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Prevention of non-contact anterior cruciate ligament injuries in soccer players. Part 2: A review of prevention programs aimed to modify risk factors and to reduce injury rates

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Abstract Soccer is the most commonly played sport in the world, with an estimated 265 million active soccer players participating in the game as on 2006. Inherent to this sport is the higher risk of injury to the anterior cruciate ligament (ACL) relative to other sports. ACL injury causes a significant loss of time from competition in soccer, which has served as the strong impetus to conduct research that focuses to determine the risk factors for injury, and more importantly, to identify and teach techniques to reduce this injury in the sport. This research emphasis has afforded a rapid influx of literature aimed to report the effects of neuromuscular training on the risk factors and the incidence of non-contact ACL injury in high-risk soccer populations. The purpose of the current review is to sequence the most recent literature relating the effects of prevention programs that were developed to alter risk factors associated with non-contact ACL injuries and to reduce the rate of non-contact ACL injuries in soccer players. To date there is no standardized intervention program established for soccer to prevent non-contact ACL injuries. Multi-component programs show better results than single-component preventive programs to reduce the risk and incidence of non-contact ACL injuries in soccer players. Lower extremity plyometrics, dynamic balance and strength, stretching, body awareness and decision-making, and targeted core and trunk control appear to be successful training components to reduce non-contact ACL injury risk factors (decrease landing forces, decrease varus/valgus moments, and increase effective muscle activation) and prevent non-contact ACL injuries in soccer players, especially in female athletes. Pre-season injury prevention combined with an in-season maintenance program may be advocated to prevent injury. Compliance may in fact be the limiting factor to the overall success of ACL injury interventions targeted to soccer players regardless of gender. Thus, interventional research must also consider techniques to improve compliance especially at the elite levels which will likely influence trickle down effects to sub-elite levels. Future research is also needed for male soccer athletes to help determine the most effective intervention to reduce the non-contact ACL injury risk factors and to prevent non-contact ACL injuries.

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Introduction

Soccer is the most commonly played sport in the world [13], with an estimated 265 million active soccer players participating in the sport as on 2006 [18]. It is considered a relatively safe sport but the growing number of participants, especially among females, has led to a substantial increase in number of injuries. Specifically, the reported incidence of anterior cruciate ligament (ACL) injuries ranges from 0.06 to 3.7 per 1,000 h of active soccer playing [7, 17], accounting for thousands of ACL tears each year. Female soccer players are at up to six times greater risk for sustaining a non-contact ACL injury compared to her male counterpart [2]. Currently, a plethora of the ACL literature is targeted to ACL injury treatment as opposed to ACL injury prevention. A literature search through Medline from late 1980s to May, 2008 resulted in 8,038 articles under the topic “ACL”, 3,736 under “ACL reconstruction”, and only 455 under “ACL prevention”. Of all articles under “ACL prevention”, only 151 deal, directly or indirectly, with prevention of injuries rather than prevention of surgical complications. Fortunately, 92 of all 151 articles have been published in the last 4 years, showing increased current interest in this area.

The relevance of the non-contact ACL injury prevention is based on the following evidence. First, ACL injuries are common major injuries in soccer [16, 66], with one of the longest disability time and a devastating influence on patient’s activity levels and quality of life [21, 22, 78]. Second, ACL injuries have the highest economic cost among injuries in soccer [21, 22]. Last, both ACL-deficient and ACL-reconstructed knees are at increased risk for secondary injury such as meniscal tears and for the early development of osteoarthritis [15, 42, 47, 55, 68].

The earlier identified gender bias for non-contact ACL injuries in soccer players led to large research efforts devoted to understanding the injury mechanisms and risk factors. A deep understanding of how athletes suffer non-contact ACL injuries and what factors place them at increased risk was a determining factor in the design of effective preventative programs. Given that prevention programs are designed to correct or alter existing modifiable risk factors in athletes, this article is a continuation of “*Prevention of non-contact ACL injuries in soccer players. Part 1: Mechanisms of injury and underlying risk factors*” [1]. The purpose of this article is twofold. First, to provide a current systematic review of the literature on preventive programs aimed to modify non-contact ACL injury risk factors and to reduce injury rates in soccer players. Second, to promote future research in this field.

We employed Medline database for literature search purposes. All articles under the topics “ACL injury prevention programs”, “prevention non-contact ACL injuries”, “ACL injuries in soccer players”, and “prevention injuries in soccer” from 1983 to 2008 were considered of potential interest for this review. Articles which did not included an intervention were excluded from this review, and only prevention programs aimed to modify risk factors for non-contact ACL injuries in soccer players and to reduce the rate of non-contact ACL injuries in soccer players were considered for this review. In addition, each reference list from the identified articles were cross-checked to verify that relevant articles were not missed for the current review.

Prevention strategies

Most preventive strategies aimed to decrease non-contact ACL injuries refer to training programs [24]. There is a lack of studies assessing the role of ground and shoe–surface interaction modifications to prevent non-contact ACL injuries. Despite some authors reported that prophylactic knee braces reduced non-contact ACL injuries in football players [71], others found contradictory data [67, 71, 74]. Thus, it is difficult to recommend knee braces to prevent non-contact ACL injuries until higher quality studies are reported. Prevention programs have focused on neuromuscular training methods to change modifiable neuromuscular and biomechanical risk factors [11, 12, 28, 35, 41, 49, 53, 60, 62, 80] and to reduce the non-contact ACL injury rates [9, 14, 20, 27, 31, 39, 44, 61, 72, 73]. Also, some consideration on the prevention of non-contact ACL injuries in ACL reconstructed patients has been placed, despite only a few studies were conducted in this field.

Prevention programs for non-contact ACL injuries, either in soccer or any other sport, are crucial to modify or eliminate risk factors in order to ultimately reduce injuries. Neuromuscular and biomechanical risk factors [1] justify the need for specific sports technique modification (in such cases where skills place the athletes to a higher risk of injury), proprioception and neuromuscular training, stretching, plyometric training, adequate hamstring/quadriceps ratios, and trunk/core control training. Most of the studies included a combination of these training components in their protocols [11, 14, 20, 27, 31, 44, 53, 60, 61, 73]. Therefore, it is difficult to determine the isolated effects of each specific component on the non-contact ACL injury rate reduction. The existing interventions are separated in two sections: programs aimed to modify risk factors, and programs aimed to decrease non-contact ACL injury rates in soccer players.

As reviewed in Part 1 Article (P1A) [1], numerous risk factors have been postulated for non-contact ACL injuries. Preventive programs emerged in order to alter modifiable risk factors. Only neuromuscular and biomechanical risk factors have received adequate attention from interventions on preventive programs. Overall, prevention programs are utilized to modify sports technique and enhance conditioning through neuromuscular control, strength, plyometric, and balance training. Among all prevention program components, plyometric training has been shown to be one of the most effective tools to reduce non-contact ACL injuries.

It was reviewed in P1A [1] that extended hip and knee joint posture upon landing was a modifiable risk factor for non-contact ACL injuries. Thus, utilizing a soft landing technique with initial contact at the forefoot with hip and knee flexion with knees over the toes were postulated to decrease the risk of non-contact ACL injuries [65]. Modification of landing technique was included in many prevention programs of non-contact ACL injuries [19, 25, 31, 44, 54, 57, 61]. As already reviewed in P1A [1], cutting maneuvers performed without adequate motor planning may increase the risk of non-contact knee ligament injury due to the increased external varus/valgus and internal/external rotation moments applied to the knee. These results are probably due to the small amount of time to make appropriate postural adjustments before performance of the task, such as the position of the foot on the ground relative to the body center of mass [5, 6]. Besier et al. [5, 6] postulated that training for the game situation should involve drills that familiarize players with making unanticipated changes of direction. They further recommended that practice sessions should also incorporate plyometrics and should focus on better interpretation of visual cues to increase the time available to pre-plan a movement. The use of a three-step deceleration technique instead of a one-step technique in order to greater dissipate and decrease the anterior shear forces has also been considered.

