Trunk Neuromuscular Function and Anterior Cruciate Ligament Injuries: A Narrative Review of Trunk Strength, Endurance, and Dynamic Control

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ABSTRACT

Trunk strength, endurance, and dynamic control may have an effect on anterior cruciate ligament (ACL) injury rates and biomechanical ACL loading variables during athletic tasks. Individuals responsible for training athletes at risk of ACL injuries should implement training programs that address these components of athletic performance. In ski racers, deficits in trunk flexion/extension strength and decreased trunk flexion/extension strength ratios have been identified as ACL injury risk factors. Trunk strength training alone is not sufficient to decrease biomechanical ACL loading, and there is no clear association between trunk endurance and ACL injury risks. Trunk dynamic control training may improve trunk and knee movements associated with decreased ACL loading during athletic tasks. Dynamic, unanticipated, and perturbed trunk functional assessments and training are recommended to challenge the trunk more during athletic tasks. Injury prevention programs should involve exercises using unstable surfaces, sports-related dual tasks, and perturbations to address trunk dynamic control. More investigation is still needed to further understand the associations between trunk neuromuscular functions and ACL injury risks during athletic tasks.

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INTRODUCTION

The anterior cruciate ligament (ACL) injury is one of the most frequent severe sports injuries, with an annual occurrence of approximately 120,000 in the United States (21). Surgical ACL reconstructions and rehabilitation are primary choices for patients after ACL injuries, creating a $7.6–$17.7 billion financial burden per year (28). ACL injuries result in abnormal neuromuscular function (14), elevated knee reinjury rates, and increased risks of knee osteoarthritis (36). A majority of ACL injuries occur without direct contact during landing, cutting, and deceleration maneuvers (16), whereas contact to the body other than the injured knee joint results in between 8 and 60% of ACL injuries in different sports (39). Efforts have been made to understand and prevent ACL injuries, but the injury rates have not significantly decreased (1).

There is a growing body of evidence supporting the role of trunk movements in the sagittal and frontal planes on the risk of ACL injuries. Analyses of ACL injury videos have shown that limited trunk flexion, increased distance between the

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center of mass (COM) and the base of support in the sagittal plane (15,38), and lateral trunk bending toward the landing or cutting leg (9,40) are associated with increased ACL injury risk. In addition, trunk contact (external objects or players contacting with the trunk region) has been frequently observed before the time of injury (9,24,42). Furthermore, trunk and/or arms contact near the time of injury accounts for more than 80% of the ACL injuries involving indirect contact (external objects or players contacting with body parts other than the injured knee) (9,23,42). Consistently, control laboratory-based studies have demonstrated that limited trunk flexion, lateral trunk bending before and during landing, and midflight external trunk perturbation result in landing and cutting mechanics associated with increased ACL loading (6,7,10,44,47). The kinetic relationships between trunk motion and knee loading may be explained by the redistributions of segment COM and angular momentum, changes of external moment arms, force and torque action and reaction, and changes in muscle lengths (39). However, although the role of trunk motion and external perturbation on ACL injury risk and ACL loading variables during athletic tasks has been summarized recently (39), there is a lack of review of the underlying neuromuscular mechanisms that may result in altered trunk motion and elevated ACL injury risk.

Trunk neuromuscular function is defined as the ability to control the trunk and maintain core stability during dynamic activities (31) through the involvement of the passive tissues, active musculature, and neural control subsystems (32). Primary lower trunk muscles include the rectus abdominis, erector spinae, quadratus lumborum, internal oblique, external oblique, and transverse abdominis (22,29). The musculature can be characterized by trunk muscle strength and endurance, and the neural control may involve proprioception, muscle activation, and the ability to respond to external perturbation (4,13,30,49,50). Deficits in the neuromuscular function of the trunk might lead to abnormal trunk motion during dynamic activities, resulting in an increased risk of ACL injuries (13). In addition, the trunk region is a significant target during training, and its neuromuscular function can be improved with specific exercises (12,13,31,41,43). Based on the abnormal trunk motion observed during ACL injuries (39) and the identified role of core stability in previous studies (5), it is crucial to clarify how the effect of certain perspectives of trunk neuromuscular functions might be related to ACL injury rates or ACL loading variables during athletic tasks.

