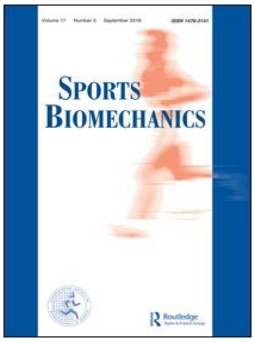

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ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/rspb20

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To cite this article: Yu Song, Ling Li, Gerwyn Hughes & Boyi Dai (2021): Trunk motion and anterior cruciate ligament injuries: a narrative review of injury videos and controlled jump-landing and cutting tasks, Sports Biomechanics, DOI: 10.1080/14763141.2021.1877337

To link to this article: https://doi.org/10.1080/14763141.2021.1877337

Published online: 04 Mar 2021.

SPORTS BIOMECHANICS
https://doi.org/10.1080/14763141.2021.1877337

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Trunk motion and anterior cruciate ligament injuries: a narrative review of injury videos and controlled jump-landing and cutting tasks

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ABSTRACT

The aims of this narrative review were to summarise trunk motion and external trunk perturbation observed in anterior cruciate ligament (ACL) injury videos and to review the association between trunk motion and ACL loading variables in controlled jump-landing and cutting tasks in non-injured populations. Video analyses have shown limited trunk flexion and increased trunk lateral bending towards the injured leg are associated with increased risk of ACL injuries, while trunk axial rotation away from the injured leg is more frequent than rotation towards the injured leg. Contact with the trunk before and at the time of the injury is common and might increase the risk of ACL injury. Controlled jump-landing and cutting studies have shown that limited trunk flexion and increased trunk lateral bending are associated with increased ACL loading. However, the findings of trunk axial rotation are not consistent with most video analyses. Mid-flight external trunk perturbation could increase ACL loading variables for one leg and is consistent with the videos of trunk-contact ACL injuries. These findings may help understand the role of trunk motion on primary ACL injury mechanisms and improve ACL injury screening tasks and ACL injury prevention strategies with the consideration of trunk motion.

ARTICLE HISTORY
Received 28 October 2020
Accepted 13 January 2021

KEYWORDS
ACL; ACL injury; injury risk; biomechanics; landing

Introduction

The anterior cruciate ligament (ACL) injury is one of the most common severe injuries in athletes (Kay et al., 2017). ACL injuries place a financial burden on society (Mather et al., 2013) and result in compromised sports careers (Wise & Gallo, 2019), abnormal strength and balance performance (Dai et al., in press), elevated rates of knee osteoarthritis (Poulsen et al., 2019), and increased risk of secondary ACL injuries (Barber-Westin & Noyes, 2020). Although extensive research has been conducted to understand ACL injury mechanisms and develop ACL prevention programmes (Dai et al., 2014), ACL injury rates have not decreased (Agel et al., 2016).

The strain experienced by the ACL is directly affected by the kinematics of the tibiofemoral joint (Englander et al., 2019). Consequently, previous studies have focused on understanding the effects of lower extremity biomechanics on ACL loading

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mechanisms and injury risk (Carlson et al., 2016; Dai et al., 2014; Sharir et al., 2016). Reduced knee flexion angles, increased tibial anterior shear and compressive forces, increased knee internal rotation angles, and increased knee abduction angles have been shown to be associated with increased ACL loading (Dai et al., 2014, 2015; Englander et al., 2019; Oh et al., 2012). Video analyses have observed that ACL injuries commonly occur shortly after the initial ground contact during landing and cutting tasks with small knee flexion angles and increased knee internal rotation and abduction angles (Carlson et al., 2016; Dai et al., 2014; Koga et al., 2010). Some evidence suggests that landing biomechanics, including decreased knee flexion angles, greater impact vertical ground reaction forces (GRF), and increased knee abduction angles and moments, are associated with increased risk of future ACL injuries (Hewett et al., 2005; Leppanen, Pasanen, Krosshaug et al., 2017; Leppanen, Pasanen, Kujala et al., 2017; Padua et al., 2015), although the sensitivities of these predictions could be poor (Krosshaug et al., 2016; Leppanen, Pasanen, Krosshaug et al., 2017; Leppanen, Pasanen, Kujala et al., 2017; Smith et al., 2012). Better identification of other biomechanical factors associated with ACL injuries will help improve ACL injury-prevention strategies.

Trunk motion includes trunk flexion-extension, lateral bending, and axial rotation around the medial-lateral, anterior-posterior, and longitudinal axes, respectively. In addition, an individual may experience trunk perturbation, defined as external forces being applied to the trunk by external objects (other players, balls, equipment, etc.). From a mechanical perspective, trunk motion could affect knee loading through multiple mechanisms. First, the trunk, head, and arms comprise nearly 60% of the bodyweight (De Leva, 1996). Trunk motion will affect the whole-body centre of mass position and redistribute the centre of mass of each segment to change the external loading imposed on the knee (Davis et al., 2019). Second, the trunk and lower extremities act as a kinetic chain, so the motion of the trunk could influence the motion and therefore loading of the knee (Hewett & Myer, 2011). Third, an individual's centre of mass is a predetermined parabola in flight when no external forces are applied. The effects of self-initiated trunk motion on the whole-body centre of mass need to be counterbalanced by the lower body, which could consequently affect landing mechanics (Hinshaw et al., 2019). Fourth, external forces may be applied to the trunk to modify the whole-body motion and knee loading during athletic tasks (Yom et al., 2014). Fifth, trunk flexion is often accompanied by anterior pelvic tilt, which will alter the length of muscles which originate on the pelvis and insert onto the tibia/fibula (e.g., rectus femoris, hamstrings, gracilis). The change in length of these muscles will alter their potential force output, based on the force-length and force-velocity relationships, which in turn will likely alter the loading of the knee (Hughes, 2014). A previous review has summarised the evidence to connect trunk lateral bending and knee abduction angles (Hewett & Myer, 2011). However, there is a lack of review of trunk motion and perturbation and their association with ACL injury risk in all three planes of motion from the perspectives of video analyses and laboratory-controlled athletic tasks (Hughes, 2014).

Therefore, the first purpose of the current narrative review was to summarise trunk motion in the sagittal, frontal, and transverse planes, as well as external perturbation applied to the trunk, observed in ACL injury videos. The second purpose was to review the association between trunk motion in the sagittal, frontal, and transverse planes and ACL loading variables in controlled jump-landing and cutting tasks in non-injured populations. The current review was focused on the mechanisms of primary ACL injuries, which were more commonly studied in video-analysis and laboratory-controlled studies compared to secondary ACL injuries.

Literature search and study selection

Potential studies were identified by searching the PubMed electronic database. Different combinations of search terms were used: 'anterior cruciate ligament', 'ACL', 'ACL injury', 'ACL injuries', 'landing', 'cutting', 'trunk', 'video', 'biomechanics', 'force', 'kinematics', and 'kinetics'. The studies relevant to the topics of the current review were included. Additional studies were included based on the references cited in previously identified studies. The current narrative review attempted to cover several topics, while there was limited literature for certain areas. Therefore, a meta-analysis with a stricter literature search and study selection strategy was not performed.

Video analyses of trunk motion during ACL injury

Video analyses of ACL injuries provide direct information on how the body's motion and the external environment may cause ACL injuries in complex sports situations. While most studies focus on knee kinematics (Dai et al., 2014; Koga et al., 2010; Krosshaug et al., 2007), several studies have quantified trunk motion in the sagittal and frontal planes near the time of ACL injuries (Table 1). Sheehan et al. (2012) evaluated sagittal-plane single-leg landing videos in ACL-injured and uninjured athletes. The ACL injuries were characterised by a greater anterior-posterior distance between the centre of mass and base of support, which resulted from increased thigh angles of the injured side and less trunk flexion. Hewett et al. (2009) compared videos of ACL injuries to controlled videos in which athletes were not injured when basketball players performed landing or cutting tasks. The analyses showed injured female players tended to demonstrate less trunk flexion and greater trunk lateral bending towards the injured leg compared to uninjured female players. Della Villa et al. (2020) assessed 134 ACL injury videos in male soccer athletes and showed that the trunk was upright and bent towards the injured leg near the time of the injury.

