors found that the hip and knee dissipated major energy during double-leg landing and the hip and ankle during a single-leg landing in the sagittal plane. In this plane, the hip and ankle were the major energy dissipaters in the single-leg landing. In the frontal plane, the hip and knee acted as the primary energy dissipaters during double-leg and single-leg landing, respectively. The knee also exhibited a greater frontal plane knee range of motion, moment, and energy dissipation in the single-leg landing compared with double-leg landing. These results point towards the same suggestion; single-leg landing may be more harmful for the knee compared with double-leg landing, and different muscle groups play a role in absorbing energy based on different planes.

3.1.4 Biomechanics: Cutting Movement

Cutting is another commonly performed maneuver in athletic events. A few studies focused on analyzing cutting mechanics in relation to ACL. A cross-sectional study with 10 healthy male soccer players to assess the external knee loads in running compared with cutting maneuvers found no differences with regard to flexion-extension knee moments across tasks, but varus-valgus and internal-external knee moments were significantly higher in cutting compared with running [13]. More precisely, a side-step cutting maneuver elicited loads of flexion, valgus, and internal rotation [13]. Additionally, Cross et al. [21] analyzed the side-step cutting maneuver of young male athletes to evaluate what stress was placed on the ACL. The mean (standard deviation) total tibial rotation was 19.8° (5.6°) during the side-step cutting. The authors concluded that although internal tibial rotation did occur at the knee, it was not maximal as greater values would occur during the swing phase in association with a greater knee flexion angle [21]. This movement would not, therefore, place the ACL at a greater risk of rupture in male athletes. They hypothesized that if the ACL ruptures during this action, it may be related to an inability to control for internal tibial rotation of the knee [21].

Male athletes participating in pivoting sports appeared to have significantly less induced internal rotation during maximal muscle activation (4.4° at 30° of knee flexion) than participants in non-pivoting sports (7.3° at 30° of knee flexion) [103]. Together with the reduced internal rotation, male athletes who engaged in pivoting sports demonstrated greater muscle activation and knee joint stiffness. This may demonstrate differences among sports on how muscles function as protective stabilizers to possibly prevent ligament injuries.

McLean et al. [66] also conducted a biomechanical study examining the relationship between lower extremity postures and peak knee valgus/abduction moment at impact during a side-step cutting task in male and female basketball players. Male players demonstrated that higher normalized (weight by height) peak stance phase knee valgus moment was associated with higher initial contact hip flexion, hip internal rotation, and knee valgus positions during side-step cutting maneuvers. Assuming that increased knee valgus loading is a risk factor for ACL injury in male athletes as well, the interesting aspect and practical implication of the findings by McLean et al. [66] is that neuromuscular control of the hip joint should also be considered in ACL injury prevention programs in addition to the knee joint.

Another study that examined knee kinematics during side-step cutting maneuvers using male rugby and soccer players found that side-step cutting induced significantly larger maximum knee flexion, abduction, and external rotation values during foot contact compared with straight running [67]. This study concluded that the kinematic differences for side-step cutting compared with running were not of sufficient magnitude to alone elicit a non-contact ACL injury. As noted by the authors, these findings may be in line with those reviewed above reported by Cross et al. [21] From a theoretical point of view, the risk of non-contact ACL injury may be increased while actions are performed with greater knee abduction [67]; thus, care must be taken when training athletes in side-step cutting so that subjects at greater risk are identified and technique modification is implemented.

3.1.5 Injury Rate in Game vs Practice Conditions

In reviewing epidemiological studies, athletic injury rates are higher in game situations compared with practices [1, 101]. More specifically, the injury rate ratio of college men's soccer players was approximately four times greater in game situations compared with practices (18.8 vs 4.3 injuries per 1,000 athlete exposures) [1, 49]. During a game situation, nearly 30 % of the injuries occurred around or in the knee joint, which was recorded as the most frequently injured body part. In addition, approximately 35 % of all ACL injury during a game were non-contact in nature [1]. These epidemiological data suggest factors associated with "game"-like situations may attribute ACL injury in the male population. Thus, various aspects of game-like situations such as unanticipated movement patterns need to be examined.