Therefore, the overall purpose of the current narrative review was to summarize the role of trunk neuromuscular function, including trunk strength, endurance, and dynamic control, on ACL injury rates or ACL loading variables during athletic tasks. The summaries of the current review may provide valuable information for (a) understanding the modifiable risk factors associated with trunk neuromuscular functions for ACL injuries, (b) identifying effective assessment strategies to assess deficits of different trunk neuromuscular functions for ACL injury risk screening, and (c) informing the development of effective trunk neuromuscular intervention programs for ACL injury prevention.

LITERATURE SEARCH AND STUDY SELECTION

Potential studies have been identified by searching the PubMed electronic database. Various combinations of search terms were used: "anterior cruciate ligament," "ACL," "ACL injury," "ACL injuries," "trunk strength," "trunk endurance," "trunk neuromuscular control," "trunk control," "trunk stability," "trunk neuromuscular training," "trunk proprioception," "core strength," "core endurance," "core neuromuscular control," "core control," "core stability," "core neuromuscular training," "core proprioception," "neuromuscular control," "injury prevention," and "muscle activation." Additional studies were included based on the references cited in previously identified studies. The current narrative review attempted to cover several topics relevant to the trunk, while there was limited literature for certain areas. Therefore, a meta-analysis with a stricter literature search and study selection strategy was not performed.

The inclusion criteria involved studies that (a) prospectively quantified the role of trunk neuromuscular function in ACL injury rates; (b) evaluated the effect of trunk neuromuscular function on knee loading variables during landing and cutting; (c) used isokinetic or isometric forces of the trunk regions for trunk strength assessments; (d) used trunk exercises for trunk strength intervention; (e) measured a maximal duration of holding the trunk in flexion, extension, or laterally aligned postures for trunk endurance assessments; (f) included trunk exercises for trunk endurance intervention; (g) assessed proprioception, muscle activation, and responses to the external perturbation for trunk dynamic control assessments; and (h) implemented trunk exercises for trunk dynamic intervention.

TRUNK STRENGTH AND ANTERIOR CRUCIATE LIGAMENT INJURY RATES

Muscular strength is defined as the ability to exert maximal force on the environment (48). Active muscle forces produce trunk movements in 3 planes and play an important role in maintaining trunk stability (4,30). The magnitude of the force depends on several characteristics such as muscle size and length, movement velocities, and neural activation. Studies that have quantified trunk strength at preinjury assessments and tracked ACL injury rates over time can elucidate a cause-and-effect relationship between trunk strength and ACL injury risk.

One study analyzed retrospective data of 175 female and 195 male adolescent alpine ski racers between 14 and 19 years from 1996 to 2006 (35). Racers performed preinjury baseline assessments for their anthropometric measurements and physical functions, including maximal isometric trunk flexion and extension strength. In 10 years, 57 ACL injuries occurred in 39 female racers and 18 male racers. Z scores for the ratio of absolute trunk flexion to extension strength and relative or absolute trunk strength were predictive variables for ACL injuries in male and female racers, with the injured groups generally demonstrating lower flexion to extension ratios and decreased overall trunk strength. Therefore, decreased trunk flexion strength relative to trunk extension strength and deficits in overall trunk flexion and extension strength are ACL injury risk factors in adolescent alpine ski racers. These findings were consistent with a simulation study, showing that peak ACL loading was 8 times more sensitive to increases in trunk extension compared with landing heights in alpine skiing landing (11). A decreased trunk flexion to extension strength ratio might contribute to the increased trunk extension during landings and increase ACL loading and injury risk in alpine ski racers. However, the study by Raschner et al. (35) assessed trunk strength using a self-developed test device, and the reliability and relationships among different trunk strength tests have been questioned (20). A more standard method to assess trunk strength is recommended to allow reliable comparisons among future studies. In addition, alpine skiing has relatively high ACL injury rates, but it may involve different ACL injury mechanisms compared with team sports that involve more jump-landing and cutting maneuvers. Thus, future studies are warranted to quantify trunk strength and ACL injury rates in team sports. Trunk strength training is critical in alpine ski racers, but its effects on ACL injury risks in other athletes are unclear.