Enhanced conditioning seems to have a protective effect on the ACL. As reviewed in P1A [1], muscular fatigue is a modifiable risk factor. Nyland et al. [56] demonstrated that hamstring fatigue produced transverse plane dynamic knee-control deficits. The authors supported knee rehabilitation and injury prevention programs that focused on coordinated lower extremity closed kinetic chain tasks, such as mini-squats, single-leg vertical and horizontal hopping, lateral shuffles in a mini-squat position, back pedaling, and quick multidirectional movement responses to cues [56]. They recommended that these tasks should be performed with the aforementioned progressions and with an emphasis on movement quality. The authors suggested that whenever a movement was out of control, or whenever the athlete was not able to correct a movement by following verbal or visual cues, or both, the task needed to be stopped. Continued performance in the presence of faulty technique increases the likelihood of the athlete's sustaining a training induced knee injury [56]. As already reviewed in P1A [1], decision-making is also relevant to prevent non-contact ACL injuries. Neuromuscular training for the prevention of non-contact ACL injuries needs to include not only training to modify the faulty lower extremity motion patterns during landing but also the training to modify the preparation of such a landing [10].

Overall, training aimed to improve hamstring-to-quadriceps, hip, and trunk muscular strength is considered adequate to reduce the risk of non-contact ACL injuries. It was reviewed in P1A [1] that hamstrings play an important role both in isolation or in co-activation with the quadriceps in protecting the ACL by preventing or decreasing the anterior, varus-valgus, and rotatory displacement of the tibia on the femur. Preventive programs have been shown to increase the hamstring peak torque and hamstring-to-quadriceps strength ratios in female athletes [34, 76], thus decreasing the risk of non-contact ACL injuries. Eccentric loading of the hamstrings was more effective in increasing hamstring-to-quadriceps strength ratios than traditional concentric exercises in professional and semi-professional male soccer players [48]. Further studies are needed to investigate the effects of eccentric-emphasized hamstring training at reducing non-contact ACL injury rates compared with concentric training in male soccer players. As reviewed in P1A [1], the gluteal muscles play an important role in stabilizing the pelvis and maintaining proper hip and knee alignment in single-leg stance. Gluetal muscles are crucial to prevent a highly dangerous position for non-contact ACL injury, the already reviewed in P1A [1] "position of no return" [36]. Coactivation of gluteus maximus and medius and hip joint position are essential elements to provide a safe biomechanical profile. As reviewed in P1A [1], relative weakness of the posterior lateral hip musculature (abductors, extensors, and external rotators), compared to the anterior medial hip musculature (flexors and adductors), coupled with increased hip flexion (e.g., secondary to hip flexor tightness, increased anterior pelvic tilt), may severely limit the ability of the gluteal muscles to stabilize the hip and maintain a neutral alignment of the hip and knee [69]. Results from plyometric training programs support the role of the hip musculature in providing dynamic restraint and control of lower extremity alignment at ground contact [12]. However, there is a clear lack of studies in assessing the effects of hip musculature training programs to modify neuromuscular/biomechanical risk factors for non-contact ACL injuries and non-contact ACL tear rates as well. As also reviewed in P1A [1], the anterior pelvic tilt has been suggested to further accentuate the functional valgus collapse of the knee [69]. Muscular tightness and shortening of the erector spinae and hip flexors, as well as elongation, inhibition, and weakening of the abdominal muscles and gluteals [69] are neuromuscular imbalances thought to contribute to an increased anterior pelvic tilt. More studies are needed to assess if training programs aimed specifically to strength abdominal, lumbar paraspinals, and gluteal muscles and stretch tight hip flexors and back extensors, could prevent non-contact ACL injuries in soccer players. Trunk musculature and positioning is further related to non-contact ACL injuries, because of its positional influence on hamstring activation [75].

Prevention programs aimed to modify risk factors for non-contact ACL injuries in soccer players

Plyometric component of preventive programs trains the muscles, connective tissue, and nervous system to effectively carry out the stretch-shortening cycle and focuses on proper technique and body mechanics [29]. Chimera et al. [12] evaluated the effects of plyometric training on muscle-activation strategies and performance of the lower extremity during jumping exercises (Table 1). Twenty healthy female soccer and field hockey college players were randomly distributed to either an experimental or a control group. All subjects participated in an off-season training that involved practice three times per week and weight training two times per week. Experimental subjects additionally performed plyometric exercises two times per week for 6 weeks. A pre-test and post-test control group design was used. The authors used surface electromyography (EMG) to assess preparatory and reactive activity of the vastus medialis and vastus lateralis, medial and lateral hamstrings, and hip abductors and adductors. Vertical jump height and sprint speed were assessed with the VERTEC and infrared timing devices, respectively. It was found a significant increase in firing of adductor muscles during the preparatory phase, with significant interactions for area, mean, and peak. The post hoc analysis revealed significant increases in preparatory adductor area, mean, and peak for experimental group. A significant increase in preparatory adductor-to-abductor muscle co-activation in the experimental group was identified, as well as a trend toward reactive quadriceps-to-hamstring muscle co-activation in the experimental group. Pearson correlation coefficients revealed significant between-groups adaptations in muscle activity patterns pre-test to post-test. Although not significant, experimental and control subjects had average increases of 5.8 and 2.0% in vertical jump height, respectively [12]. The authors concluded that increased preparatory adductor activity and adductor-to-abductor co-activation represent pre-programed motor strategies learned during the plyometric training. They further stated that these data strongly support the role of hip-musculature activation strategies for dynamic restraint and control of lower extremity alignment at ground contact, and recommended that plyometric exercises should be incorporated into the training regimens of female athletes because they may reduce the risk of injury by enhancing functional joint stability in the lower extremity [12]. The involvement of hockey players may limit the extrapolation of conclusions to soccer players, since hockey playing actions are generally characterized by a greater trunk, hip, and knee flexion than soccer actions. Also, the small sample size and the assessment methods (surface EMG) could explain the lack of significant differences in reactive muscle activation in the quadriceps and hamstrings muscle groups.

Paterno et al. [60] conducted a single-group pre-test/post-test study where 41 healthy female soccer, basketball and volleyball players underwent a 6-week neuromuscular training program designed to decrease the incidence of non-contact ACL injuries (Table 1). Single-limb postural stability for both lower extremities was assessed in all participants before and after the training program with a Biodex Stability System. The neuromuscular training program consisted of three 90-min training sessions per week for 6 weeks. Specifically, the three components of the dynamic neuromuscular training protocol utilized in this study included balance training and hip/pelvis/trunk strengthening, plyometrics and dynamic movement training, and resistance training. Each training component focused on regular instruction regarding appropriate technique from the instructor with continuous feedback to the athlete both during and after training. Following the completion of the training program, each subject was re-evaluated to determine change in total, anterior–posterior, and medial–lateral single-limb stability. The subjects showed a significant improvement in single-limb total stability and anterior–posterior stability but not medial–lateral stability for both the right and left lower extremity following training. In addition, the subjects demonstrated significantly better total postural stability on the right side as compared to the left. It was concluded that a 6-week neuromuscular training program designed to decrease the incidence of non-contact ACL injuries improves objective measures of total and anterior-posterior single-limb postural stability in high school female soccer, basketball, and volleyball players [60]. To our opinion, improvements in postural stability cannot definitely be attributed to the intervention due to the lack of a control group. Also, the authors did not perform a post-season testing; thus it is unknown whether improvements persist through the season or not.

The authors included trunk training in their protocol. As reviewed in P1A [1], athletes with decreased neuromuscular control of the body's core, measured during sudden force release tasks and trunk repositioning, are at increased risk of knee injury [79]. Zazulak et al. [79] suggested that athletes may be evaluated for deficits in core stability before competition and prophylactically treated with dynamic neuromuscular training targeted toward their specific deficits in core motor control. The authors recommended the implementation of interventions that incorporate core stability training, including proprioceptive

Table 1 Summary of prevention programs aimed to modify risk factors for non-contact ACL injuries in soccer players