Some studies have also qualitatively described trunk motion in ACL injury videos. Boden et al. (2000) mentioned that many injured athletes experienced trunk extension in sudden deceleration tasks. Stuelcken et al. (2016) observed trunk lateral bending to the injured leg in 44% of the injuries. Montgomery et al. (2018) found minimal trunk axial rotation or trunk axial rotation towards the injured leg near the time of injury in male rugby players, while three other studies found that the trunk was likely to have minimal axial rotation or rotate towards the uninjured leg in male soccer and female netball players (Della Villa et al., 2020; Stuelcken et al., 2016; Walden et al., 2015).

In summary, the findings of both quantitative and qualitative video analyses suggest that limited trunk flexion, increased distance between the centre of mass and the base of support in the sagittal plane, and trunk lateral bending towards the landing or cutting leg are associated with increased risk of ACL injuries. Inconsistencies have been observed for trunk axial rotation, but three of the four studies have observed that the trunk is more likely to rotate away from the injured leg. Despite the valuable information provided by

Table 1. Video analyses of trunk motion and perturbation and injury mechanisms in anterior cruciate ligament (ACL) injuries.

Studies	Sports	Samples	Trunk Motion	Trunk Perturbation	Injury Manoeuvres, Percentages (Absolute Numbers)	Contact Mechanisms, Percentages (Absolute Numbers)
Boden et al. (2000)	Basketball, football, soccer, and volleyball.	ACL injury video: 16 males and 7 females. Questionnaire: 65 males (72 knees) and 25 females (28 knees).	The trunk was in extension during many mechanisms.	Not reported.	Non-contact injury videos: Deceleration with changing direction: 40% (6) Deceleration without changing direction: 27% (4) Single-leg landing: 20% (3) Double-leg landing: 13% (2)	Videos: Non-contact: 65% (15) Direct contact: 35% (8) Questionnaire: Non-contact: 71% (71) Direct contact: 28% (28) Unclear contact: 1% (1)
Brophy et al. (2015)	Professional and collegiate soccer.	32 males' and 23 females' ACL injury videos.	Not reported.	Not reported.	Tackling: 51% (28) Being tackled: 7% (4) Cutting: 15% (8) Kicking: 7% (4) Heading and landing: 5% (3) Receiving: 5% (3) Running/jumping: 7% (4) Dribbling: 2% (1)	Non-contact: 44% (24) Indirect contact: 36% (20) Direct contact: 20% (11)
Cochrane et al. (2007)	Professional men's Australian football.	34 ACL injury videos.	Not reported.	Not reported.	Non-contact and indirect contact injuries: Sidestepping: 43% (10) Landing: 26% (6) Stopping/slowing: 13% (3) Landing/stepping: 13% (3) Crossover cutting: 4% (1)	Non-contact: 56% (19) Indirect contact: 12% (4) Direct contact: 32% (11)
Della Villa et al. (2020)	Professional men's soccer.	134 ACL injuries videos.	The trunk was upright (0°) and laterally bent to the injured leg (5°) at initial contact. The trunk was mostly either in a neutral position (34%) or rotated towards the uninjured leg (53%) at initial contact. The trunk remained upright (0°) and bent ipsilaterally (5°) and had a greater prevalence of trunk axial rotation towards the uninjured side (83%) at the time of injury.	The contact with the trunk consisted of 84% of the contact before the injury and 84% of the indirect contact at the estimated time of the injury.	Non-contact and indirect contact injuries: Pressing or tackling: 42% (55) Being tackled: 18% (24) Kicking; 16% (19) Landing: 7% (8) Others: 10% (12)	Non-contact: 44% (59) Indirect contact: 44% (59) Direct contact: 12% (16)

(*Continued*)

Table 1. (Continued).

Studies	Sports	Samples	Trunk Motion	Trunk Perturbation	Injury Manoeuvres, Percentages (Absolute Numbers)	Contact Mechanisms, Percentages (Absolute Numbers)
Grassi et al. (2017)	Professional men's soccer.	34 ACL injury videos.	Not reported.	Contact with the trunk consisted of 85% of the indirect contact.	Tackling: 15% (5) Pressing: 26% (9) Kicking: 21% (7) Dribbling: 18% (6) Others: 10% (7)	Non-contact: 44% (15) Indirect contact: 21% (7) Direct contact: 35% (12)
Hewett et al. (2009)	Professional basketball.	Videos of 10 female and 7 male injured players and 6 female uninjured players.	Lateral trunk bending towards the injured leg at initial contact tended to be greater for injured female players (11.1 ± 2 deg) compared to injured male players (−5.5 ± 9.5 deg) and uninjured female players (4.2 ± 9.6 deg). Injured female players demonstrated less trunk flexion (1.6 ± 9.3 deg) at initial contact compared to uninjured female players (14.0 ± 7.3 deg).	Not reported.	Landing and cutting.	Only non-contact injuries were selected. (17)
Johnston et al. (2018)	Professional men's American football.	69 ACL injury videos.	Not reported.	Not reported.	Non-contact and indirect contact injuries: Landing: 12% (6) Pivoting/cutting: 60% (30) Running: 10% (5) Decelerating: 10% (5) Others: 8% (4)	Non-contact: 23% (16) Indirect contact: 49% (34) Direct contact: 28% (19)
Koga et al. (2010)	Women's team handball and basketball.	10 ACL injury videos.	Not reported.	All indirect contact involved the trunk being pushed or held by other players.	Cutting: 70% (7) Single-leg landing: 30% (3)	Only non-contact and indirect contact injuries were selected. Non-contact: 40% (4) Indirect contact: 60% (6)
Krosshaug et al. (2007)	Professional, collegiate, and high school basketball.	22 females' and 17 males' ACL injury videos.	Not reported.	Half of the female injuries involved collisions or pushing before the time of injury. Only two injuries occurred with no other players within 1 m.	Landing: 59% (23) Cutting: 10% (4) Direct contact:10% (4) Unclear: 21% (8)	Non-contact: 72% (28) Indirect contact: 8% (3) Direct contact: 10% (4) Unclear contact: 10% (4)

(*Continued*)

Table 1. (Continued).

Studies	Sports	Samples	Trunk Motion	Trunk Perturbation	Injury Manoeuvres, Percentages (Absolute Numbers)	Contact Mechanisms, Percentages (Absolute Numbers)
Montgomery et al. (2018)	Professional men's rugby.	35 ACL injury videos.	The trunk was either in neutral or rotated towards the injured leg at the time of the injury in non-contact injuries.	Not reported.	Rucking: 11% (4) Tackling: 14% (5) Being tackled: 26% (9) Running: 40% (14) Setting play and kicking: 9% (3)	Non-contact: 43% (15) Indirect contact: 23% (8) Direct contact: 29% (10) No consensus of the contact type: 6% (2)
Olsen et al. (2004)	Professional women's team handball.	ACL injury videos: 20 Questionnaire: 32	Not reported.	60% of the injuries had some form of perturbation, such as out of balance, being pushed or held, or trying to avoid a collision. All the indirect contact involved contact with the upper body.	Videos: Cutting: 60% (12) Single-leg landing:13% (4) Deceleration: 10% (2) Running: 5% (1) Collision: 5% (1)	Videos: Non-contact: 65% (13) Indirect contact: 30% (6) Direct contact: 5% (1) Questionnaire: Non-contact: 62.5% (20) Contact: 37.5% (12)
Sheehan et al. (2012)	Basketball, soccer, American football, and handball.	13 ACL-injured females and 7 ACL injured males. 13 female controls and 7 male controls.	ACL-injured athlete demonstrated greater distances between the centre of mass to the base of support (1.5 ± 0.5 vs. 0.7 ± 0.7 femur length) and limb angles (48 ± 12 vs. 31 ± 22 deg) and less trunk flexion angles (4 ± 14 vs. 16 ± 13 deg) compared to controls.	Not reported.	Running and decelerating: 75% (15) Jump-landing: 25% (5)	Only non-contact injuries were selected. (20)
Stuelcken et al. (2016)	Professional women's netball.	16 ACL injury videos.	69% of the injuries showed trunk axial rotation away from the side of the injured knee before the landing was completed. 44% of the injuries showed trunk lateral bending towards the side of the injured knee before the landing was completed.	44% of the injuries involved contact whilst in the air, while 19% of the injuries had contact at/after landing.	Landing: 81% (13) Running and cutting: 19% (9)	Non-contact: 50% (8) Indirect contact: 50% (8)
Walden et al. (2015)	Professional men's soccer.	39 ACL injury videos.	The trunk was mostly neutral (36%) or rotating towards the uninjured leg (48%) at the time of non-contact and indirect contact injuries.	Before the injury, 21% of the non-contact and indirect contact injuries experienced contact with the trunk or arms. At the time of injury, all the indirect contact was to the trunk or arms.	Non-contact and indirect contact injuries: Pressing: 33% (11) Kicking: 15% (5) Heading and landing: 15% (5) Others: 36% (12)	Non-contact: 64% (25) Indirect contact: 21% (8) Direct contact: 15% (6)