TRUNK ENDURANCE AND ANTERIOR CRUCIATE LIGAMENT INJURY RATES

Muscular endurance is defined as the ability to maintain force production over repeated or prolonged contractions, and trunk endurance is another musculature aspect that may affect trunk kinematics (4,37). Commonly used trunk endurance tests involve holding the trunk in flexion, extension, or laterally aligned postures for a maximal duration (26). Previous studies have prospectively quantified the effects of trunk endurance on overall lower extremity injuries and found that decreased trunk endurance (45,46) and hip strength (8,26) were associated with an increased risk of lower extremity injuries in athletes. However, most of these studies did not differentiate ACL injuries from the overall lower extremity injuries. Only 1 study mentioned a female athlete with an ACL injury who demonstrated decreased hip muscle strength and trunk endurance compared with the performance of the uninjured group (26). The trunk extension endurance was only one-third, and the lateral endurance was only half of the performance of the uninjured group for this injured athlete. These preliminary findings support a potential link between trunk endurance and ACL injury risk, but more studies with a focus on ACL injuries are needed to test these hypotheses. Thus, trunk extension and lateral endurance training may be a part but should not be the only focus for preventing ACL injuries based on current evidence.

TRUNK DYNAMIC CONTROL AND ANTERIOR CRUCIATE LIGAMENT INJURY RATES

In addition to muscular strength and endurance, trunk dynamic control is another important characteristic for maintaining a stable trunk (4,49,50). Trunk dynamic control highlights the interactions between the body and the external environment through constant feedback and movement adjustments. The trunk dynamic control may involve and can be assessed through proprioception (the active repositioning error of the trunk), muscle activation (the amount of activated muscle relative to overall muscle volume), and responses to the external perturbation (the reactive repositioning error of the trunk) (4,49,50).

Prospective studies quantified the association between trunk proprioception and trunk responses to external perturbation on the overall knee and ACL injuries (49,50). Researchers followed 277 collegiate athletes for 3 years, and 6 ACL injuries occurred during the study period. At baseline assessments, the trunk proprioception was evaluated by actively reproducing the trunk position that participants had passively experienced in the transverse plane in a seated position. The trunk's responses to external perturbation were assessed by an apparatus quickly releasing a force from a preloaded trunk in 3 directions (flexion, extension, and lateral) in a semiseated position. The errors during the proprioceptive repositioning tasks predicted overall knee injuries but did not significantly predict ACL injuries, likely due to the low number of injury cases. Meanwhile, the ACL-injured athletes showed a greater trunk displacement responding to the suddenly released force than uninjured athletes. Increased flexion, extension, and lateral trunk displacements after perturbation predicted ACL injuries with 83% sensitivity and 76% specificity. The author concluded that deficits in trunk dynamic control might contribute to unstable movement patterns through the trunk and lower extremity kinetic chain and increase ACL injury risk.

In summary, ineffective responses to external perturbation to the trunk may be associated with increased ACL injury risk. Future studies may include trunk perturbation tasks that are more sports related to better represent the dynamic nature of the athletic maneuvers commonly seen in ACL injuries. The association between trunk proprioception and ACL injury risk might be weaker and require a larger sample size to identify their relationship. Trunk muscle activation during high-risk tasks is another dynamic control component that warrants future investigation. Overall, because of the difficulty to evaluate and track a large sample size to observe sufficient ACL injuries for statistical power, there were limited studies that have directly quantified trunk neuromuscular control and ACL injury rates. Although there are increasing studies to predict ACL injury from lower extremity biomechanics, it is recommended that future studies can incorporate trunk neuromuscular control into lower extremity assessments to potentially increase the sensitivity and specificity of ACL injury prediction. Practitioners are suggested to incorporate trunk perturbation exercises to screen for future ACL injury risks.

TRUNK STRENGTH AND JUMP-LANDING AND CUTTING MECHANICS ASSOCIATED WITH ANTERIOR CRUCIATE LIGAMENT LOADING

One strategy to overcome the difficulty in directly assessing trunk neuromuscular control and ACL injury risk is to assess the relationship between trunk neuromuscular control and variables associated with ACL loading during athletic tasks. Although actual ACL injuries are not likely to occur in a laboratory setting, indirect relationships can be established based on well-understood ACL loading mechanisms (3). These relationships have been assessed through correlational and interventional studies.