Reference	Targeted risk factor	Subjects/design	Training protocol	Results	Observations
Chimera et al. [12]	Muscle co-activation imbalance with sport specific exercises	18 female soccer and field hockey players/pre-test and post-test control-group design	Plyometric exercises 2 times/week, 20–30 min/day for 6 weeks	Increased in pre-activation of hip adductor muscles; increase in adductor-to-abductor muscle co-activation	Hip musculature activation may help control lower extremity alignment
Paterno et al. [60]	Improved postural stability that would allow performance of general athletic maneuvers in a powerful, efficient, and safe manner. Sagittal and coronal plane knee laxity. Postural control	41 female soccer, basketball, volleyball players; single-group pre-post test design	Pre-season 6-week, 90 min/session, 3 times/week. Balance, hip-pelvis-trunk strengthening, plyometric, resistance training	Significant higher total and sagittal plane knee stability; no differences in coronal plane knee stability Improved overall postural stability, did not change postural stability in medial/lateral plane	Hip-pelvis-trunk strengthening control training may contribute to improved dynamic balance
Lephart et al. [41]	Deficient neuromuscular and biomechanical mechanisms that contribute to inadequate dynamic knee stability. Muscles strength and activation time, landing mechanics	27 (14 plyometric; 13 basic strength) Female soccer, basketball players; uncontrolled randomized cohort group pre-post test design	8-week plyometric training; 2 groups: plyometric versus basic resistance for phase I both groups did identical training that consisted of six lower extremity flexibility, resistance exercises and balance for 30 min/day, 3 times/week. Phase II integrated plyometric exercises agility training exercises into the plyometrics group's training program. While the basic training group only increased existing training volume	Both groups improved knee extensor isokinetic strength and increased initial and peak knee and hip flexion, and time to peak knee flexion during the task. The peak pre-active EMG of the gluteus medius and integrated EMG for the gluteus medius during the pre-active and reactive time periods were significantly greater for both groups. Higher knee extensor strength in 2 groups; landing with more hip/knee flexion	Basic training alone induces favorable neuromuscular/biomechanical adaptations; lack of control group limits the potential for conclusions
Myer et al. [53]	Muscle co-activation imbalance; increased activation time; decreased strength; landing mechanics coronal plane knee loads, sagittal plane mechanics during a drop vertical jump and improved performance	53 (12 control athletes; 41 interventions) female soccer, basketball, volleyball players; controlled single-group pre-post test design. Prospective controlled trial	6-week, 3 times/week, 90 min/session, plyometric, core strengthening, balance, resistance, and speed training. Each component of the training focused on comprehensive biomechanical analysis by the instructor, with feedback given to the subject both during and after training	Trained group: increased squat, bench press, single-leg hop distance, vertical jump, speed, knee flexion angle at landing, and decreased knee valgus and varus torques	Comprehensive training program that demonstrated multiple benefits in adolescent female athletes
Pollard et al. [62]	Increased hip internal rotation, hip adduction, and knee valgus collapse during landing	18 female soccer players aged 14–17-year-old; longitudinal single-group pre-post test design study	In-season injury prevention training consisting on a 20-min program before soccer practice, including 5 stretching, 3 strengthening, 5 plyometric, and 3 agility exercises	Significantly less hip internal rotation and greater hip abduction at landing. No changes in knee valgus or knee angles post-season	Limited sample size may explain lack of effect on knee kinematics

Table 1 continued

Reference	Targeted risk factor	Subjects/design	Training protocol	Results	Observations
Holcomb et al. [35]	Altered isokinetic hamstrings to quadriceps ratio	12 Female soccer players/single-group pre-post test design	4 times/week, 6-week standard off-season training was modified with the addition of 2 hamstring isolated strengthening exercises	Increased functional (eccentric hamstring: concentric quadriceps ratio) ratio	Eccentric hamstring to concentric quadriceps ratio exceeded 1 after training
Myer et al. [49]	Increased knee abduction moment at landing	27 (16 in the high-risk group (12 subjects followed the intervention; 4 served as controls) and 11 in the low-risk group for an ACL injury (4 subjects followed the intervention; 7 served as controls) female soccer and basketball players; prospective controlled trial	7-week, 3 times/week, neuromuscular training program	Knee abduction torque at landing decreased in high-risk group, but not in low-risk or controls	Values of abduction moment in the high-risk group did not reach that of low-risk group
Chappell and Limpisvasti [11]	Dynamic knee valgus moments, increased knee flexion angles, and increased hip flexion during the stance phase of both drop jump and stop jump tasks	30 female soccer and basketball players/single-group pre-post test design	6-week, 6 times/week. Combined core strengthening exercises, dynamic joint stability and balance training, jump training, and plyometric exercises. The protocol consisted of 10 exercises and was designed to be performed daily during a 10–15-min period before practice	Stop jump (stance phase): knee valgus moment decreased; drop jump (stance phase): increased knee flexion angle. Improved jumping performance	Neuromuscular training improvements were not consistent across jumping tasks
Herman et al. [28]	Anterior tibial shear force, vertical ground-reaction force, knee valgus moment, knee extension moment, hip adduction moment, hip internal rotation moment, during the landing phase of a stop-jump task	66 (33 controls; 33 interventions) recreational females who participated in a sport or exercise such as basketball, soccer, or volleyball 1–3 times per week or who previously engaged in such sports at the high school varsity level and currently competes at least once a month/prospective controlled cohort trial	9-week, 3 times/week, resistance bands and exercise balls to train quadriceps, hamstrings, gluteus medius, and gluteus maximus muscles	Training increased strength but did not alter landing biomechanics	Strength training alone does not alter lower limb biomechanics
Zebis et al. [80]	Neuromuscular patterns that increase extended knee and increased knee valgus angles during landing	20 (12 female elite soccer players; 8 elite female handball players). Prospective controlled trial	One season of intervention, twice a week, 20 min per session. Neuromuscular program aimed to improve awareness and neuromuscular control of the hip, knee, and ankle muscles during standing, running, cutting, jumping, and landing tasks with simultaneous ball handling; Use of wobble board and balance mat	Increased pre-landing and landing electromiographic activity of the semitendinous muscles, while quadriceps electromiography activity remained unchanged	Small number of participants, not powered to measure potential injury reduction and did not quantify the targeted risk factors (i.e., knee flexion and knee valgus angles)

exercise, perturbation, and correction of body sway, has the potential to reduce non-contact ACL injury risk in both female and male athletes. Also, it was shown that increased trunk flexion during landing also increased hip and knee flexion angles [8]. Increased hip and knee flexion angles at landing while avoiding excessive anterior translation was shown in P1A [1] to be a more desirable landing technique in order to reduce the risk of non-contact ACL injuries [32, 65]. Blackburn and Padua [8] stated that incorporating greater trunk flexion as an integral component of non-contact ACL injury prevention programs may be warranted. Future research should focus on controlled, prospective longitudinal studies of defined populations of athletes who are followed through multiple sport seasons to correlate core stability profiles with injury risk. The efficacy of neuromuscular training interventions targeted toward the improvement of core stability measures is also a high priority for future studies [79].

Lephart et al. [41] investigated the effects of an 8-week plyometric and basic resistance training program on neuromuscular and biomechanical characteristics in young female soccer and basketball players (Table 1). Athletes were distributed to either a plyometric intervention group or a basic resistance training program group. Both programs consisted of two 4-week phases. Phase I was identical for both groups and consisted of 6 flexibility, 11 resistance, and 3 balance exercises. Phase II for the plyometric group added 11 plyometric and 7 agility exercises to those for Phase I. Phase II for the basic resistance training group included the same exercises of Phase I with an increased amount of time and number of repetitions for each one. Knee and hip strength, landing mechanics, and muscle activity were recorded before and after the intervention programs. In the jump-landing task, subjects jumped as high as they could and landed on both feet. EMG peak activation time and integrated EMG of thigh and hip muscles were recorded prior to (pre-active) and subsequent to (reactive) foot contact. Both groups improved knee extensor isokinetic strength and increased initial and peak knee and hip flexion, and time to peak knee flexion during the task. The peak pre-active EMG of the gluteus medius and integrated EMG for the gluteus medius during the pre-active and reactive time periods were significantly greater for both groups. Therefore, the authors found that a basic training program alone induced favorable neuromuscular and biomechanical changes in high school female soccer and basketball players. They suggested that the plyometric program may further be utilized to improve muscular activation patterns [41]. The home-based nature of this program impeded the authors to unequivocally control the real compliance and performance of the exercises. This study design in fact compared plyometric and resistance training to resistance training alone. Considering the comparison essence of this study, a plyometric group not performing resistance exercises might be better to truly know the effects of the plyometric training alone. Also, agility and plyometric exercises were only performed for 4 weeks. As the authors suggested, this might be insufficient time to evoke neuromuscular and biomechanical additional benefits.