3.1.6 Knee Kinematics in Anticipated vs Unanticipated Situations

Based on the conclusion that injury rates in game situations are nearly four times higher relative to practice injury rates, and that over one-third of ACL injuries occurs with a non-contact mechanism, decision making may play an important role in the risk of non-contact ACL injury in male athletes. A recent study performed by Mache et al. [63] compared landing kinetics and kinematics between anticipated and unanticipated conditions. In this study, anticipated condition at initial contact produced lower hip and knee flexion, lower knee abduction and higher ankle plantar flexion in the drop jump, and lower hip abduction and higher ankle plantar flexion in drop landing compared with preplanned condition. Peak joint angles during landing in decision-making conditions were lower for knee abduction and ankle inversion, and higher for knee external rotation and ankle dorsiflexion in the drop jump, and lower for hip adduction and knee internal rotation, and higher for knee external rotation and ankle dorsiflexion and eversion for drop landing, compared with preplanned conditions. Peak joint moments during landing in decision-making conditions were lower for knee extension, knee external rotation, and ankle plantar flexion, and higher for hip adduction in the drop jump, and lower for hip extension, hip adduction, and knee extension for drop landing, compared with preplanned conditions. Thus, prevention programs should incorporate unanticipated conditions.

Knee kinematics and kinetics during anticipated and unanticipated side-step maneuvers in male soccer players were also compared between anticipated and unanticipated situations [59]. This study noted that male soccer players elicited smaller hip external rotation at the initial foot contact during anticipated conditions compared with unanticipated conditions. Additionally, the unanticipated conditions produced a peak knee valgus/abduction moment 70 and 25 % greater compared with anticipated conditions. Furthermore, the knee valgus/abduction moments were even greater in low skill level players compared with high skill level players in more complex unanticipated conditions. Additionally, a recent study also reported an 80 % greater peak valgus knee moment in unanticipated side stepping activities compared with anticipated side stepping movements [30].

The knee kinematic differences between anticipated and unanticipated conditions were also investigated by Besier et al. [11] who assessed the muscle activation strategies during running and cutting maneuvers in young healthy male soccer players. Under the anticipated condition, muscular activation was specific and selective to stabilize lower extremity joints. However, unlike the anticipated condition, the muscular contraction was no longer selective under the unanticipated condition. Instead, the muscular contraction was generalized during the unanticipated condition. Another study performed by the same authors documented increased varus-valgus and internal-external knee moments in unanticipated side-step and crossover tasks compared with the anticipated conditions [12]. The increased frontal/coronal and horizontal plane torques may increase the potential for non-contact ACL injuries during unanticipated movements. The authors attributed these results to the small amount of time to make appropriate postural adjustments before performance of the task, such as the position of the foot on the ground relative to the body center of mass. Reviewed studies reported increased knee joint kinematics under unanticipated conditions compared with anticipated conditions.

3.1.7 Foot Positioning in Dynamic Motion

The effects of foot positioning technique on knee loads during side-step cutting was assessed using healthy male athletes [27]. This study reported that imposed techniques consisting of foot placement away from midline and lateral trunk flexion opposite to the cutting direction resulted in increased peak knee valgus moments in the weight-acceptance phase [27]. Higher peak knee internal rotation moments were also found in the same maneuver (foot placement away from midline and lateral trunk flexion in opposite to the cutting direction) [27]. When the technique of side-step cutting was performed with the foot internally rotated, there were lower mean flexion-extension moments, whereas the wide foot condition resulted in higher mean flexion-extension moments of the knee joint. Thus, foot rotation in either direction can influence ACL loading.

More recently, Dempsey et al. [25] investigated both kinematics and kinetics of the hip, knee, and ankle joints in male team athletes performing overhead catch and landing tasks. The interesting aspect of this study was the demonstration of the differences in knee kinetics depending on the type of catch before landing. If the ball moves towards the preferred landing leg, knee valgus moments are increased during landing. They also found that landing with the foot and knee in external rotation, hip abduction and internal rotation, and trunk lateral flexion were associated with both higher knee valgus and internal rotation loads. Thus, these loads and postures during landing were suggested to increase the risk of non-contact ACL injuries.