CORRELATIONAL STUDIES

The correlations between trunk strength and trunk, hip, and knee kinematics during landings have been investigated in 2 previous studies (27,34). In one study, the maximal isokinetic trunk flexion and extension strength were assessed in a standing position, with the trunk moving between 458 of flexion and 108 of extension (34). Significantly negative but weak correlations were found between trunk extension strength and knee valgus displacement during double-leg landings. In the other study, the lateral trunk maximal isometric strength was assessed in a side plank position using a handheld dynamometer placed on the iliac crest (27). However, no significant correlations were observed between lateral trunk strength and trunk, hip, and knee kinematics during single-leg landings. Overall, these 2 studies suggested minimal to weak correlations between trunk strength and lower extremity kinematics associated with ACL loading during landings.

INTERVENTIONAL STUDIES

Despite weak correlations between trunk strength and ACL loading variables during athletic tasks, intervention programs have been developed to alter ACL loading variables through trunk strength training (Table 1). Most previous strength intervention programs involved multiple exercise modalities, so it was difficult to identify the isolated effect of strengthening the trunk. Therefore, the current subsection only included the studies implementing trunk strengthening exercises to modify ACL loading variables or risk factors.

Sasaki et al. (37) investigated the effect of trunk strength training on the trunk, hip, and knee muscle strength and landing mechanics in female collegiate basketball athletes. The training included the plank, side plank, and Nordic hamstrings exercises 4 times or more each week for 8 weeks. After the training, the intervention group significantly increased the isokinetic strength of the trunk extensors and flexors, knee flexors, and hip flexors and abductors in a seated or prone position. Regarding landing biomechanics, the training group demonstrated decreased ACL loading variables during double-leg landings. Kumahara et al. (25) investigated the effect of the same trunk training on trunk muscle strength, neuromuscular control, and knee kinematics during landings after 6 and 12 months of training in male pediatric soccer athletes. The training group significantly increased the trunk flexion and extension strength at both 6 months and 12 months posttraining compared with baseline. The training group showed decreased ACL loading variables at 6 months posttraining, whereas no significant differences were seen at 12 months posttraining compared with baseline. Jamison et al. (18) compared the effect of 6-week trunk training and traditional resistance training on the trunk and leg strength, trunk endurance, and knee moments during cutting tasks in males. The trunk training included plank, side plank, sagittal and diagonal abdominal curls, lunges, hip abduction, supine bridge, and quadruped exercises 3 times each week. The trunk flexion, extension, and lateral strength were assessed in a semikneeling position by pulling against the cable attached around the 10th thoracic vertebra. The leg strength was estimated using a calculation based on a 1 repetition maximum during the deadlift. The trunk endurance was assessed by recording the performance in plank, side plank, and trunk flexor exercises. After training, the leg strength increased in both groups, whereas the trunk lateral strength (bending to the dominant side) only increased for the trunk training group. The lateral endurance increased and was greater than the resistance training group. Only 1 ACL loading variable increased after traditional resistance training compared with no significant changes after training.

In summary, minimal to weak correlations have been observed between trunk strength and lower extremity kinematics associated with ACL loading during landings. Future studies are encouraged to identify the correlations between trunk strength measured by different assessments and trunk movements, as well as lower extremity kinematics during landing and cutting tasks. In addition, trunk strength can be significantly improved through specific trunk strength intervention programs. However, the effects of trunk strength training on landing or cutting mechanics were not consistent among different populations, assessment time points, and athletic tasks. Overall, trunk strength training alone may not be sufficient to significantly decrease ACL loading variables during jump-landing and cutting tasks, but the modalities of trunk strength training may be improved. Previous studies have generally included preplanned and voluntary trunk exercises with slow movement speeds for training,

Table 1
Intervention studies targeted the trunk neuromuscular function on ACL loading variables