Myer et al. [53] examined the effects of a comprehensive neuromuscular training program on measures of performance and lower-extremity movement biomechanics in high-school female soccer, basketball and volleyball players (Table 1). Forty-one athletes, approximately 15 years of age, underwent a 6-week (three times a week) duration training program that included 90-min sessions with four main training components: plyometric and movement, core strengthening and balance, resistance training, and speed training. Twelve age-, height-, and weight-matched controls underwent the same testing protocol twice at 6 weeks apart. Trained athletes demonstrated increased predicted one repetition maximum squat and bench press. Right and left single-leg hop distance, vertical jump, and speed in a 9-m sprint increased with training. Pre- and post-test three-dimensional motion analysis demonstrated increased knee flexion–extension range of motion during the landing phase of a vertical jump. Training decreased knee valgus and varus torques. Control subjects did not demonstrate significant alterations during the 6-week interval. The results of this study supported the hypothesis that the combination of multiple-injury prevention-training components into a comprehensive program improves measures of performance and movement biomechanics [53]. While this program reported successful reduction of injury risk factors, high compliance and improved performance, the duration (90-min sessions) of the intervention may be ultimately be a deterrent for coaches to implement similar strategies. Future work is needed to improve the efficiency of protocols to be implemented for soccer pre-season training.

Pollard et al. [62] investigated the influence of in-season injury prevention training on hip and knee kinematics during a landing task (Table 1). The authors conducted a longitudinal pre-post intervention study with 18 healthy female soccer players aged 14–17-year-old. An injury prevention program was provided to athletes during a season of soccer practice, and testing sessions were carried out prior to and following the soccer season. The program was specifically designed to replace the traditional 20-min soccer warm-up and included five stretching, three strengthening, five plyometrics, and three agility exercises. Three-dimensional kinematic analysis was employed in testing sessions while soccer players were performing a drop landing task. Peak hip and knee joint angles were measured during the early deceleration phase of landing. At the end of the soccer season, athletes demonstrated significantly less hip internal rotation and greater hip abduction angles during the landing task. Unfortunately, no differences in knee valgus or knee flexion angles were found post-season. The authors concluded that "a season of soccer practice combined with injury prevention training is effective in altering lower extremity motions" [62]. However, the lack of a control group impedes to unequivocally attribute the significant differences in landing kinematics to this intervention. Also, the absence of significant changes in knee kinematics may be explained by the small sample size. Prevention programs need to be meticulously designed, conducted, and assessed in order to limit potential confounding factors. Many studies exclusively involve coaches for the implementation and recording of data from prevention programs. In this study, the coach exclusively recorded the subjects' compliance and implemented the prevention program after receiving written and videotape instructions. It might be argued that the involvement of external specialized instructors may help reduce potential biases in this kind of interventions.

As reviewed in P1A [1], adequate hamstring:quadriceps force ratio is an important component of dynamic knee joint stability. When the quadriceps are stronger than the hamstrings, excessive anterior translation may occur during dynamic activities such as landing, changing direction, or cutting, and the ACL will experience higher shear forces. If the hamstrings are too weak to counteract this force, the ACL is placed to a higher risk of injury. Holcomb et al. [35] investigated the effects of a 6-week hamstring-emphasized resistance training on hamstring:quadriceps strength ratios in female soccer players (Table 1). Twelve athletes were tested before and after the resistance training program, which included four sessions a week with the following exercises: single leg curls, straight leg dead lifts, good morning exercises, trunk hyperextensions, resisted sled walking, and exercise ball leg curls. Peak torque during concentric and eccentric actions for both hamstrings and quadriceps was measured with an isokinetic dynamometer. Each muscle action was tested at three angular velocities in the following order: concentric 240, 180, and 60° s^{-1} and eccentric 60, 180, and 240° s^{-1}. The hamstring:quadriceps strength ratio was evaluated using concentric muscle actions (concentric hamstrings:concentric quadriceps), what was denominated conventional ratio. The authors properly stated that because concentric actions do not occur simultaneously in opposing muscles, a more functional assessment comparing eccentric hamstring:concentric quadriceps actions was necessary. Hence, mean conventional and functional hamstring:quadriceps ratios data were analyzed. The results revealed a significant main effect for factor with the functional ratio but not for the conventional ratio. The mean functional ratio increased from 0.96 ± 0.09 in pre-test to 1.08 ± 0.11 in post-test. These results suggested that 6 weeks of strength training emphasizing hamstring training is sufficient time to significantly increase the functional ratio. The functional ratio after training exceeded 1.0, which is specifically recommended for prevention of non-contact ACL injuries [35]. However, it remains uncertain if an isolated increase in hamstring strength will simultaneously correlate with increases in reaction time, contractility, and improvements in single leg balance. The inclusion of other effective components to correct or compensate a higher number of modifiable risk factor, such as plyometric and proprioception training, would be recommended.

Myer et al. [49] compared the effects of a tri-weekly 7-week duration neuromuscular training program between high-risk and low-risk female soccer and basketball subjects (Table 1). As reviewed in P1A [1], the knee abduction moment during landing from a jump was found to be a predictor of non-contact ACL injury in female athletes. Based on data from previous research [33], 16 subjects (4 of them served as controls) were classified into the high-risk (knee abduction moment >25.25 Nm) and 11 (7 of them served as controls) into the low-risk (knee abduction <25.25 Nm) groups for non-contact ACL injury [49]. Knee kinematics and kinetics were measured during a drop vertical jump (DVJ) test at pre/post training. Athletes classified as high-risk significantly decreased their knee abduction moments by 13% following training. Neither athletes grouped into the low-risk category nor control subjects from both groups demonstrated any change into their abduction moments following training. These results indicated that "high-risk" female athletes decreased the magnitude of the previously identified risk factor to non-contact ACL injury following neuromuscular training. Unfortunately, the mean values for the high-risk subjects were not reduced to levels similar to low-risk group following training. Targeting female athletes who demonstrate high-risk knee abduction loads during dynamic tasks may improve efficacy of neuromuscular training. It was suggested that increased training volume or more specific techniques may be necessary for high-risk athletes to substantially decrease non-contact ACL injury risk [49].

Chappell and Limpisvasti [11] conducted a controlled single-group laboratory study evaluating the effect of a neuromuscular training program on the biomechanics of select jumping tasks in female athletes (Table 1). Thirty female soccer and basketball players performed vertical jump, hopping tests, and two jumping tasks (drop jump and stop jump). All subjects completed a 6-week neuromuscular training program with core strengthening, dynamic joint stability and balance, jump, and plyometric training. Overall, the program included ten exercises performed daily during a 10–15-min period. Three-dimensional motion analysis and force plate data were used to compare the kinetics and kinematics of jumping tasks before and after training. Dynamic knee valgus moment during the stance phase of stop jump tasks decreased after completion of the neuromuscular training program, but differences were not observed for the drop jump. Initial and maximum knee flexion angles increased during the stance phase of drop jumps after training, but differences were not observed for the stop jump. The athletes showed improved performance in vertical jump, right 1-legged hop, and left 1-legged hop. Completion of a 6-week neuromuscular training program improved athletic performance measures and changed movement patterns during jumping tasks in the subject population. Hence, the use of this neuromuscular training program could potentially modify the collegiate athlete's motion strategies, improve performance, and lower the athlete's risk for injury [11]. More significant differences might be observed if a greater sample size and training period had been used in this study. Also, the inclusion of athletes from only one university may increase internal but decrease external validity.

Interestingly, Herman et al. [28] investigated the effects of an isolated tri-weekly strength training program on lower extremity biomechanics of female soccer, basketball, and volleyball recreational players during a stop-jump task (Table 1). The strength training program employed resistance bands and exercise balls and was focused on quadriceps, hamstring, gluteus medius, and gluteus maximus exercises. Hip and knee three-dimensional kinematic and kinetic data were collected for 66 female recreational athletes (33 interventions and 33 controls) while performing three stop-jump tasks before and after completing the 9-week strength-training program (intervention) or a 9-week period of no strength training (control). Maximum voluntary isometric contraction strength data were also collected for each subject before the stop-jump tasks in each data collection session. Knee and hip joint angles as well as resultant forces and moments were calculated. The intervention group significantly increased the strength of all muscles. No significant differences were observed in knee and hip kinematics and kinetics between groups before and after the strength-training protocol. The authors concluded that strength training alone does not alter knee and hip kinematics and kinetics in female recreational athletes. Therefore, strength training as a single intervention method may not be sufficient to reduce the risk of non-contact ACL injury in female soccer, basketball, and volleyball players [28]. A reviewed in P1A [1], dynamic joint stability is not only provided by muscles itself. Instead, participation of the elastic components of the musculotendinous unit and the sensorial and neural system is crucial to provide a reduced risk of ligamentous injuries. An isolated strength training performed with resistance bands and exercise balls [28] may be too focused on the muscle component and may minimize potential improvements in other important components of the dynamic joint stability function. In fact, Hernana et al. [28] demonstrated improvements in maximum voluntary isometric contraction strength but not in biomechanical parameters. It seems that single-component preventive programs do not have a significant impact on biomechanical risk factors in female athletes. Most likely, the introduction of "at-risk" techniques awareness, technique modification, proprioception training, and plyometric training is essential to evoke changes in kinematics and kinetics of joints during sports tasks.