Non-contact: no external objects or players contacting with any body parts; Indirect contact: external objects or players contacting with body parts other than the injured knee; Direct contact: external objects or players contacting with the injured knee.

video analyses, several limitations should be noted. First, while researchers attempted to obtain videos that closely captured the sagittal and frontal planes' motion, the three-dimensional (3D) nature of athletic movements and the uncontrolled camera positions could introduce errors. Second, there is a lack of quantification of transverse plane motion, potentially due to the difficulty of obtaining such videos. Third, researchers developed 3D image-matching techniques to overcome the limitations of two-dimensional (2D) analyses, but these analyses were only applied to the knee joint with noticeable errors (Krosshaug & Bahr, 2005). On the other hand, more accurate methods, such as the direct linear transformation procedure, often require camera calibration and may not be widely applicable (Dai et al., 2015). Fourth, injury videos do not directly provide kinetic data, which are important for assessing the loading of the ACL. Therefore, future studies are needed to improve the accuracy of kinematic analyses with uncalibrated cameras, and further efforts are needed to derive valid kinetic variables from these kinematic data. In addition, quantitative assessments of 3D trunk motion, particularly trunk axial rotation, should be considered. Collectively, these advances will help further understand whole-body motion and lower limb joint kinetics during ACL injury events.

Video analyses of trunk perturbation during ACL injury

Most ACL injuries occur without direct contact with the injured knee, but indirect contact, defined as contact with other body parts, is common (Table 1). Overall, previous studies have reported a range of indirect-contact ACL injuries from 8% to 60% (pooled percentages: non-contact (47%), indirect contact (34%), and direct contact (19%)), primarily in soccer, basketball, team handball, rugby, and netball (Brophy et al., 2015; Cochrane et al., 2007; Della Villa et al., 2020; Grassi et al., 2017; Johnston et al., 2018; Koga et al., 2010; Krosshaug et al., 2007; Montgomery et al., 2018; Olsen et al., 2004; Stuelcken et al., 2016; Walden et al., 2015). In addition, contact with the trunk and/or arms consisted of more than 80% of the indirect contact near the time of ACL injuries (Della Villa et al., 2020; Grassi et al., 2017; Koga et al., 2010; Olsen et al., 2004; Walden et al., 2015). Furthermore, contact with the trunk was frequently observed prior to the time of non-contact and indirect-contact ACL injuries (Della Villa et al., 2020; Krosshaug et al., 2007; Walden et al., 2015).

In summary, contact with the trunk prior to or during the early phase of landing and cutting might increase the risk of ACL injury. Contact with the trunk could increase trunk lateral bending and decrease trunk flexion (Walden et al., 2015), which have been previously proposed as high-risk trunk motions for ACL injuries. Contact with the trunk in flight could also shift the centre of mass of the trunk and lead to landings primarily on a single leg (Stuelcken et al., 2016; Walden et al., 2015). Lastly, contact with the trunk might directly apply force and perturbation to the whole body, resulting in increased knee loading and suboptimal knee controls (Della Villa et al., 2020). However, previous studies are limited to qualitative analysis of the presence of trunk contact. Future quantitative studies are encouraged to document the timing and location of the contact with the trunk. The duration, type, and estimated forces of contact will help understand the mechanical effects of the contact on body movements and consequent landing and cutting mechanics. In addition, knee mechanics should be compared between trunk-contact injuries and non-contact injuries to identify whether trunk-contact induces different ACL injury mechanisms.

Sagittal-plane trunk motion and knee loading during jump-landing and cutting tasks

Another strategy to overcome the limitations of video analyses is to assess the effects of kinematic patterns and perturbation observed in ACL injuries on controlled jump-landing and cutting biomechanics in non-injured populations. Although actual ACL injuries are not likely observed in a laboratory setting, accurate kinematic and kinetic data can be collected to quantify the relationship between altered trunk motion and ACL loading variables. These relationships have been assessed through correlational analyses, short-term training through instruction and feedback, and long-term intervention.

Many studies have determined the influence of trunk flexion on knee loading in jump-landing tasks. Blackburn and Padua (2008, 2009) found that active trunk flexion increased both hip and knee flexion angles and decreased peak vertical GRF and mean quadriceps muscle activity compared to neutral trunk flexion in a double-leg drop landing. Shimokochi et al. (2013) demonstrated that increased trunk flexion resulted in increased knee flexion angles and decreased peak vertical GRF and internal knee extension moments compared to neutral and limited trunk flexion in a single-leg landing. Saito et al. (in press) also showed that increased trunk flexion increased knee flexion angles and hamstring/quadriceps activity ratio compared to neutral and trunk extension conditions in a single-leg landing. In addition, a correlation study showed a negative relationship between the anterior centre of pressure positions, likely resulting from greater trunk bending, and internal knee extension moments in a single-leg landing (Shimokochi et al., 2009). In a simulation study, the researchers introduced changes to landing height and trunk extension and assessed their effects on peak ACL forces in downhill skiing landing. Peak ACL forces were approximately eight times more sensitive to trunk extension compared to landing height (Heinrich et al., 2018). Previously mentioned studies have emphasised trunk position at the initial ground contact and trunk motion during the initial landing phase. Meanwhile, Davis et al. (2019) quantified the effect of mid-flight trunk flexion and extension on landing mechanics. Mid-flight trunk extension resulted in a more posteriorly positioned whole-body centre of mass related to the knee joints in flight and at initial ground contact of landing. Decreased knee and hip flexion angles and increased peak posterior GRF, internal knee and hip extension moments, and knee adduction moments were observed for the trunk extension condition.

Less research has been conducted to quantify the effects of sagittal-plane trunk motion on knee loading in cutting tasks. Jamison et al. (2013) observed that greater co-contraction of the back extensors at the level of the 5th lumbar spine significantly correlated with increased peak external knee abduction moments and less change of trunk flexion in side-cutting tasks. The authors suggested that a stiffened spine before landing may reduce the range of motion of the trunk flexion, leading to increased knee abduction moments. Whyte et al. (2018) demonstrated that unanticipated cross-cutting resulted in decreased trunk flexion and lateral bending towards the cutting direction, as well as increased internal knee extension and abduction moments, compared to anticipated cross-cutting. The authors interpreted that unanticipated cutting resulted in

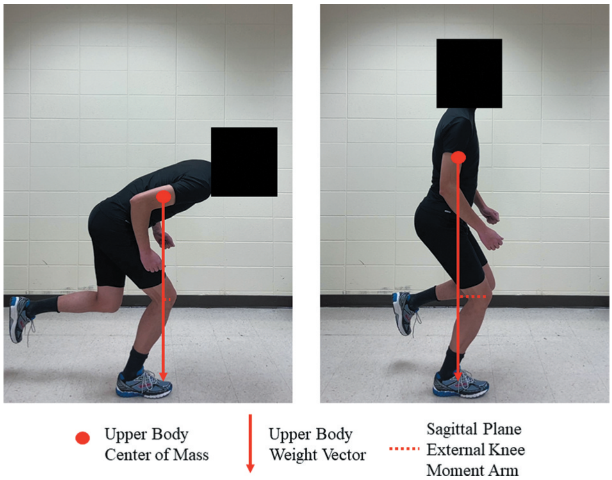

Figure 1. Limited trunk flexion (right) increases the external flexion moment arm of the upper body centre of mass about the knee joint in the sagittal plane compared to increased trunk flexion (left) in a single-leg stance posture.

decreased efficiency of redirecting the centre of mass towards the cutting direction, demonstrated by altered trunk kinematics. The altered trunk motion then led to changes in knee biomechanics associated with increased ACL loading.