Studies	Sports/samples	Tasks	Targeted trunk function	Intervention exercises	Intervention volume	Key results
Sasaki et al. (37)	Female collegiate basketball athletes Training group: 9 subjects (19.7 6 0.9 y) Control group: 8 subjects (20.3 6 2.5 y)	Drop vertical jump task from a 31-cm box	Trunk strength	Plank; side plank; Nordic hamstrings	Plyometric exercises with 2 or 3 levels. Overall, it took less than 10 min each session and at least 4 times per wk for 8 wk	Isokinetic peak trunk flexion and extension, hip flexion and abduction, and knee flexion strength increased after training. Peak trunk flexion angle increased, and the first peak knee valgus moment decreased after training. Knee and trunk flexion strength were greater, and trunk lateral bending angle was smaller in the training group than in the control group after training
Kumahara et al. (25)	Male pediatric soccer athletes Training group: 53 subjects after 6 mo and 49 subjects after 12 mo (11.8 6 1.1 y) Control group: 100 subjects after 12 mo (11.7 6 0.5 y)	Drop vertical jump task from a 35-cm box	Trunk strength	Plank; side plank; Nordic hamstrings	Plyometric exercises with 2 levels. Overall, it took around 5 min and each session at least 3 times per wk for 12 mo	Trunk flexion and extension strength increased after 6 it and 12 mo in the training group, respectively, and were greater in the training group than in the control group after 12 mo only. The knee to hip separation ratio in the frontal plane and peak knee flexion angles increased after 6 mo in the training group. The Y Balance Test reach distance in all directions increased after 6 and 12 mo on both legs in the training group, except the posteromedial direction on the nondominant side

Table 1
(continued)

Jamison et al. (18)	Male collegiate students had high school American football playing experiences Training group: 11 subjects (20.5 6 1.2 y) Control group (traditional resistance training): 11 subjects (20.3 6 1.5 y)	Unanticipated side-step cutting	Trunk strength	Plank; side plank; sagittal abdominal curl; diagonal abdominal curl; lunges; quadruped exercises; supine bridge; hip abduction	Plyometric exercises with 2 to 6 levels. Overall, the trunk training took 15 min each session and 3 times per wk for 6 wk	The training group increased in the trunk lateral bending strength (to the dominant side) and trunk flexion angles responded to a sudden force after training. The control group increased in the trunk flexion and lateral bending (to the dominant side) angles responded to a sudden force, and knee abduction moment after training. Leg strength increased in both groups after training. Side plank holding time increased in the training group and was greater than that in the control group
Pfile et al. (33)	Female high school lacrosse and soccer athletes Trunk focus group: 8 subjects (14.5 6 0.8 y) Plyometric group: 8 subjects (15.3 6 1.04 y) Control group: 6 subjects (14.8 6 0.4 y)	Drop vertical jump task from a 25-cm box	Trunk endurance	Side plank; abdominal draw in; crunch; lumbar extension; side-lying hip abduction and external rotation; lunges	Plyometric exercises with 2 levels. Overall, it took less than 20 min each session and 3 times per wk for 4 wk	The knee internal rotation moment decreased in the control group during the study period. The knee flexion angle and moment, knee internal rotation angle, and knee valgus moment decreased in the plyometric group after training. The knee flexion angle, hip flexion angle, and hip internal rotation moments decreased, whereas knee internal rotation angle increased in the trunk focus group after training. The plyometric group had a greater knee internal rotation angle than the trunk focus group before training; the difference was no longer present after training

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Araujo et al. (2)	Female capoeira athletes Training group: 16 subjects (27.3 6 3.7 y) Control group: N/A[a]	Drop vertical jump task from a 40-cm box	Trunk endurance	Plank; side plank; supine bridge; abdominal crunch; Russian twist; split leg scissors	Plyometric exercises with 3 levels. Overall, it took around 5–7 min each session and 3 times per week for 6 wk	Peak vertical GRF decreased 16%, and peak loading rate decreased 55% after training
Jeong et al.(19)	Recreationally active males Training group: 32 subjects (22.9 6 2.4 y) Control group: 16 subjects (23.1 6 1.1 y)	Side-step cutting	Trunk endurance	Plank; side plank; leg raise; crunch; superman; plank hip twist; supine bridge	Plyometric exercises with 2 levels. Overall, it took around 15 min each session and 3 times per week for 10 wk	Plank and side plank holding time and trunk flexion angle increased while hip adduction and knee valgus angles decreased in the training group. Muscle activations increased in the RA, VM, semitendinosus, VM/VL ratio, RA/ES ratio, and H/Q ratio while decreased in the rectus femoris after training. Weak negative correlations showed between side plank holding time and hip adduction and knee valgus angle changes, respectively. A weak negative correlation showed between plank holding time and knee valgus angle changes

Table 1
(continued)