Zebis et al. [80] investigated the effects of a neuromuscular training program on knee joint motor control during side-cutting in female elite soccer and handball players (Table 1). Neuromuscular activity at the knee joint was measured during side-cutting before and after a 6-month period (control season) of regular training (i.e., without prophylactic training) in 12 female elite soccer players and 8 female handball players. After the control season, 12 months of prophylactic neuromuscular training was implemented, and the effect of neuromuscular training on neuromuscular activity at the knee joint, joint angles at the hip and knee, and ground reaction forces were recorded during a side-cutting maneuver. Neuromuscular activity in the pre-landing phase was obtained 10 and 50 ms before foot strike on a force plate and at 10 and 50 ms after foot strike on a force plate. The neuromuscular training program included six progressive levels, each consisting of three exercises. Each of the six levels had to be followed two times per week for 3 weeks before progressing to the next level. After completing the program (18 weeks), the six levels were performed again with increasing difficulty of the exercises. The focus of each exercise was targeted to improve the athlete's awareness and neuromuscular control of the lower extremity muscles during sports-related tasks with simultaneous ball handling. Exercises included movement on both the wobble board and balance mat. The principal examiner conducted successive follow-ups every second week [80]. Neuromuscular training markedly increased pre-landing and landing activity activation of the semitendinosus, while quadriceps EMG activity remained unchanged. The authors suggested that the neuromuscular adaptation of increased hamstring activation following the season of neuromuscular training had the potential to reduce dynamic valgus in the targeted athletes [80]. Also, a higher hamstrings activation could better counteract an anteriorly directed force that would place the ACL to a greater risk of rupture.

Prevention programs aimed to reduce non-contact ACL injury rates in soccer players

Caraffa et al. [9] conducted in 1996 the first interventional study on prevention of non-contact ACL injuries in 600 semi-professional and amateur male soccer players (Table 2). Twenty soccer teams (10 semi-professional and 10 amateur) underwent a proprioception training program of increasing difficulty over a 3-season period in addition of their regular training sessions, whereas 20 soccer teams continued training as usual and served as controls. The proprioception intervention was applied during preseason and consisted of a 5-phase progressive balance training program. Every day during the preseason training (a minimum of 30 days), they had to train at least 20 min per day. Each phase consisted of 2–6 days of training. Phase 1 included balance training without a board. Soccer players were instructed to stand alternately on one leg for 2.5 min four times a day. In phase 2, each leg was alternatively trained with a rectangular balance board for the same time period each day. A round board was used in phase 3, where athletes preformed the same protocol as in phase 2. Phase 4 was a combination of rectangular and round boards, whereas phase 5 proprioception training included a so-called BAPS board (Camp. Jackson, Mich.) or a similar multiplanar board. Each training phase also consisted of two subphases, anterior up-step and posterior up-step exercises. During their active soccer seasons, the players were instructed to train according to the given program at least three times a week. The authors found a significant reduction in the incidence of a confirmed ACL injury per team and year in the trained group compared to the control group (0.15 and 1.15, respectively) [9]. Unfortunately, the authors did not differentiate between contact and non-contact ACL injuries. This program was limited to proprioceptive neuromuscular facilitation strengthening and did not include flexibility, agility, or plyometric training. However, it might be expected that the excluded components were trained during normal soccer training sessions in both groups, but data on usual training was not reported. The intervention required additional equipment and was not considered to be cost-effective or feasible to extrapolate to a large-scale cohort [70]. The training program reported by Caraffa et al. was relevant to provide a more balanced agonist–antagonist muscle activation pattern and a higher joint stiffness, thus improving dynamic knee stabilizers. A potential limitation to these results was the undefined compliance and adherence to the training protocol.

Hewett et al. [31] investigated the effects of a neuromuscular training on knee injury prevention in high-school female soccer, basketball, and volleyball players in a prospective controlled non-randomized design (Table 2). A group of female athletes underwent a 6-week neuromuscular training program and were compared to matched untrained males and females athletes. The program was 60–90 min in length and was completed 3 days a week on alternate days and incorporated a combination of flexibility, strengthening (through weight training), and plyometric exercises. As reviewed in P1A [1], muscle stiffness provides joint stability. Plyometric training works through the stretch-shortening cycle activating neural, muscular, and elastic components, and therefore should enhance dynamic stiffening [24]. It may decrease muscle activation time and increase the force generated by these muscles, especially if combined with weight training. The program consisted of three phases of 2-week duration each: the technique phase (Phase I), the fundamental phase (Phase II), and the performance phase (Phase III) [31]. During the technique phase, proper jump technique was demonstrated and drilled. The fundamentals phase concentrated on building a base of strength, power, and agility. Finally, the performance phase focused on achieving maximum vertical jump height. The authors detailed the whole program in the aforementioned publication [31]. Throughout each session of the first two phases, exercises were increased by duration. Each athlete was encouraged to do as many jumps as possible using proper technique. 1–2 min of recovery time was allotted between each exercise. Stretching was performed immediately before jump training. Weight training was performed after jump training with a 15-min rest period and an abbreviated stretching regimen [31]. The knee injury incidence per 1,000 athlete-exposures was 0.43 in untrained female athletes, 0.12 in trained female athletes, and 0.09 in male athletes. Untrained female athletes had a significantly higher incidence of knee injury than trained female athletes and than untrained male controls. The incidence of knee injury in trained female athletes was not significantly different from that in untrained male athletes. The difference in the incidence of non-contact injuries between both female groups was also significant. Specifically with regard to soccer players, 5 non-contact ACL injuries were reported in the untrained females, 0 in the trained females, and 1 in the untrained males group [31]. Additionally, in a previous study, Hewett et al. [34] demonstrated that a similar program decreased peak landing forces, varus/valgus moments, and increased effective muscle activation. As reviewed in P1A [1], a dynamic valgus collapse at landing was found to be a predictor of non-contact ACL injury. Also, as earlier stated, increased peak landing force is a risk factor for non-contact ACL injury, especially if associated with decreased hip and knee flexion angles. Hence, plyometric training is considered an essential component of preventive programs, however, the development and initial evaluation of this program was performed in volleyball

Table 2 Summary of prevention programs aimed to reduce the non-contact ACL injury rates in soccer players

Reference	Targeted risk factor	Subjects/design	Training protocol	Results	Observations
Caraffa et al. [9]	Lower extremity proprioception and dynamic balance	600 (300 control athletes; 300 intervention) semi-professional and professional male soccer players/prospective controlled design	Preseason (30 days) daily 20-min 5 phase progressive proprioception training with balance boards plus 3 times a week during the season (for a total of 3 seasons). Also followed neuromuscular facilitation program during the season	Significant reduction in the incidence of ACL injuries per team and year in the trained group	Not disclosed for contact or non-contact ACL injuries; requires additional equipment; undefined compliance and adherence to training protocol. Data on usual training was not reported
Hewett et al. [31]	Hamstring strength and landing forces	366 female soccer, basketball, volleyball players under went training and were compared to control 434 males and 463 females/ prospective cohort design	6-week neuromuscular training (flexibility, strengthening, plyometric); 60–90 min/session 3 days/week	Training reduced non-contact ACL injury incidence (0 ACL injuries) relative to males (1) and untrained females (5)	Incidence of ACL injury in trained females was reduced to similar levels to that of male subjects
Heidt et al. [27]	Avoidance of movements that increase risk of injury	300 young female soccer players; 42 underwent training program/ prospective cohort design	7-week preseason cardiovascular, plyometric, strength, flexibility, and agility drills	Decrease in overall injuries; no differences in ACL injury between trained and untrained subjects	Small number of participants in the intervention group
Soderman et al. [72]	Lower extremity proprioception and dynamic balance	221 (100 control athletes; 121 intervention) semi-professional female soccer players/prospective randomized controlled trial	7-month duration, 10–15 min/day, 3 times/week of balance training	No reduction in ACL injury rates with training protocol	Single-component program; more ACL injuries in trained group. Not disclosed by contact versus non-contact injuries
Junge et al. [39]	The intervention strategy was aimed first at raising the coaches' and players' motivation for and awareness of injury prevention strategies, and then at imparting the necessary knowledge and techniques to carry these strategies through	194 young male soccer players from 14 amateur teams. Prospective controlled intervention study	1 season in-session preventive program including warm-up, balance, strength, coordination, and endurance training. In addition, each player was informed of their baseline results and was instructed on how to improve his individual weaknesses	6.7 injuries per 1,000 h of training and player in intervention group versus 8.5 in control group. Greatest results on mild, overuse, and in-training session injuries. Greater effects in low-skill than in high-skill teams	Specific ACL injury rates not disclosed
Mandelbaum et al. [44]	Proper techniques such as: landing technique, stressing "soft landing" and deep hip and knee flexion as opposed to landing with a "flat foot" in lower extremity extension. Muscle co-activation imbalance; increased activation time; decreased strength; landing mechanics	5,703 (3,818 control athletes; 1,885 interventions) young female soccer players; prospective controlled cohort design during a 2-season period	2–3 times/week, 20 min/session; education and 3 basic warm-up activities, 5 stretching techniques for the trunk and lower extremity, 3 strengthening exercises, 5 plyometric activities, and 3 soccer specific agility drills to replace traditional warm-up. The protocol was performed before athletic activity	88 and 74% ACL injury reduction in first and second season, respectively	Voluntary enrolment of participants; on-the-field training program