In summary, the literature has documented that trunk extension or limited trunk flexion may result in knee mechanics associated with increased ACL loading during jump-landing and cutting tasks. First, trunk extension would move the centre of mass of the upper body backward. From a top-down perspective, this backward movement will likely increase the external moment arm of the upper body centre of mass about the knee joint and therefore impose a greater knee moment (Figure 1). Second, increased trunk flexion is typically accompanied by hip and knee flexion to keep the whole-body centre of mass within the base of support. Increased lower extremity flexion allows individuals to increase the time and range of motion to reduce their downward momentum, which may decrease impact vertical GRF, knee moments, and average quadriceps muscle activities. Third, mid-flight trunk extension may result in backward movements of the upper body centre of mass, which needs to be counterbalanced by the forward movement of the lower body. As a result, the knee could be placed further forward from the centre of mass and experience greater external loading (Figure 2). These findings in controlled jump-landing and cutting tasks were consistent with previously reviewed video analyses, suggesting limited trunk flexion and increased distance between the centre of mass and base of support in the sagittal plane were associated with increased risk of ACL injuries.

Frontal and transverse planes trunk motion and knee loading during jump-landing and cutting tasks

Jump-landing studies have also assessed the effects of frontal plane trunk motion on knee mechanics. Saito et al. (in press) observed that trunk lateral bending to either side

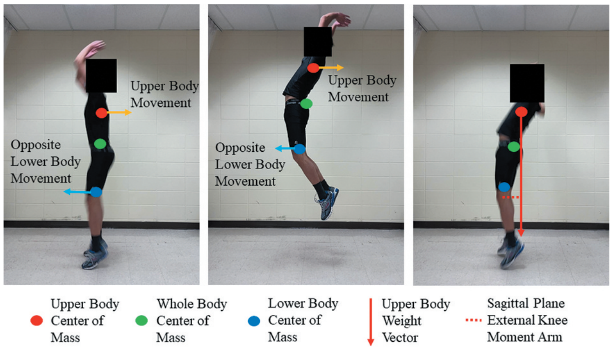

Figure 2. The takeoff (left), maximal height (middle), and initial ground contact (right) of a jump-landing with mid-flight trunk extension. Mid-flight trunk extension results in backward movements of the upper body centre and forward movement of the lower body, leading to increased external flexion moment arm of the upper body centre of mass about the knee joint in the sagittal plane.

increased peak knee valgus angles compared to the neutral condition in a single-leg landing. Chijimatsu et al. (2020) instructed participants to limit trunk lateral bending in a single-leg landing task through video feedback. The training decreased trunk lateral bending, peak external knee abduction moments, and knee abduction and internal rotation angles at initial ground contact. Regarding mid-flight trunk motion, Dempsey et al. (2012) demonstrated that landing after catching a laterally placed ball in mid-flight increased peak external knee abduction moments compared to catching a medially placed ball in a single-leg landing task. Similarly, Zahradnik et al. (2020) showed that mid-flight reaching of a laterally placed volleyball with trunk lateral bending decreased knee flexion angles and increased impact vertical GRF for the leg ipsilateral to the reaching direction. Hinshaw et al. (2019) assessed the effects of mid-flight trunk lateral bending on the centre of mass trajectories and knee mechanics during a double-leg landing. The mid-flight trunk lateral bending moved the trunk centre of mass to one side, and the countermovement of the lower body resulted in asymmetric landing posture at initial ground contact. Consequently, the leg ipsilateral to the bending direction experienced great impact vertical GRF and increased knee abduction and internal rotation angles during landing compared to the neutral trunk condition. The effects of trunk lateral bending on ACL injury risk were further supported by a prospective one-year follow-up study (Dingenen et al., 2015). Young female athletes who suffered ACL injuries demonstrated greater trunk lateral bending towards the landing leg and greater knee valgus angles in a single-leg landing task at baseline compared to those who did not suffer ACL injuries. Less research has been conducted to quantify the effects of trunk axial rotation on jump-landing mechanics. One study by Critchley et al. (2020) showed that mid-flight trunk axial rotation resulted in decreased knee flexion angles and increased peak impact vertical GRF, internal knee extension moments, and knee abduction and internal rotation angles for the ipsilateral leg compared to the neutral trunk condition during double-leg landings.

Similar effects of trunk lateral bending and axial rotation on knee loading have been observed in side-cutting tasks. Dempsey et al. (2007) found that trunk lateral bending towards the cutting leg resulted in increased peak external knee abduction moments compared to trunk bending towards the cutting direction (opposite to the cutting leg). In addition, trunk axial rotation towards the cutting leg increased peak knee internal rotation moments compared to the neutral condition. Furthermore, a wider foot placement, which involved an increased lateral distance between the centre of mass and foot in the frontal plane, increased the peak knee abduction and internal rotation moments compared to the neutral condition. Consistently, several correlational studies have demonstrated that peak external knee abduction moments positively correlated with trunk lateral bending and axial rotation towards the cutting leg as well as the width of the cutting foot placement in side-cutting tasks (Frank et al., 2013; Havens & Sigward, 2015; Jamison et al., 2012; Jones et al., 2015; Kristianslund et al., 2014). Dempsey et al. (2009) conducted an intervention study to quantify the effects of 6-week technique training focusing on narrow foot placement and minimal trunk lateral bending in side-cutting tasks. Following the training, participants demonstrated decreased trunk lateral bending and peak external knee abduction moments. A recent review (Fox, 2018) has recommended trunk lateral bending and rotation towards the cutting direction as preferred techniques to reduce knee loading without compromising performance. Meanwhile, a narrow foot placement might be beneficial for ACL injury prevention but could decrease performance.

In summary, the literature has well documented that trunk lateral bending could lead to knee mechanics associated with increased ACL loading for the leg ipsilateral to the bending direction in jump-landing and cutting tasks. First, trunk lateral bending could shift the trunk centre of mass and GRF vector laterally relative to the hip and knee and subsequently increase external knee abduction moments and knee abduction angles (Hewett & Myer, 2011, Figure 3). Second, trunk lateral bending could move most of the bodyweight towards one leg and therefore increase asymmetry between legs during double-leg landings. Third, mid-flight trunk lateral bending requires the lower body to move in the opposite direction, resulting in further landing asymmetries in double-leg landings. Excessive trunk lateral bending might move the contralateral leg to a much higher location than the ipsilateral leg so that the ipsilateral leg would land much earlier and experience great landing forces (Hinshaw et al.,

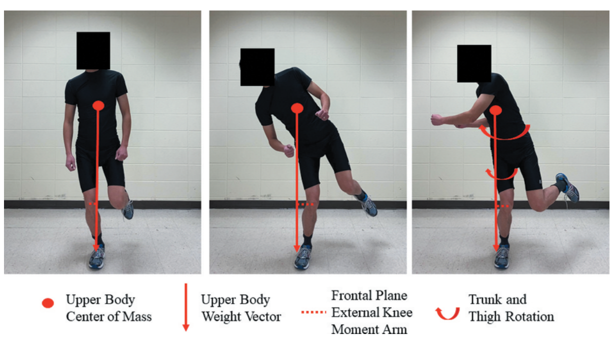

Figure 3. Increased trunk lateral bending (middle) increased the external abduction moment arm of the upper body centre of mass about the knee joint in the frontal plane compared to the neutral trunk (left) in a single-leg stance posture. Increased trunk axial rotation towards the stance leg (right) increased the external abduction moment arm of the upper body centre of mass about the knee joint in the frontal plane and thigh external rotation compared to the neutral trunk (left) a single-leg stance posture.