Hewett et al. (12)	Female basketball, volleyball, and soccer athletes Training group: 222 subjects (14.0 6 1.7 y) Control group: 148 subjects (13.8 6 1.8 y)	Drop vertical jump task, single-leg drop task, and single-leg cross drop task from a 31-cm box	Trunk dynamic control	Table lateral and double crunches; BOSUb single-leg pelvic bridge and single-knee hold; back hyperextension with ball reach; tuck, lateral, and lunge jumps; hop-hold; lunge; single-leg lateral Airex and 908 hop-holds	Plyometric exercises with 5 levels. Overall, it took around 30 min each session and 2 to 3 times per week for 10 wk	For the single-leg cross drop task, the training group showed an increased peak trunk flexion angle and decreased peak trunk extension angle, whereas the control group showed a decreased peak trunk flexion angle and increased peak trunk extension angle. For the single-leg drop task, the training group showed increased hip external rotation moment and impulse, whereas the control group showed decreased moment and impulse. Athletes were defined as high-risk beneficial more on the trunk flexion and extension angles from training
Whyte et al. (43)	Male collegiate soccer athletes Training group: 15 subjects (22.05 6 1.47 y) Control group: 16 subjects (21.76 6 1.59 y)	Anticipated and unanticipated side-step and crossover cuttings	Trunk dynamic control	Dynamic plank; dynamic side plank; transversus abdominis activation; dynamic bridge; trunk curl; lunge	Plyometric exercises with 2 to 3 levels. Overall, it took 10–14 min each session and 3 times per week for 6 wk	For the anticipated condition, hip extension moment increased, whereas knee valgus and external rotation moments decreased during the side-step cutting task in the training group. Posterior GRF decreased in both anticipated and unanticipated conditions after training. Ankle plantar flexion angle decreased during crossover cutting in the training group

[a]N/A 5 no report.

[b]Domed Balance Trainer (TEAM BOSU, Canton, OH).

ACL 5 anterior cruciate ligament; ES 5 erector spinae; GRF 5 ground reaction force; H 5 hamstrings; Q 5 quadriceps; RA 5 rectus abdominis; VL 5 vastus lateralis; VM 5 vastus medialis.

whereas 1 study has suggested the need to include whole-body sports-related perturbation training for dynamic trunk strength training to elicit improvements in knee mechanics during athletic tasks. Furthermore, the athletic tasks were also performed without self-initiated or external perturbation to the trunk. As such, future studies are warranted to incorporate dynamic trunk strength training with perturbation and quantify its effects on knee mechanics during athletic tasks with trunk perturbation or higher demands of trunk strength. Overall, trunk strength training is recommended to be included as a fundamental component of ACL injury prevention programs.

TRUNK ENDURANCE AND JUMP-LANDING AND CUTTING MECHANICS ASSOCIATED WITH ANTERIOR CRUCIATE LIGAMENT LOADING

INTERVENTIONAL STUDIES

Although there is a lack of correlation studies to assess trunk endurance and ACL loading variables during athletic tasks, intervention programs have been developed to target ACL loading variables through trunk endurance training. The current subsection included the studies targeting trunk endurance through static holding exercises.

Pfile et al. (33) reported the effect of trunk endurance training on the trunk and lower extremity kinematics and kinetics during landing in female high school team-sports athletes. The training included side plank, abdominal draw in, crunch, lumbar extension, side-lying hip abduction and external rotation, and lunges exercises 3 times each week for 4 weeks. The increased ACL loading variables observed after training could result from a relatively short and less uncontrolled training program. Araujo et al. (2) investigated the effect of trunk training on the landing force in female capoeira athletes. The training included plank, side plank, supine bridge, abdominal crunch, Russian twister, and split-leg scissor exercises 3 times each week for 6 weeks. The authors reported decreased ACL loading variables after training. In addition, Jeong et al. (19) reported the effect of trunk training on trunk endurance, trunk and lower extremity kinematics, and muscle activation during cutting tasks in males. The training included plank, side plank, leg raise, crunch, superman, plank hip twist, and supine bridge exercises 3 times each week for 10 weeks. The trunk endurance was assessed through the holding time of the plank and side plank postures. Decreased ACL loading variables have been found after training.