Table 2 continued

Reference	Targeted risk factor	Subjects/design	Training protocol	Results	Observations
Pfeiffer et al. [61]	Jump-landing and running-deceleration mechanics	1,439 athletes (862 in the control group and 577 in the treatment group) female soccer, basketball, volleyball/prospective controlled trial	9-week, twice a week, 20 min/session, deceleration, directional changes, body awareness, plyometric training program designed to be at the beginning or end of practice. Focused on sound body mechanics when decelerating during running with directional changes and when landing on one or two feet	Rate of non-contact ACL injuries per 1,000 exposures was 0.167 in treatment group and 0.078 in controls; Odds ratio 2.05 ($P > 0.05$)	May not have had enough exposure to the treatment to influence reduction in ACL injury incidence; program implemented after training sessions
Engebretsen et al. [14]	Reduced function in the ankle, knee, hamstring, or groin from previous injury	508 male soccer players (120 low risk controsl, 195 high risk controls, 193 high risk interventions)/prospective randomized control trial	3 times a week for 10 weeks during the preseason, in separate training sessions done in addition to the regular team training. Based on risk history athletes were to perform from 1 up to 4 of the exercise program targeted to the ankle, knee, groin or hamstring	Questionnaire identified high-risk athletes but the training regimen did not reduce their risk	Poor compliance may have limited the potential effects of training
Gilchrist et al. [20]	Neuromuscular control and avoidance of improper biomechanical techniques	Sixty-one teams with 1,435 female soccer players (852 control athletes; 583 interventions)/prospective RCT design	In season 12 week warm-up that consisted of stretching, strengthening, plyometrics, agilities, and avoidance of high-risk positions depicted on a video	Overall 41% reduction in ACL injuries	Proprioception training was applied through on-the-field exercises
Steffen et al. [73]	Muscle co-activation imbalance, dynamic knee valgus collapse, increased activation time	2,092 (1,001 control; 1091intervention) female soccer players; prospective cluster-randomized controlled trial	8-month, 15 consecutive sessions then once a week, 15 min/session during warm-up, stability, balance, plyometrics, and eccentric hamstrings exercise, landing technique modification program	No differences in overall injury rates nor any specific injury between groups	Poor compliance may have limited potential to reduce injury incidence; specific non-contact ACL injuries were not reported

players [34]. Thus, the direct applicability of this program to reduce risk factors in soccer athletes is not clearly delineated. In addition, as the authors recognized, there were more volleyball players in the trained group; this may decrease the extrapolation of these results to soccer players.

Heidt et al. [27] studied the effects of pre-season conditioning on female soccer players injuries aged 14–18-year-old, with no assessment specifically focused on ACL tears (Table 2). Three hundred female soccer players were enrolled in the study, and 42 of them underwent a 7-week program including 20 sessions with sport-specific cardiovascular conditioning, plyometric work, sport cord resistance drills, strength training, and flexibility exercises to improve one's speed and agility. The authors found a significant decrease in the overall injury rates. The decrease in ACL injuries was not significant, occurring in 2.4% of athletes in the trained group versus 3.1% in the untrained group [27]. It was concluded that pre-season conditioning reduces the overall injury rates, but no significant differences were found for ACL injury rates, perhaps due to the small cohort included in the study [70].

Soderman et al. [72] conducted a similar study than that reported by Caraffa et al., but involving a smaller number of participants and only applied to female soccer players (Table 2). In a prospective randomized controlled design, 221 semi-professional and amateur female soccer players from Sweden were distributed to either an intervention or control group. During an outdoor season (April–October), all players were followed for the number, incidence, and type of injuries. The intervention group underwent a training program consisting of 10–15 min of balance training in a balance board that included five exercises with progressively increasing level of difficulty (height of the balance board). The players were standing on one leg at a time with their knee in a slightly flexed position. The exercises were carried out for three sets of 15 s per repetition on each leg. The players were instructed to perform the training program at home, initially each day for 30 days and then three times per week during the rest of the season. Both groups continued their usual training. No significant differences were found between groups in number of injuries, incidence, and type of injury. Surprisingly, four ACL injuries were reported for the intervention group as opposed to one in the control group, but the authors did not stratify for contact or non-contact mechanisms. Among all players injured during the 3-month period before the investigation, the incidence of new injuries was higher in the control group than in the intervention group, but the type of new injuries were not detailed. Unfortunately, the program did not include strength, plyometrics, flexibility, or agility training. Compliance was questionable as the subject drop-out rate was 37%, and no information on the additional training performed in each soccer team was reported [70]. Differences from the study of Caraffa et al. [72] were attributed to the gender differences, playing division, and total exposure time. A potential limitation to these results was the home-based nature of this program.

Junge et al. [39] evaluated the effects of a prevention program on the incidence of soccer injuries in male amateur soccer players (Table 2). Seven soccer teams took part in a prevention program that focused on education and supervision of coaches and players, while seven other teams were instructed to train and play soccer as usual [39]. Over 1 year, all injuries were documented weekly by physicians, and complete weekly injury reports were available for 194 players. The prevention program included general interventions such as warm-up, regular cool-down, taping of unstable ankles, adequate rehabilitation, and promotion of the spirit of fair play as well as specially designed ten exercises to improve the stability of ankle and knee joints, the flexibility and strength of the trunk, hip, and leg muscles, as well as to improve coordination, reaction time, and endurance [39]. The incidence of injury per 1,000 h of training and playing soccer was 6.7 in the intervention group and 8.5 in the control group, which equates to 21% fewer injuries in the intervention group. The greatest effects were observed for mild injuries, overuse injuries, and injuries incurred during training. The prevention program had greater effects in low-skill than in high-skill teams. The incidence of soccer injuries can be reduced by preventive interventions, especially in lower skill level youth teams. Coaches and players need better education regarding injury prevention strategies and should include such interventions as part of their regular training [39]. Unfortunately, specific ACL injury rates were not reported. The differentiation in injury rates among high- and low-skill teams allowed the authors to control for a potential confounding factor (i.e., skill level). Differences in injury rate as a function of skill level may be explained, in part, by differences in the received intervention, which was individualized to their skill condition. These differences must be kept in mind when comparing injury rates among high- and low-skill teams.

Mandelbaum et al. [44] proposed a program to prevent injuries and to enhance performance in female soccer players aged 14–18-year-old (Table 2). This 2-year prospective controlled non-randomized intervention consisted of education, stretching, strengthening, plyometrics, and sports-specific agility drills designed to replace the traditional warm-up. Athletes from intervention group performed a sports-specific training intervention before athletic activity over the 2-year period, whereas the control group performed their traditional warm-up before each session. The authors found a 88 and 74% decrease in the ACL injuries in the intervention group compared to the control group during the first and second seasons, respectively. The authors detailed the "PEP Program: Prevent

Injury and Enhance Performance" program in their publication. The program aimed to anticipate external forces or loads to stabilize the joint, thus protecting the inherent structures. An emphasis on activities such as "on-the-field" proprioception exercises, having a proper landing technique, engaging knee and hip flexion on landing and lateral maneuvers, avoiding excessive genu valgum on landing and squatting, increasing core, hamstring, gluteus medius, and hip abductor strength, and addressing proper deceleration techniques were given in this study [44]. The voluntary enrolment of athletes into the intervention group was one of the weaknesses of this study [70]. Perhaps serving as an inherent selection bias, the decrease in injury rates in the intervention group may be affected by a greater interest in injury prevention. However, the study was an on-the-field warm-up program that required only traditional soccer equipment (cones and soccer ball) making it a practical and cost-effective way to address the incidence of ACL injury. Moreover, it was a 2–3 times a week program with a duration of 20 min per session over the course of the 12-week soccer season, what made this program suitable to fit with the already existing training programs in each soccer team. The multi-component nature of this program allowed the authors to address most of the modifiable risk factors that were considered in P1A [1] for female athletes.