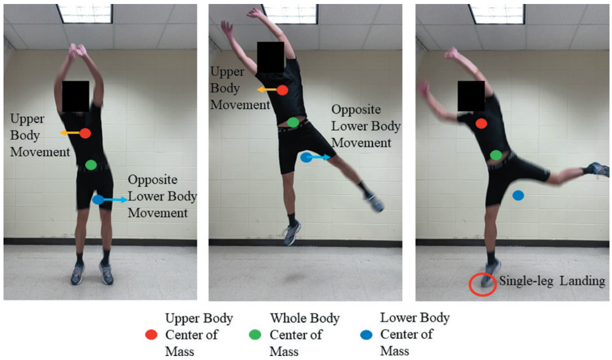

Figure 4. The takeoff (left), maximal height (middle), and initial ground contact (right) of a jump-landing with mid-flight trunk lateral bending. Mid-flight trunk lateral bending results opposite movements of the upper body and the leg opposite to the trunk bending direction, leading to a single-leg landing.

2019, Figure 4). The effects of mid-flight trunk motion on landing mechanics may also help to explain why volleyball and badminton players have increased rates of ACL injuries to their non-dominant limb during jump-landing tasks (Devetag et al., 2018; Kimura et al., 2010). Since these athletes commonly strike a ball with their dominant upper limb while they are in the air, they are subsequently more likely to bend their trunk towards the non-dominant side in mid-flight (Hinshaw et al., 2019). The increased knee loading associated with trunk lateral bending towards the ipsilateral leg is consistent with the findings of previously reviewed video analyses.

Regarding trunk axial rotation, the shift of the bodyweight towards the ipsilateral leg could increase impact vertical GRF and knee loading compared to the contralateral leg in double-leg landings (Figure 3). The greater distribution of the weight on the lateral side of the ipsilateral leg might also increase knee abduction angles (Hewett & Myer, 2011). Also, trunk axial rotation is likely to rotate the ipsilateral femur externally and increase knee internal rotation angles (Critchley et al., 2020). The increased knee loading associated with trunk axial rotation for the ipsilateral knee, however, does not appear to be consistent with most video analyses, showing the trunk to be more likely rotating away from the injured leg in ACL injuries (Della Villa et al., 2020; Stuelcken et al., 2016; Walden et al., 2015). These inconsistencies could be due to several observations. First, previous video analyses only qualitatively defined trunk axial rotation as neutral, towards the injured or towards the uninjured leg. For a 2D analysis, a top view of the transverse plane will be needed to accurately quantify the trunk axial rotation relative to the injured leg, so previous observations in the sagittal and frontal planes may introduce significant errors. Second, studies have shown that individuals preferred to primarily use the leg opposite to the planned movement direction to complete a lateral jump or landing task (Critchley et al., 2020; Stephenson et al., 2018). Similarly, when a change of direction could be performed as either a side-cutting or cross-cutting manoeuvre in sports situations, individuals are more likely to choose a side-cutting manoeuvre with the trunk rotating away from the cutting leg and towards the cutting direction. The commonly observed trunk axial rotation away from the injured leg could be related to the preference of a specific leg during landing and side-cutting tasks. These findings suggest that the influence of trunk axial rotation in elevating ACL injury risk does not appear to be as clear cut as trunk extension and lateral bending.

Although there is extensive literature related to trunk motion and ACL loading variables in controlled jump-landing and cutting tasks, the effects of trunk axial rotation on single-leg landing mechanics and the effects of trunk motion on cross-cutting mechanics may require additional investigation. In addition, participants were given instructions to intentionally increase or decrease trunk motions in certain directions in most studies. However, in sports situations, athletes typically alter their trunk motion to achieve sports goals. Future studies are encouraged to incorporate performance demands (Critchley et al., 2020; Dempsey et al., 2012; Zahradnik et al., 2020), action-reaction (Almonroeder et al., 2020; Stephenson et al., 2018), and attention and secondary tasks (Almonroeder et al., 2019; Dai et al., 2018; Widenhoefer et al., 2019) into jump-landing and cutting tasks to induce sports-specific trunk motion. Moreover, a previous study has shown that females athletes who demonstrated increased trunk displacements in a reactive perturbation task had increased risk of suffering future ACL injuries (Zazulak et al., 2007). The interaction among trunk strength, trunk activation, and trunk motion may provide insight into the different trunk control strategies utilised in jump-landing and cutting tasks.

External trunk perturbation and knee loading during jump-landing tasks

Limited information was found regarding the effect of external trunk perturbation on knee loading during jump-landing and cutting tasks. Yom et al. (2014) quantified the effect of mid-flight external perturbation on lower extremity biomechanics during a double-leg landing. A lateral pulling force was applied to the acromioclavicular joint on the dominant-leg side when participants dropped from a bar. The lateral pulling force resulted in decreased knee flexion angles at initial ground contact, increased impact vertical GRF, as well as increased knee abduction angles and moments of the dominant leg during landing. The findings suggested that external perturbation to the trunk could significantly increase ACL loading variables for one leg. The increased loading could be due to the use of the ipsilateral leg to decelerate the horizontal velocity caused by the pulling force. The pulling force could also create an angular momentum so that the contralateral leg was lifted to compensate for the rotation, resulting in the landing being primarily performed by the ipsilateral leg. However, these two postulations could not be confirmed since the whole-body velocities, angular momentums, and contralateral leg motion were not analysed in this previous study.

There is a paucity of research assessing external trunk perturbation on jump-landing and cutting mechanics. Future studies are encouraged to determine the effects of different tasks (jump-landing vs. cutting), timing (before vs. after initial ground contact), location (proximal vs. distal trunk), directions (anterior-posterior vs. mediolateral), types (anticipated vs. unanticipated) of external trunk perturbation on ACL loading variables. In addition, bilateral landing data and whole-body movements need to be quantified to understand the mechanisms of external trunk perturbation and altered landing mechanics.

Practical implications

The summaries of the current narrative review have several practical implications. First, the consistent findings of trunk motion in video-analysis and laboratory-controlled studies have provided valuable information to understand ACL injury mechanisms. Coaches, athletes, trainers, and clinicians need to be aware of high-risk trunk motion associated with ACL injuries and adopt effective strategies to minimise the elevated risk. Trunk motion and perturbation may be incorporated into the training of jump-landing and cutting techniques. Athletes can be encouraged to return to a protective trunk position and adopt soft landing techniques after purposeful trunk motion or unanticipated trunk perturbation (Critchley et al., 2020). Second, the role of trunk motion on ACL injury risk has highlighted the potential effects of trunk muscle strength and activation on jump-landing and cutting mechanics. Neuromuscular training of the trunk to maintain a relatively safe position after completing sports-specific tasks will be desirable. Third, for recreational athletes whose priority of sports participation is not performance, they may consider avoiding high-risk trunk motion to decrease ACL injury risk. Fourth, the observed trunk motion and perturbation may be used to design novel ACL injury risk screening tasks to identify high-risk populations. Previous screening protocols have generally used the double-leg jump-landing task (Hewett et al., 2005; Leppanen, Pasanen, Krosshaug et al., 2017; Padua et al., 2015). Future studies might consider incorporating tasks that challenge the trunk, such as mid-flight reaching and external pulling/pushing forces, to identify individuals who respond inefficiently to these challenges. Fifth, the findings have encouraged innovative strategies to minimise the increased knee loading in jump-landing. For example, the increased distance between the centre of mass and base of support is associated with increased ACL loading because of the increased internal knee moments required to maintain balance. However, when the sports environment allows, athletes may choose to lose balance and fall on the ground to decrease knee loading (Li et al., in press). Overall, despite increasing literature regarding the mechanical connections between trunk motion and ACL injury risk, future investigation is still warranted in many identified areas. In addition, meta-analyses are encouraged in well-studied areas such as the effects of trunk flexion-extension on controlled landing mechanics and the effects of trunk lateral bending on controlled cutting mechanics to summarise the magnitudes of changes in ACL loading variables associated with trunk motion. The long-term goals are to develop sensitive ACL injury screening tasks and evidence-based ACL injury prevention strategies to decrease sports-related ACL injuries through a better understanding of trunk motion and ACL injuries.