3.1.8 Effect of Playing Surface

To effectively position foot during dynamic movements, the influence of surfaces needs to be examined. A total of 11 studies were found to investigate the effects of playing surfaces on the risk of ACL injury in male athletes [3]. The findings of these studies suggest that artificial turf increases the risk of ACL injury in male athletes compared with natural grass [3], which is more prevalent in American Football. To investigate the effect of playing surfaces, Ford et al. [38] recruited a sample of male football players and compared the effects of natural grass and new generation turf. The authors found that turf surface had higher peak pressures within the central forefoot and lesser toes compared with natural grass, but the latter had higher relative load within the medial forefoot and lateral mid-foot compared with the turf surface. The higher peak pressure on turf likely generates greater GRF and contributes to risk of ACL injury.

An association between playing surfaces and foot loading patterns was investigated using different types of maneuvers [34]. In a controlled laboratory study where in-shoe pressure measurements were obtained, a total of 21 male soccer players performed normal runs, cutting maneuvers, sprints, and goal shots on both grass and red cinder surfaces. The authors found no effect of playing surfaces on foot loading, but higher foot loading was observed in the medial part of the foot for cutting maneuvers, in the first and second metatarsals for sprinting, and in the lateral part of the foot for kicking action.

3.1.9 Effect of Fatigue

A few studies focused on investigating the effect of fatigue on knee mechanics. To study the effects of fatigue on knee kinetics and kinematics, a set of exercises that induce a volitional exhaustion was administrated, and subsequently, stop-jump tasks was performed by male and female recreational athletes [18]. In this study, the authors reported that male athletes had significantly increased peak proximal tibial anterior shear forces, increased valgus moments, and decreased knee flexion angles during landing of stop-jump tasks when fatigued [18]. However, fatigue did not show similar effects on the peak knee extension moment in male athletes.

McLean et al. [65] conducted a study that examined the effects of muscular fatigue on lower extremity kinematics and kinetics during landing in male and female athletes. Fatigue condition was induced by a 4-min step-up maneuver and measured by heart rate. In male athletes, no significant fatigue differences were found between pre- and post-fatigue conditions for contact time (stance phase) during jump landing in either the dominant or non-dominant lower extremity. However, male athletes had greater knee abduction and internal rotation displacement in fatigue conditions compared with non-fatigue conditions during the stance phase of jump landing tasks.

Lower extremity landing mechanics caused by neuromuscular fatigue was examined among male athletes who play recreational soccer, tennis, basketball, and volleyball [54]. This study found that neuromuscular fatigue was related to in the male sample an increased in maximum hip flexion, maximum knee flexion, and maximum ankle dorsiflexion angles during landing. Fatigue caused male athletes to land with less hip compression, anterior hip shear force, and lower peak knee compression and shear forces. Regarding joint kinetics, neuromuscular fatigue caused male athletes to land with less hip and knee extensor moment and peak knee adduction/valgus moment, but more peak ankle dorsiflexion moment. Therefore, neuromuscular fatigue may cause kinematic and kinetic changes that may be related to risk factors for ACL injury.

3.2 Neuromuscular Evidence

The investigation of neuromuscular characteristics in male athletes consisted of training status, inter-joint coordination, proprioception, muscle strength and activation, anticipation vs unanticipated actions, and muscular fatigue. Most evidence refers to muscle strength and activation, and muscular fatigue, and the sports involved include soccer, weight lifting, basketball, American football, running, and a combination of sports. Table 1 summarizes the available evidence in terms of neuromuscular characteristics potentially related to knee mechanics in male athletes. Other studies providing information potentially related to risk factors for ACL injury in male athletes that was not categorized in biomechanical and neuromuscular subcategories were summarized in Table 1 [2, 8, 15, 35, 36, 50, 51, 57, 58, 68, 77].

3.2.1 Neuromuscular Parameter Differences Between Trained vs Untrained

Because the studies in Sect. 3.2 reported altered mechanics of lower extremity in fatigued conditions, several studies investigated neuromuscular parameters between trained and untrained male population. Muaidi et al. [69] compared proprioception between Olympic-level male soccer players and sex-matched non-athletes. In this study, the top-level players demonstrated significantly better proprioception than non-athletes. The authors commented that training likely plays a major role in the enhancement of proprioception, thus emphasizing how important it would be in prevention programs to improve ligament protection through proprioception.