Contrary to the prior presented evidence, Pfeiffer et al. [61] found no reduction in the non-contact ACL injury rate after applying a knee ligament injury preventive program for female soccer, basketball, and volleyball players consisting of strengthening and plyometric exercises (Table 2). In their prospective controlled non-randomized intervention, the authors incorporated a 20-min strength and plyometric-based post-training exercise program twice a week for a total of 9 weeks with a 2-year follow-up. The program was focused on deceleration, directional changes (run forward, stops, run backward in W shape), plyometric training through jump and landing (one or two feet in both forward and backward direction), and teaching proper body position (alignment hip, knee, ankle). Flexibility, agility, and proprioception exercises were not included in this intervention. The program was previously reported to decrease the peak vertical impact force and the rate of force development in a cohort of college females [37]. The lack of non-contact ACL injury rates reduction in the study of Pfeiffer et al. [61] demonstrated a lack of correlation between biomechanical and clinical findings in this program. It was suggested that 9 weeks may be not enough for neuromuscular adaptation to occur [70], despite other studies showed significant improvements with similar duration of interventions [27, 31, 72]. As reviewed in P1A [1], muscular fatigue is considered a modifiable risk factor for sustaining non-contact ACL injuries in female athletes. Importantly, the program reported by Pfeiffer et al. was conducted post-training, what delineates this study from those reported by other authors. Hence, it was hypothesized that neuromuscular fatigue prevented any benefit of this intervention at reducing non-contact ACL injury rates [70]. The non-randomized design can be also considered a potential limitation in this study, although we recognize that coaches are usually not interested in participating in randomized studies.

Engebretsen et al. [14] aimed to target reduced function in the ankle, knee, hamstring, or groin from previous injury (Table 2). They evaluated 508 male soccer players (120 low risk controls, 195 high risk controls, and 193 high risk interventions) in a prospective randomized control trial. The authors prescribed a pre-season intervention three times a week for 10 weeks, and an in-season intervention in separate training sessions performed in addition to the regular team training. Based on risk history, athletes were to perform from 1 up to 4 of the program exercises targeted to the ankle, knee, groin or hamstring. While they did not report a reduction in injury, they indicated that poor compliance may have limited the potential effects of training. However, their results also indicated that questionnaire identified high-risk athletes, but the training regimen did not reduce their risk. Thus, similar to the results of Myer et al. [49] who evaluated an injury risk factor, they were able to identify high-risk athletes, but were not able to reduce injury risk to that of the identified low risk athletes [14]. This may be due to the lack of compliance or that the program design was too general to specifically address one injury pattern. Identification of high-risk athletes is crucial, but precise analysis of the deficits noted in that specific population may need to be addressed with a very specific program to reduce their "high risk" status.

Gilchrist et al. [20] conducted a randomized 1-year intervention to prevent non-contact ACL injuries on young female soccer players (Table 2). The implemented program was entitled "PEP: Prevent Injury and Enhance Performance" and was utilized in an aforementioned study involving female soccer players between the ages of 14 and 18 [44]. It included gluteus medius, hip extensors and abductors, hamstrings and core strength, flexibility, agility, proprioception, and plyometric training. Agility exercises included deceleration and sport-specific tasks, and plyometric training was applied emphasizing hip and knee position and landing technique in multi-planar tasks. Interestingly, proprioception training was applied through on-the-field exercises. Exercises were complemented with educational videos. An overall 72% reduction in non-contact ACL injury was demonstrated, with a 100% reduction of in practice contact and non-contact ACL injuries, and a 100% reduction in contact and non-contact ACL injuries in the last 6 weeks of season [19]. In follow-up to this pilot study Gilchrist et al. [20] employed a prospective randomized controlled design with 61 teams involving 1,435 female soccer players (852 control athletes and 583 interventions). They utilized in season 12-week warm-up that consisted of stretching, strengthening, plyometrics, agilities, and avoidance of high-risk positions depicted on a video. Similarly, they reported a 41% reduction in non-contact ACL injuries with the prescribed protocol in the interventional athletes [20]. There was a 72% reduction in non-contact ACL injuries. When the data were stratified for weeks in the season, there was a 100% reduction of non-contact ACL injury in the intervention group for game and practice in the last 6 weeks of the season. In addition, when athletes that had sustained an ACL injury in the past and had successfully returned to a high level of play, there was a 100% reduction in reoccurrence of non-contact ACL injury and an 80% reduction of contact reoccurrence. It is sometimes difficult to prevent the control group of performing any of the exercises in the designed preventive program. A control of training sessions in control subjects is needed in order to avoid any exposure to potentially preventive exercises that were applied to the intervention group. Also, a validation of all reports obtained by coaches or anyone else in the soccer team is warranted. The authors of this study tried to minimize both potential concerns. In addition, any subgroup analysis must be planned a priori to ensure that adequate statistical power is achieved. A low number of non-contact ACL injuries at the end of the program may lead to a non-significant difference due to an underpowered analysis. Gilchrist et al. performed a power calculation for their desired subgroup analysis, but the required number of teams was not reached because of time and funding reasons.

Steffen et al. [73] investigated the effects of a preventive program on the reduction of soccer injuries in female players (Table 2). They conducted a cluster-randomized controlled trial over an 8-month season where the program was implemented for 15 min in the warm-up of training sessions. The prevention program was introduced to the teams in the intervention group in the beginning of the pre-season. Coaches were asked to use the program every training session for 15 consecutive sessions and thereafter once a week during the rest of the season, replacing any warm-up routine normally used by the team. The training program included core stability, balance-proprioception, plyometrics (dynamic stabilization), and eccentric hamstrings (Russian hamstring curl) exercises. Emphasis was placed on core stability, hip control, and proper knee alignment to avoid excessive genu valgum in the static and dynamic balance exercises, as well as in landings from jumps. The entire program was detailed in the article. A total of 396 players (20%) sustained 483 injuries. No difference was observed in the overall injury rate between the intervention and control group, or in the incidence for any type of injury. During the first 4 months of the season, the training program was used during 60% of the soccer training sessions, but only 14 out of 58 intervention teams completed more than 20 prevention training sessions. In conclusion, the authors observed no effect of the injury prevention program on the injury rate, most likely because the compliance with the program was low [73]. In addition, the intervention program may have been too general to address the specific injury rates identified in this specific population. The authors also identified two other potential limitations, the lack of randomization and the low study power. As they further discuss, individual data were not recorded and subgroup analyses were not possible in this study. Specific non-contact ACL injuries were not reported by the authors, thus limiting the applicability of this study for the present review.

Discussion

The present literature review elicited several conclusions. First, there is no standardized intervention program established for soccer to prevent knee injury. Second, multi-component programs show better results than single-component preventive programs to reduce the risk and incidence of non-contact ACL injuries in soccer players. Third, lower extremity plyometrics, dynamic balance and strength, stretching, body awareness and decision-making, and targeted core and trunk control appear to be successful training components to reduce non-contact ACL injury risk factors (decrease landing forces, decrease varus/valgus moments, and increase effective muscle activation) and prevent non-contact ACL injuries in soccer players, especially in female athletes. Fourth, pre-season injury prevention combined with an in-season maintenance program may be advocated to prevent injury. Finally, future research is also needed for male soccer athletes to help determine the most effective intervention to reduce the non-contact ACL injury risk factors and to prevent non-contact ACL injuries in this high-risk group.