Conclusion

Video analyses have shown limited trunk flexion, increased distance between the whole-body centre of mass and the base of support, and increased trunk lateral bending towards the injured leg to be associated with increased risk of ACL injuries, while trunk axial rotation away from the injured leg is more frequently observed than rotation towards the injured leg. Contact with the trunk before and at the time of the injury is common and might increase the risk of ACL injury. The findings of controlled jump-landing and cutting studies have found that limited trunk flexion, increased distance between the centre of mass and base of support, and increased trunk lateral bending are associated with increased ACL loading, supporting the findings from the video-analysis studies. However, the findings of trunk axial rotation are not consistent with most video analyses. Mid-flight external trunk perturbation could increase ACL loading variables for one leg and is consistent with the videos of trunk-contact ACL injuries. The summaries of this narrative review may help understand the role of trunk motion on primary ACL injury mechanisms and improve the design of ACL injury screening tasks and ACL injury-prevention strategies with the consideration of trunk motion.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

Yu Song's graduate assistantship was supported by the National Science Foundation (1933409). Yu Song also received a scholarship from the China Scholarship Council. Boyi Dai received funding from the National Science Foundation (1933409).

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References

Agel, J., Rockwood, T., & Klossner, D. (2016). Collegiate ACL injury rates across 15 sports: National collegiate athletic association injury surveillance system data update (2004-2005 Through 2012-2013). *Clinical Journal of Sport Medicine*, *26*(6), 518–523. https://doi.org/10.1097/JSM.0000000000000290

Almonroeder, T. G., Kernozek, T., Cobb, S., Slavens, B., Wang, J., & Huddleston, W. (2019). Divided attention during cutting influences lower extremity mechanics in female athletes. *Sports Biomechanics*, *18*(3), 264–276. https://doi.org/10.1080/14763141.2017.1391327

Almonroeder, T. G., Tighe, S. M., Miller, T. M., & Lanning, C. R. (2020). The influence of fatigue on decision-making in athletes: A systematic review. *Sports Biomechanics*, *19*(1), 76–89. https://doi.org/10.1080/14763141.2018.1472798

Barber-Westin, S., & Noyes, F. R. (2020). One in 5 athletes sustain reinjury upon return to high-risk sports after ACL reconstruction: A systematic review in 1239 athletes younger than 20 years. *Sports Health*, *12*(6), 587–597. http://doi.org/10.1177/1941738120912846

Blackburn, J. T., & Padua, D. A. (2008). Influence of trunk flexion on hip and knee joint kinematics during a controlled drop landing. *Clinical Biomechanics*, *23*(3), 313–319. https://doi.org/10.1016/j.clinbiomech.2007.10.003

Blackburn, J. T., & Padua, D. A. (2009). Sagittal-plane trunk position, landing forces, and quadriceps electromyographic activity. *Journal of Athletic Training*, *44*(2), 174–179. https://doi.org/10.4085/1062-6050-44.2.174

Boden, B. P., Dean, G. S., Feagin, Jr, J. A., & Garrett, Jr, W. E. (2000). Mechanisms of anterior cruciate ligament injury. *Orthopedics*, *23*(6), 573–578. https://doi.org/10.3928/0147-7447-20000601-15

Brophy, R. H., Stepan, J. G., Silvers, H. J., & Mandelbaum, B. R. (2015). Defending puts the anterior cruciate ligament at risk during soccer: A gender-based analysis. *Sports Health*, *7*(3), 244–249. http://doi.org/10.1177/1941738114535184

Carlson, V. R., Sheehan, F. T., & Boden, B. P. (2016). Video analysis of anterior cruciate ligament (ACL) injuries: A systematic review. *JBJS Reviews*, *4*(11), e5. https://doi.org/10.2106/JBJS.RVW.15.00116

Chijimatsu, M., Ishida, T., Yamanaka, M., Taniguchi, S., Ueno, R., Ikuta, R., Samukawa, M., Ino, T., Kasahara, S., & Tohyama, H. (2020). Landing instructions focused on pelvic and trunk lateral tilt decrease the knee abduction moment during a single-leg drop vertical jump. *Physical Therapy in Sport*, *46*, 226–233. https://doi.org/10.1016/j.ptsp.2020.09.010

Cochrane, J. L., Lloyd, D. G., Buttfield, A., Seward, H., & McGivern, J. (2007). Characteristics of anterior cruciate ligament injuries in Australian football. *Journal of Science and Medicine in Sport*, *10*(2), 96–104. https://doi.org/10.1016/j.jsams.2006.05.015

Critchley, M. L., Davis, D. J., Keener, M. M., Layer, J. S., Wilson, M. A., Zhu, Q., & Dai, B. (2020). The effects of mid-flight whole-body and trunk rotation on landing mechanics: Implications for anterior cruciate ligament injuries. *Sports Biomechanics*, *19*(4), 421–437. https://doi.org/10.1080/14763141.2019.1595704

Dai, B., Mao, D., Garrett, W. E., & Yu, B. (2014). Anterior cruciate ligament injuries in soccer: Loading mechanisms, risk factors, and prevention programs. *Journal of Sport and Health Science*, *3*(4), 299–306. https://doi.org/10.1016/j.jshs.2014.06.002

Dai, B., Mao, M., Garrett, W. E., & Yu, B.,(2015). Biomechanical characteristics of an anterior cruciate ligament injury in javelin throwing. *Journal of Sport and Health Science*, *4*(4), 333–340. https://doi.org/10.1016/j.jshs.2015.07.004

Dai, B., Cook, R. F., Meyer, E. A., Sciascia, Y., Hinshaw, T. J., Wang, C., & Zhu, Q. (2018). The effect of a secondary cognitive task on landing mechanics and jump performance. *Sports Biomechanics*, *17*(2), 192–205. https://doi.org/10.1080/14763141.2016.1265579

Dai, B., Layer, J. S., Bordelon, N. M., Critchley, M. L., LaCroix, S. E., George, A. C., Li, L., Ross, J. D., & Jensen, M. A. (in press). Longitudinal assessments of balance and jump-landing performance before and after anterior cruciate ligament injuries in collegiate athletes. *Research in Sports Medicine*. http://doi.org/10.1080/15438627.2020.1721290

Davis, D. J., Hinshaw, T. J., Critchley, M. L., & Dai, B. (2019). Mid-flight trunk flexion and extension altered segment and lower extremity joint movements and subsequent landing mechanics. *Journal of Science and Medicine in Sport*, *22*(8), 955–961. https://doi.org/10.1016/j.jsams.2019.03.001

de Leva, P. (1996). Adjustments to Zatsiorsky-Seluyanov's segment inertia parameters. *Journal of Biomechanics*, *29*(9), 1223–1230. http://doi.org/10.1016/0021-9290(95)00178-6

Della Villa, F., Buckthorpe, M., Grassi, A., Nabiuzzi, A., Tosarelli, F., Zaffagnini, S., & Della Villa, S. (2020). Systematic video analysis of ACL injuries in professional male football (soccer): Injury mechanisms, situational patterns and biomechanics study on 134 consecutive cases. *British Journal of Sports Medicine*, *54*(23), 1423–1432. https://doi.org/10.1136/bjsports-2019-101247

Dempsey, A. R., Lloyd, D. G., Elliott, B. C., Steele, J. R., Munro, B. J., & Russo, K. A. (2007). The effect of technique change on knee loads during sidestep cutting. *Medicine and Science in Sports and Exercise*, *39*(10), 1765–1773. https://doi.org/10.1249/mss.0b013e31812f56d1

Dempsey, A. R., Lloyd, D. G., Elliott, B. C., Steele, J. R., & Munro, B. J. (2009). Changing sidestep cutting technique reduces knee valgus loading. *The American Journal of Sports Medicine*, *37*(11), 2194–2200. https://doi.org/10.1177/0363546509334373

Dempsey, A. R., Elliott, B. C., Munro, B. J., Steele, J. R., & Lloyd, D. G. (2012). Whole body kinematics and knee moments that occur during an overhead catch and landing task in sport. *Clinical Biomechanics*, *27*(5), 466–474. https://doi.org/10.1016/j.clinbiomech.2011.12.001