The same finding was reported by another study in which endurance of knee musculature between male American Football players and average healthy male individuals was compared and concluded that American Football players demonstrated better muscle endurance in knee extension and flexion compared with healthy male controls. Knee rotatory strength was compared between soccer players and non-athletes [69]. This study reported that soccer players had greater isometric muscle strength compared with the control group. These findings may have practical implications, as specific programs aimed at improving knee dynamic stabilization by strengthening the musculature around the knee joints could result in improved protection of static (ligament) stabilizers.

3.2.2 Muscle Activation and Inter-joint Muscular Coordination

Wojtys et al. [103] evaluated muscular protection of the knee in torsion in size-matched athletes. The authors provided comparative data between male athletes participating in pivoting sports (basketball, volleyball, and soccer players) and male athletes not participating in pivoting sports (bicycling, crew, and running). They found that male athletes from pivoting sports demonstrated significantly greater joint stiffness with muscle contraction (275 % at 30° of knee flexion) compared with male athletes in non-pivoting sports (170 % at 30° of knee flexion). This finding can be interpreted as a potential benefit because athletes may respond to specific training with adaptations theoretically protective against ACL damage. Furthermore, this study found that male athletes participating in pivoting sports exhibited significantly larger knee flexor and extensor peak torques compared with male athletes from non-pivoting sports [103]. This finding suggests that some neuromuscular adaptations may develop, depending on the type of sport that may modify forces acting over a specific joint. The authors summarized the factors that determine tensile stiffness of muscles [103]: level of muscle activation; cross-sectional area of the muscle fibers; imposed change in muscle length; velocity of the imposed change in muscle length; and the tendon length and stiffness. Neuromuscular preventive programs may improve these factors to help protect the ACL during playing actions.

The term inter-joint coordination refers to the relationships of the angular positions and velocities between two or more joints [16]. In a cross-sectional study that compared inter-joint lower limb coordination between chronic ACL-deficient and healthy male subjects [85], the subjects performed eight movements; forward squats, backward squats, sideways squats, squats on one leg, going up a step, going down a step, walking three steps, and stepping in place. Essentially, the authors found that different synergies were employed for going up a step, walking three steps, squatting sideways, and squatting forward for both legs in the injured subjects compared with the healthy group. The authors found no increased asymmetry in the ACL-deficient group, but this was attributed to a small sample size (six injured, nine uninjured). The asymmetry index for squatting on one leg, squatting forward, and walking three steps was associated with pain, symptoms, activities of daily living, sport and recreational function, and knee-related quality of life assessed through the knee injury and osteoarthritis outcome score. The authors concluded that the analysis of inter-joint coordination may be efficient in characterizing motor deficits in people with knee injuries. All biomechanical changes during landing attributed to muscular fatigue and potential lack of inter-joint muscular coordination may be related to ACL injury, but this hypothesis still needs to be tested in the male athlete with an appropriate study design [3].

3.2.3 Prophylactic Bracing/Taping Evidence

The effect of ankle taping was compared through ankle and knee biomechanics during planned and unplanned running and side-step maneuvers [87]. This study reported that ankle tape reduced peak knee internal rotation and varus moments during all running and side-step tasks in both planned and unplanned situations.

Rishiraj et al. [80] evaluated the effects of a functional knee brace on peak GRF during drop-jump landing in male basketball and field hockey athletes. Players wearing prophylactic knee braces landed with significantly lower peak vertical GRF compared with players with no knee brace. The authors suggested the benefit of knee braces to protect the ACL at the beginning of landing while neuromuscular restraints are still not activated.

Knee kinematics and GRF was also compared during a landing task between healthy male athletes with and without a knee brace [104]. This study documented that the knee brace decreased the knee range of motion and angular velocity compared with unbraced conditions, but had no effect in peak vertical and anterior-posterior GRF. The use of knee brace reduced the anterior tibial translation and axial tibial rotation compared with unbraced subjects. Therefore, wearing a prophylactic brace may confer beneficial effects to the knee joint.