In summary, trunk endurance can be significantly improved by specific intervention programs. The trunk exercises may increase trunk flexion and decrease hip adduction moment and knee valgus during cutting tasks in males. However, the decreased knee flexion angles in female athletes might be due to a different training period, less controlled training programs, and different types of sports. In addition, trunk endurance might have a greater effect on knee control in the frontal plane but a less effect on the sagittal and transverse plane knee motion. These specific changes could be related to the goals of endurance exercises, which were to hold a neutral trunk position in a static or semistatic posture. These training goals might be transferred to maintaining a neutral trunk with decreased lateral bending, which resulted in decreased knee frontal-plane angles (6,9,40). However, it did not encourage active trunk flexion during the exercise, which limited the transfer effects on increased knee flexion (15,38). Although future studies are needed to include a larger sample size with both sexes and different sports, endurance training alone did not seem to result in consistent changes in landing and cutting biomechanics. The differences between the slow endurance training exercises and the dynamic nature of athletics might have limited the effects of trunk endurance training on landing and cutting biomechanics. Thus, trunk endurance training is not likely to be the focus for ACL injury prevention purposes.

TRUNK DYNAMIC CONTROL AND JUMP-LANDING AND CUTTING MECHANICS ASSOCIATED WITH ANTERIOR CRUCIATE LIGAMENT LOADING

CORRELATIONAL STUDIES

Two studies quantified the relationships between trunk muscle activation and trunk and lower extremity muscle activation or biomechanics during landing and cutting tasks (17,34). In addition to trunk strength, Prieske et al. (34) also assessed rectus abdominis and erector spinae activation during prelanding and landing. Significant weak positive correlations were observed between trunk muscle activation and lower extremity muscle activation at a certain phase of the landings during several landing conditions. The authors suggested that the trunk muscle was activated before the leg muscle activation, and greater trunk flexion and extension muscle activation before or during landing may increase leg muscle activation levels. Jamison et al. (17) evaluated trunk muscle activation in internal obliques, external obliques, and erector spinae during cutting tasks. Although no significant correlations were found between muscle activation and lateral bending of the trunk, greater erector spinae coactivation before initial contact correlated with decreased changes in trunk flexion angle and increased peak knee abduction moment during the early landing phase. The authors suggested that increased trunk extensor coactivation may stiffen the spine and limit the trunk's ability to absorb the kinetic energy, resulting in increased knee abduction moments.

INTERVENTIONAL STUDIES

Previous intervention programs target trunk dynamic control commonly using unstable surfaces, simulating catching-ball maneuvers, and trunk dynamic exercises (12,43). The current subsection included the studies implementing trunk dynamic control exercises to modify ACL loading variables or risk factors. Hewett et al. (12) evaluated the effect of trunk dynamic control training on trunk kinematics and hip moments during landing in adolescent female athletes. The training involved lateral jump, hop-hold, BOSU single-knee hold, BOSU single-leg pelvic bridge, tuck and lunge jumps, single-leg lateral Airex hop-hold, lunge, table lateral and double crunches, back hyperextension with ball reach, and single-leg 908 hop-hold exercises 2 to 3 times each week for 10 weeks. Decreased knee loading in the sagittal plane has been found after training (7,38). Whyte et al. (43) investigated the effectiveness of 6-week trunk dynamic control training on trunk kinematics and lower extremity biomechanics during anticipated and unanticipated cutting tasks in male collegiate athletes. The training involved transversus abdominis activation, trunk curl, dynamic bridge, dynamic plank, dynamic side plank, and lunge exercises 3 times each week. The training did not result in significant changes in trunk motion, whereas the changes in knee biomechanics were associated with decreased ACL loading.

In summary, the trunk muscle was activated before the leg muscle activation, and greater trunk muscle activation before or during landing may increase leg muscle activation levels. However, increased trunk extensor coactivation alone potentially stiffens the spine and limits the trunk's ability to absorb the kinetic energy, resulting in increased knee abduction moment. In addition, the trunk dynamic control exercises possibly increase the hip abduction strength and landing trunk flexion angle in female athletes. The trunk dynamic control exercises might decrease posterior ground reaction force, knee valgus, and knee external rotation moment during cutting tasks in males. The limited evidence generally supports a connection between trunk dynamic control and the significant effects of trunk dynamic control training on landing and cutting biomechanics associated with decreased ACL loading. Compared with trunk strength and endurance, trunk dynamic control exercises are more dynamic and specific to the athletic tasks associated with ACL injuries. Although trunk strength and endurance are likely to improve alone with trunk dynamic control exercise, the specific trunk activation patterns and the trunk's reaction to internal or external perturbation are the unique components of the dynamic control exercises. Future studies are warranted to develop more trunk dynamic control programs and assess their effects on landing and cutting biomechanics under anticipated and unanticipated conditions as well as with or without perturbation. Dynamic, unanticipated, and perturbed trunk exercises are recommended to be included in ACL injury prevention programs.