Devetag, F., Mazzilli, M., Benis, R., La Torre, A., & Bonato, M. (2018). Anterior cruciate ligament injury profile in Italian serie A1-A2 women's volleyball league. *Journal of Sports Medicine and Physical Fitness*, *58*, 92–97. http://doi.org/10.23736/S0022-4707.16.06731-1

Dingenen, B., Malfait, B., Nijs, S., Peers, K. H. E., Vereecken, S., Verschueren, S. M. P., & Staes, F. F. (2015). Can two-dimensional video analysis during single-leg drop vertical jumps help identify non-contact knee injury risk? A one-year prospective study. *Clinical Biomechanics*, *30*(8), 781–787. https://doi.org/10.1016/j.clinbiomech.2015.06.013

Englander, Z. A., Baldwin, E. L., Smith, W. A. R., Garrett, W. E., Spritzer, C. E., & DeFrate, L. E. (2019). In vivo anterior cruciate ligament deformation during a single-legged jump measured by magnetic resonance imaging and high-speed biplanar radiography. *The American Journal of Sports Medicine*, *47*(13), 3166–3172. https://doi.org/10.1177/0363546519876074

Fox, A. (2018). Change-of-Direction Biomechanics: Is what's best for anterior cruciate ligament injury prevention also best for performance? *Sports Medicine*, *48*(8), 1799–1807. https://doi.org/10.1007/s40279-018-0931-3

Frank, B., Bell, D. R., Norcross, M. F., Blackburn, J. T., Goerger, B. M., & Padua, D. A. (2013). Trunk and hip biomechanics influence anterior cruciate loading mechanisms in physically active participants. *The American Journal of Sports Medicine*, *41*(11), 2676–2683. https://doi.org/10.1177/0363546513496625

Grassi, A., Smiley, S. P., Roberti Di Sarsina, T., Signorelli, C., Marcheggiani Muccioli, G. M., Bondi, A., Romagnoli, M., Agostini, A., & Zaffagnini, S. (2017). Mechanisms and situations of anterior cruciate ligament injuries in professional male soccer players: A YouTube-based video analysis. *European Journal of Orthopaedic Surgery & Traumatology*, *27*(7), 967–981. https://doi.org/10.1007/s00590-017-1905-0

Havens, K. L., & Sigward, S. M. (2015). Cutting mechanics: Relation to performance and anterior cruciate ligament injury risk. *Medicine and Science in Sports and Exercise*, *47*(4), 818–824. https://doi.org/10.1249/MSS.0000000000000470

Heinrich, D., van den Bogert, A. J., & Nachbauer, W. (2018). Peak ACL force during jump landing in downhill skiing is less sensitive to landing height than landing position. *British Journal of Sports Medicine*, *52*(17), 1086–1090. https://doi.org/10.1136/bjsports-2017-098964

Hewett, T. E., Myer, G. D., Ford, K. R., Heidt, R. S., Colosimo, A. J., McLean, S. G., van den Bogert, A. J., Paterno, M. V., & Succop, P. (2005). Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: A prospective study. *The American Journal of Sports Medicine*, *33*(4), 492–501. https://doi.org/10.1177/0363546504269591

Hewett, T. E., Torg, J. S., & Boden, B. P. (2009). Video analysis of trunk and knee motion during non-contact anterior cruciate ligament injury in female athletes: Lateral trunk and knee abduction motion are combined components of the injury mechanism. *British Journal of Sports Medicine*, *43*(6), 417–422. https://doi.org/10.1136/bjsm.2009.059162

Hewett, T. E., & Myer, G. D. (2011). The mechanistic connection between the trunk, hip, knee, and anterior cruciate ligament injury. *Exercise and Sport Sciences Reviews*, *39*(4), 161–166. https://doi.org/10.1097/JES.0b013e3182297439

Hinshaw, T. J., Davis, D. J., Layer, J. S., Wilson, M. A., Zhu, Q., & Dai, B. (2019). Mid-flight lateral trunk bending increased ipsilateral leg loading during landing: A center of mass analysis. *Journal of Sports Sciences*, *37*(4), 414–423. https://doi.org/10.1080/02640414.2018.1504616

Hughes, G. (2014). A review of recent perspectives on biomechanical risk factors associated with anterior cruciate ligament injury. *Research in Sports Medicine*, *22*(2), 193–212. https://doi.org/10.1080/15438627.2014.881821

Jamison, S. T., Pan, X., & Chaudhari, A. M. W. (2012). Knee moments during run-to-cut maneuvers are associated with lateral trunk positioning. *Journal of Biomechanics*, *45*(11), 1881–1885. http://doi.org/1881-1885.10.1016/j.jbiomech.2012.05.031

Jamison, S. T., McNally, M. P., Schmitt, L. C., & Chaudhari, A. M. W. (2013). The effects of core muscle activation on dynamic trunk position and knee abduction moments: Implications for ACL injury. *Journal of Biomechanics*, *46*(13), 2236–2241. https://doi.org/10.1016/j.jbiomech.2013.06.021

Johnston, J. T., Mandelbaum, B. R., Schub, D., Rodeo, S. A., Matava, M. J., Silvers-Granelli, H. J., Cole, B. J., ElAttrache, N. S., McAdams, T. R., & Brophy, R. H. (2018). Video analysis of anterior cruciate ligament tears in professional american football athletes. *The American Journal of Sports Medicine*, *46*(4), 862–868. https://doi.org/10.1177/0363546518756328

Jones, P. A., Herrington, L. C., & Graham-Smith, P. (2015). Technique determinants of knee joint loads during cutting in female soccer players. *Human Movement Science*, *42*, 203–211. https://doi.org/10.1016/j.humov.2015.05.004

Kay, M. C., Register-Mihalik, J. K., Gray, A. D., Djoko, A., Dompier, T. P., & Kerr, Z. Y. (2017). The epidemiology of severe injuries sustained by National Collegiate Athletic Association Student-Athletes, 2009-2010 through 2014-2015. *Journal of Athletic Training*, *52*(2), 117–128. http://doi.org/10.4085/1062-6050-52.1.01

Kimura, Y., Ishibashi, Y., Tsuda, E., Yamamoto, Y., Tsukada, H., & Toh, S. (2010). Mechanisms for anterior cruciate ligament injuries in badminton. *British Journal of Sports Medicine*, *44*(15), 1124–1127. https://doi.org/10.1136/bjsm.2010.074153

Koga, H., Nakamae, A., Shima, Y., Iwasa, J., Myklebust, G., Engebretsen, L., Bahr, R., & Krosshaug, T. (2010). Mechanisms for noncontact anterior cruciate ligament injuries: Knee joint kinematics in 10 injury situations from female team handball and basketball. *The American Journal of Sports Medicine*, *38*(11), 2218–2225. https://doi.org/10.1177/0363546510373570

Kristianslund, E., Faul, O., Bahr, R., Myklebust, G., & Krosshaug, T. (2014). Sidestep cutting technique and knee abduction loading: Implications for ACL prevention exercises. *British Journal of Sports Medicine*, *48*(9), 779–783. https://doi.org/10.1136/bjsports-2012-091370

Krosshaug, T., & Bahr, R. (2005). A model-based image-matching technique for three-dimensional reconstruction of human motion from uncalibrated video sequences. *Journal of Biomechanics*, *38*(4), 919–929. https://doi.org/10.1016/j.jbiomech.2004.04.033

Krosshaug, T., Nakamae, A., Boden, B. P., Engebretsen, L., Smith, G., Slauterbeck, J. R., Hewett, T. E., & Bahr, R. (2007). Mechanisms of anterior cruciate ligament injury in basketball: Video analysis of 39 cases. *The American Journal of Sports Medicine*, *35*(3), 359–367. https://doi.org/10.1177/0363546506293899

Krosshaug, T., Steffen, K., Kristianslund, E., Nilstad, A., Mok, K. M., Myklebust, G., Andersen, T. E., Holme, I., Engebretsen, L., & Bahr, R. (2016). The vertical drop jump is a poor screening test for ACL injuries in female elite soccer and handball players: A prospective cohort study of 710 athletes. *The American Journal of Sports Medicine*, *44*(4), 874–883. http://doi.org/10.1177/0363546515625048