3.3 Neuromuscular Consequences of ACL injury

Ingersoll et al. [52] documented a review paper based on the existing literature regarding the neuromuscular consequences of ACL injury and reconstruction. Most of the reviewed studies focused on the female population, and the evidence regarding male athletes was limited. However, variables that potentially affect ACL injury in male athletes include: muscle activation, muscle strength, hypotrophy, joint coordination, and prophylactic brace and taping in dynamic movements. Table 2 summarizes the existing evidence related to biomechanical and neuromuscular consequences of ACL injury in male athletes. Several ideas for further research in the field of risk factors for ACL injury in males have been developed based on what is known about the effects of ACL injury (Table 2). However, it should be noted that the presence of biomechanical and neuromuscular modifications after ACL injury in male athletes is not equivalent to the presence of risk factors for injury.

4 Conclusions

While more research evidence of risk factors for ACL injury in the male population may be documented in the near future, the following recommendations will serve as a guide to elaborate prevention programs, which should incorporate:

- Prevention programs should include multiple-plane biomechanical components.
- Compared with double-leg maneuvers, single-leg movements including cutting demonstrate more risk on ACL so that prevention training programs need to incorporate aspect of single-leg training.
- Because ACL injury occurs at a higher rate in games compared with practice settings, reaction and decision making to unanticipated conditions should be a focus of the prevention programs.
- A correct foot positioning in dynamic movements needs to be a part of the prevention programs.

Table 2 Summary of evidence of the biomechanical and neuromuscular consequences of ACL injury in male athletes and potential future directions for research

Parameter	ACL injury consequences	Future research for risk factors
Biomechanical		
Walking	Step length and walking base were smaller compared with uninjured knee [55, 56]	Is there any difference in step length and walking base between ACL-injured and uninjured male athletes?
	Higher peak knee flexion during walking [6]	Is there any kinematic difference in dynamic situations between ACL-injured and uninjured male athletes?
	Lower knee extensor moment [5]	Is there any kinetic difference in dynamic situations between ACL-injured and uninjured male athletes?
Neuromuscular		
Muscle activation	Decreased volitional activation of quadriceps in both the injured and uninjured sides [96–98]	Is volitional activation of quadriceps and hamstrings different between ACL-injured and uninjured male athletes?
	ACL mechanical stimulation elicits short- and medium-latency hamstring reflexes [42]	Is there any difference between ACL-injured and uninjured male athletes for hamstring reflex latencies after ACL mechanical stimulation?
Muscle strength	ACL mechanical stimulation elicits smaller hamstring reflexes than anterior tibial translation [41, 42]	Is there any difference between ACL-injured and uninjured male athletes for quadriceps and hamstring strength, and quadriceps/hamstring strength ratio?
	Quadriceps and hamstring strength deficit [93, 94], worst for the quadriceps [93]	
	Greater side-to-side asymmetry for quadriceps than hamstrings [94]	Is there any difference between ACL-injured and uninjured male athletes for side-to-side quadriceps and hamstring strength and activation symmetry?
Atrophy	Slight significant hypertrophy of hamstrings [62]	Is hamstring muscle trophy different between ACL-injured and uninjured male athletes?
	Quadriceps atrophy [62]	Is quadriceps muscle trophy different between ACL-injured and uninjured male athletes?
	No correlation between quadriceps atrophy and loss of isokinetic strength [62]	Is isokinetic strength for quadriceps and hamstrings different between ACL-injured and uninjured male athletes?
Balance	More anterior and medially positioned COP relative to the foot before initiation of static balance [91]	Is there any difference between location of COP relative to the foot in static and dynamic situations between ACL-injured and uninjured male athletes?

ACL anterior cruciate ligament, *COP* center of pressure

- Playing surface needs to be considered to reduce ACL injury.
- Fatigue likely attributes risk movements of ACL injury so that prevention programs need to stress the quality of dynamic movements.
- Neuromuscular aspects including proprioception, muscle activation, and inter-joint coordination need to be focused in the prevention programs.
- Protecting knee joint by bracing or taping may bring prophylactic benefit.

The design of best prevention programs is based on adequate evidence in terms of risk factors of ACL injury. Modifiable risk factors such as biomechanical and neuromuscular factors are among the most important for designing prevention programs. Despite inadequate evidence for male athletes at this point, the recommendations for prevention programs may have to come from own clinical experience and research evidence of biomechanical and neuromuscular characteristics associated with aberrant knee mechanics that may potentially increase the risk of ACL injury. Future studies are warranted to investigate male specific ACL injury risk factors in prospective design. Based on the evidence, a male-specific prevention program needs to be developed.

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