PRACTICAL APPLICATIONS

The current narrative review has several practical applications. First, trunk strength training alone is not sufficient to decrease biomechanical ACL loading during athletic tasks. Although trunk strength training is an essential component of a strength and conditioning program, other training might be needed in combination with trunk strength training to decrease ACL injury risk. Second, there is no clear association between trunk endurance and ACL injury risks. The semistatic nature of most trunk endurance training might have limited training effects on trunk and knee control during dynamic landing and cutting tasks. Therefore, trunk endurance training may be incorporated as a part but not the only trunk training component in ACL injury prevention programs. Third, trunk dynamic control seems to be the critical component of the trunk neuromuscular function associated with ACL injury risks compared with trunk strength and endurance in the general athletic population. Dynamic, unanticipated, and perturbed trunk functional assessments and training are recommended to challenge the trunk more during athletic tasks. Injury prevention programs, therefore, should recommend involving trunk dynamic control exercises using unstable surfaces, sports-related dual tasks, and perturbations. Sports-related dual tasks can be achieved by catching/passing a ball while kneeling/lying on BOSU (round) or Swiss ball. Perturbations can also be achieved by pushing from coaches, trainers, or teammates during jump-landing training.

FUTURE DIRECTIONS

In general, there are limited studies that have directly or indirectly quantified the association between trunk function and ACL injury risk. Several factors need to be considered to fully elucidate the relationship between different perspectives of trunk function and ACL injuries. First, there is a lack of standard measurements of trunk function, especially for trunk strength and dynamic control. Compared with isometric trunk strength, isokinetic strength measurement might be more representative of the dynamic strength in athletic tasks. However, the postures, joint range of motion, and movement velocities used in the isokinetic tests need to be standardized. In addition, limited studies have quantified the trunk's responses to external perturbation using a self-developed apparatus (49,50). Future studies are encouraged to develop equipment, tasks, and measurable outcomes that can reliably quantify the trunk's stability under perturbation during dynamic tasks. Second, the double-leg jump-landing and sidecutting tasks are commonly used to assess ACL loading variables (39). However, these tasks are generally preplanned without additional challenges to the trunk. Practitioners are encouraged to incorporate unanticipated and internal or external trunk perturbation through using unstable surfaces, sports-related dual tasks, or unanticipated trunk perturbation created by teammates and coaches/trainers to challenge the role of the trunk in maintaining safe knee positions during athletic tasks. Trunk fatigue is another factor to be considered as trunk strength is likely to decrease under fatigued conditions, and trunk endurance might play a more important role when fatigued. Third, previous inconsistent findings could also be caused by different training modalities, quality of training control, and athletic populations, and these factors need to be considered in designing prospective and interventional studies.

CONCLUSIONS

The literature on the association between trunk neuromuscular function and ACL injury risk or loading during athletic tasks is too limited to make conclusive recommendations. Based on the current evidence, trunk dynamic control seems to be the critical factor that affects knee movement and ACL injury risk. The specific trunk activation patterns and the trunk's reaction to internal or external perturbation are the unique components of the dynamic control exercises and should be built into athletic tasks. Future studies are encouraged to assess the trunk's functions under a more dynamic, unanticipated, and perturbed condition to challenge the role of the trunk in maintaining safe knee positions during athletic tasks. Injury prevention programs should include trunk dynamic control exercises using unstable surfaces, sports-related dual tasks, and perturbations. This information is needed to fully understand the role of the trunk on ACL injury risk and to develop trunk assessment for ACL injury risk screening as well as improve trunk training strategies to prevent ACL injuries.

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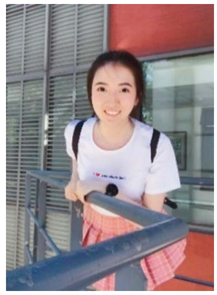

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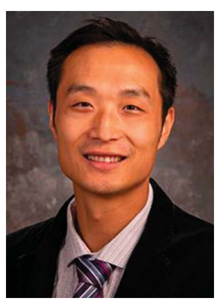

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