Leppanen, M., Pasanen, K., Krosshaug, T., Kannus, P., Vasankari, T., Kujala, U. M., Bahr, R., Perttunen, J., & Parkkari, J. (2017). Sagittal Plane hip, knee, and ankle biomechanics and the risk of anterior cruciate ligament injury: A prospective study. *Orthopaedic Journal of Sports Medicine*, *5*(12), 2325967117745487. https://doi.org/10.1177/2325967117745487

Leppanen, M., Pasanen, K., Kujala, U. M., Vasankari, T., Kannus, P., Ayramo, S., Krosshaug, T., Bahr, R., Avela, J., Perttunen, J., & Parkkari, J. (2017). Stiff landings are associated with increased acl injury risk in young female basketball and floorball players. *The American Journal of Sports Medicine*, *45*(2), 386–393. https://doi.org/10.1177/0363546516665810

Li, L., Baur, M., Baldwin, K., Kuehn, T., Zhu, Q., Herman, D., & Dai, B. (in press). Falling as a strategy to decrease knee loading during landings: Implications for ACL injury prevention. *Journal of Biomechanics*. http://doi.org/10.1016/j.jbiomech.2020.109906

Mather, R. C., Koenig, L., Kocher, M. S., Dall, T. M., Gallo, P., Scott, D. J., Bach, B. R., Spindler, K. P., & Knee Group, M. O. O. N. (2013). Societal and economic impact of anterior cruciate ligament tears. *The Journal of Bone and Joint Surgery. American Volume*, *95*(19), 1751–1759. http://doi.org/10.2106/JBJS.L.01705

Montgomery, C., Blackburn, J., Withers, D., Tierney, G., Moran, C., & Simms, C. (2018). Mechanisms of ACL injury in professional rugby union: A systematic video analysis of 36 cases. *British Journal of Sports Medicine*, *52*(15), 994–1001. https://doi.org/10.1136/bjsports-2016-096425

Oh, Y. K., Lipps, D. B., Ashton-Miller, J. A., & Wojtys, E. M. (2012). What strains the anterior cruciate ligament during a pivot landing? *The American Journal of Sports Medicine*, *40*(3), 574–583. https://doi.org/10.1177/0363546511432544

Olsen, O. E., Myklebust, G., Engebretsen, L., & Bahr, R. (2004). Injury mechanisms for anterior cruciate ligament injuries in team handball: A systematic video analysis. *The American Journal of Sports Medicine*, *32*(4), 1002–1012. http://doi.org/10.1177/0363546503261724

Padua, D. A., DiStefano, L. J., Beutler, A. I., de la Motte, S. J., DiStefano, M. J., & Marshall, S. W. (2015). The Landing Error Scoring System as a screening tool for an anterior cruciate ligament injury-prevention program in elite-youth soccer athletes. *Journal of Athletic Training*, *50*(6), 589–595. http://doi.org/10.4085/1062-6050-50.1.10

Poulsen, E., Goncalves, G. H., Bricca, A., Roos, E. M., Thorlund, J. B., & Juhl, C. B. (2019). Knee osteoarthritis risk is increased 4-6 fold after knee injury - a systematic review and meta-analysis. *British Journal of Sports Medicine*, *53*(23), 1454–1463. http://doi.org/10.1136/bjsports-2018-100022

Saito, A., Okada, K., Sasaki, M., & Wakasa, M. (in press). Influence of the trunk position on knee kinematics during the single-leg landing: Implications for injury prevention. *Sports Biomechanics*. http://doi.org/10.1080/14763141.2019.1691642

Sharir, R., Rafeeuddin, R., Staes, F., Dingenen, B., George, K., Vanrenterghem, J., & Robinson, M. A. (2016). Mapping current research trends on anterior cruciate ligament injury risk against the existing evidence: In vivo biomechanical risk factors. *Clinical Biomechanics*, *37*, 34–43. https://doi.org/10.1016/j.clinbiomech.2016.05.017

Sheehan, F. T., Sipprell, W. H., & Boden, B. P. (2012). Dynamic sagittal plane trunk control during anterior cruciate ligament injury. *The American Journal of Sports Medicine*, *40*(5), 1068–1074. https://doi.org/10.1177/0363546512437850

Shimokochi, Y., Yong Lee, S., Shultz, S. J., & Schmitz, R. J. (2009). The relationships among sagittal-plane lower extremity moments: Implications for landing strategy in anterior cruciate ligament injury prevention. *Journal of Athletic Training*, *44*(1), 33–38. https://doi.org/10.4085/1062-6050-44.1.33

Shimokochi, Y., Ambegaonkar, J. P., Meyer, E. G., Lee, S. Y., & Shultz, S. J. (2013). Changing sagittal plane body position during single-leg landings influences the risk of non-contact anterior cruciate ligament injury. *Knee Surgery, Sports Traumatology, Arthroscopy*, *21*(4), 888–897. https://doi.org/10.1007/s00167-012-2011-9

Smith, H. C., Johnson, R. J., Shultz, S. J., Tourville, T., Holterman, L. A., Slauterbeck, J., Vacek, P. M., & Beynnon, B. D. (2012). A prospective evaluation of the Landing Error Scoring System (LESS) as a screening tool for anterior cruciate ligament injury risk. *The American Journal of Sports Medicine*, *40*(3), 521–526. https://doi.org/10.1177/0363546511429776

Stephenson, M. L., Hinshaw, T. J., Wadley, H. A., Zhu, Q., Wilson, M. A., Byra, M., & Dai, B. (2018). Effects of timing of signal indicating jump directions on knee biomechanics in jump-landing-jump tasks. *Sports Biomechanics*, *17*(1), 67–82. https://doi.org/10.1080/14763141.2017.1346141

Stuelcken, M. C., Mellifont, D. B., Gorman, A. D., & Sayers, M. G. (2016). Mechanisms of anterior cruciate ligament injuries in elite women's netball: A systematic video analysis. *Journal of Sports Sciences*, *34*(16), 1516–1522. https://doi.org/10.1080/02640414.2015.1121285

Walden, M., Krosshaug, T., Bjorneboe, J., Andersen, T. E., Faul, O., & Hagglund, M. (2015). Three distinct mechanisms predominate in non-contact anterior cruciate ligament injuries in male professional football players: A systematic video analysis of 39 cases. *British Journal of Sports Medicine*, *49*(22), 1452–1460. https://doi.org/10.1136/bjsports-2014-094573

Whyte, E. F., Richter, C., O'connor, S., & Moran, K. A. (2018). The effect of high intensity exercise and anticipation on trunk and lower limb biomechanics during a crossover cutting manoeuvre. *Journal of Sports Sciences*, *36*(8), 889–900. https://doi.org/10.1080/02640414.2017.1346270

Widenhoefer, T. L., Miller, T. M., Weigand, M. S., Watkins, E. A., & Almonroeder, T. G. (2019). Training rugby athletes with an external attentional focus promotes more automatic adaptions in landing forces. *Sports Biomechanics*, *18*(2), 163–173. https://doi.org/10.1080/14763141.2019.1584237

Wise, P. M., & Gallo, R. A. (2019). Impact of anterior cruciate ligament reconstruction on ncaa fbs football players: Return to play and performance vary by position. *Orthopaedic Journal of Sports Medicine*, *7*(4). https://doi.org/10.1177/2325967119841056

Yom, J. P., Simpson, K. J., Arnett, S. W., & Brown, C. N. (2014). The effects of a lateral in-flight perturbation on lower extremity biomechanics during drop landings. *Journal of Applied Biomechanics*, *30*(5), 655–662. https://doi.org/10.1123/jab.2013-0331

Zahradnik, D., Jandacka, D., Beinhauerova, G., & Hamill, J. (2020). Associated ACL risk factors differences during an unanticipated volleyball blocking movement. *Journal of Sports Sciences*, *38*(20), 2367–2373. https://doi.org/10.1080/02640414.2020.1785727

Zazulak, B. T., Hewett, T. E., Reeves, N. P., Goldberg, B., & Cholewicki, J. (2007). Deficits in neuromuscular control of the trunk predict knee injury risk: A prospective biomechanical-epidemiologic study. *The American Journal of Sports Medicine*, *35*(7), 1123–1130. https://doi.org/10.1177/0363546507301585