Twenty studies regarding soccer players (mostly females) were reviewed. Tables 1 and 2 summarize all reviewed studies in soccer. Only very few of all studies regarding preventive programs have been conducted with a randomized controlled trial design. The preventive programs outlined produced improvements in neuromuscular and biomechanical risk factors [12, 28, 35, 41, 49, 53, 60, 80], and largely resulted in a significant decrease in number of non-contact ACL injuries [9, 20, 31, 34, 39, 44], despite some authors found no reduction in the rate of non-contact ACL tears in female soccer, basketball, and volleyball players after strengthening and plyometric exercises [61, 72, 73]. Some studies have assessed the effects of prevention programs on neuromuscular and biomechanical modifiable risk factors [11, 12, 28, 35, 41, 49, 53, 60, 62, 80], whereas others simply observed the effects of these programs on injury rates [9, 14, 20, 27, 31, 39, 44, 61, 72, 73]. Almost all interventions have been conducted in young female athletes, so there is a clear need of studies regarding male soccer players, since non-contact ACL injuries do occur in this cohort as well. The most effective preventive interventions appear to be comprised of a multi-component program: stretching, strengthening, aerobic, plyometrics, risk awareness training, and proprioception training. Plyometric and proprioception training are among the most commonly applied exercise strategies to reduce the risk of non-contact ACL injuries. The former is based on evidence that the stretch-shortening cycle activates neural, muscular, and elastic components, thus enhancing joint stability (dynamic stiffening). The later is supposed to stimulate the somatosensory system, and therefore should improve co-activation and joint stiffness [24].

Most studies use common equipments in their preventive programs: jump box, videos, balance boards, sports cord, cones, balls, and soccer field. However, the use of novel devices has been recently reported to increase knee stability. Melnyk et al. [46] investigated the effect of acute exposure to whole-body vibration on stretch reflexes involved in knee joint control. Stretch reflexes of the hamstring muscles by inducing an anterior tibial translation during standing were evoked in all subjects (intervention and control groups). Individuals undergoing a session of mechanical vibratory stimulation demonstrated a decreased anterior tibial translation than the control subjects. This was suggested to be directly associated with an increase of hamstring short latency response size in response to the anterior tibial movement [46]. Further research investigating the effects of a whole-body vibration training program in a randomized controlled design should elucidate whether this method would decrease the risk of non-contact ACL injury. A three-group design (control, conventional training, and whole-body vibration) would be desirable to better elucidate the effects of whole-body vibration on knee stability. Nevertheless, the use of a vibratory platform in soccer teams could be limited by economic aspects. In general, it is better accepted to implement preventive programs with conventional equipments, but if promising results are shown with the use of the vibratory platform, it might be considered by many elite soccer teams.

Movement and awareness training strategies (cognitive training, kinesthesia visualization, verbalization, and feedback) should provide more efficient biomechanical positioning for protective mechanisms and should help the athletes to cope with unanticipated movements [24]. Education and enforced awareness of dangerous positions and mechanisms of non-contact ACL injury has also been shown to decrease non-contact ACL injuries [38]. Henning [23] identified three potentially dangerous maneuvers in basketball that he proposed should be modified through training to prevent non-contact ACL injury. Preliminary work implementing the different techniques on a small sample of athletes showed a trend toward a decrease in injury rates between the trained versus untrained study groups [23]. Conversely, Arnason et al. [3] reported that video-based awareness programs without a neuromuscular training component were not effective to reduce injury rates in elite soccer players. A primary goal of interventional training should be to focus on teaching athletes to land and decelerate with reduced coronal plane motion and increased knee flexion. Myer et al. [52] demonstrated that this effect can be achieved with both the plyometric-based and dynamic balance-oriented training protocol in female volleyball players. A commonality between the two tested training protocols was their utilization of athlete awareness and trainer feedback techniques to reduce dynamic lower extremity valgus. However, the feedback timing used to improve lower extremity coronal plane strategies were different in each case. Due to differences in the way that feedback was applied to the two groups during training, and the evidence that isolated plyometric training increases hip adductor activation [12], it was hypothesized that dynamic balance training would more effectively facilitate lower extremity control in the coronal plane, particularly during the dynamic stabilization testing. The findings of Myer et al. only partially supported this hypothesis, as decreased lower extremity valgus following training was observed for both training groups during both tasks. These results might suggest that while improvements in lower extremity valgus may be related to feedback and adjustments made during training, they are not dependent on the associated mode of exercise. Onate et al. [58, 59] demonstrated that the use of videotape feedback can also result in safer landing biomechanics in young recreational athletes. The results of the current study suggest that improved lower extremity coronal plane control may be possible through either a plyometric-based or dynamic balance-oriented training mode. While we can only speculate at this point, these results suggest that further success may be possible if augmented (videotape) feedback techniques and exercise modes used with combined plyometric and dynamic balance training techniques are utilized together in interventional protocols. The effects of athlete awareness programs and trainer feedback techniques in soccer players need further research.

Most prevention programs are 6–8 weeks in duration, despite the fact that not enough has been done to investigate the ideal duration of these programs. Gilchrist et al. [20] found that the PEP intervention was more successful at reducing injury rates in the last 6 weeks of the collegiate soccer season, perhaps due to the fact that the athletes has more exposures to the program and a greater opportunity for neuromuscular re-education to occur, imparting a protective benefit during the course of the season. Many studies were applied during pre-season performed with a 2–3 sessions per week frequency. On-the-field programs may be more realistic, cost-effective and feasible to be offered at most athletes instead of laboratory protocols. This notion can affect compliance rates and overall statistical outcomes. Biomechanical analysis of each player before the season could be useful to identify potential risk factors to be corrected during practice sessions. Programs have been offered as warm-up exercises, but exercises included during training sessions need to be considered. In-season training alone is probably the most cost-effective and efficient method for achieving beneficial injury prevention effects, though the lack of high-intensity overload in these programs likely precludes measurable performance enhancement effects [30]. Recent studies employing the in-season training program of Mandelbaum et al. [20, 64] demonstrated that the non-contact ACL injury reduction is reached later in the season in collegiate soccer. Thus, exercises performed under sports-related tasks that can be performed in an in-season warm-up setting may be beneficial to induce desired injury reduction in soccer. However, Pfeiffer et al. found no significant reduction in non-contact ACL injury rates for female soccer players after a post-training injury prevention program. Therefore, fatigue may be an important factor to consider when prescribing a program for neuromuscular training. A fatigued athlete may not have the ability to adopt a new motor planning schema, and even more deleteriously, reinforce a patho-kinematic one.

Despite the fact that there is still a high number of unanswered questions regarding preventive programs, there is a good Level 2 evidence, and some limited Level I evidence, that suggests that neuromuscular training reduces the non-contact ACL injury risk in female athletes [24, 30], and further studies should elucidate specific adaptations in male soccer players following similar programs. ACL injuries in elite male soccer players have a deep impact on economic aspects of soccer, and the psychological and emotional well-being of the individual player. In addition, non-contact ACL injury prevention programs have been shown to enhance sports performance, however, it was recommended that study designs should incorporate measures of performance and measure functional outcomes [63]. Neuromuscular training programs for female and non-professional athletes can be effective at improving performance measures of speed, strength, and power [40, 50, 77]. Females and non-professionals often show dramatic performance gains from neuromuscular training, as they often display decreased baseline levels of strength and power compared to their male counterparts and professional counterparts, respectively [34, 43, 52]. As reviewed in P1A [1], dynamic neuromuscular training has also been demonstrated to reduce gender-related differences in force absorption, active joint stabilization, muscle imbalances and functional biomechanics while increasing strength of structural tissues (bones, ligaments, and tendons). These ancillary effects of neuromuscular training, which likely reduce the risk of injury in soccer athletes, are positive results of training; however, without the performance enhancement training effects, athletes may not be motivated to participate in a neuromuscular training program [53].

There is a clear need of research in male soccer players regarding all areas covered by this review article. Only three studies were conducted exclusively involving male soccer players [9, 14, 39]. The inclusion of preventive programs throughout the entire season in professional and semi-professional male soccer teams is not yet completely accepted by some coaches. It is probable that as successful non-contact ACL injury prevention programs in male and female soccer players continue to be integrated into the community, it may change the current perceived relevance of preventing injuries in soccer. As reviewed in this article, most preventive programs are time efficient and should be introduced during pre-season training. Most are even included in the warm-up session to increase the compliance of such interventions. In addition, neuromuscular training programs aimed at non-contact ACL injury prevention demonstrate a significant decrease on non-contact ACL injury rates in female soccer players [30]. Prevention training that is oriented only toward reducing non-contact ACL injuries in female athletes may have poor compliance rates as low as 28% [54]. However, training targeted toward improving measures of performance can have better compliance ranging from 80 to 90% [4, 26, 40, 77]. Hence, if protocols are designed to focus on performance enhancement, while incorporating proven non-contact ACL injury prevention techniques, combined performance and prevention training could be instituted on a widespread basis with potentially higher athlete compliance and greater benefits for professional and non-professional athletes [50]. Because preventive programs do not increase the number of injuries and were shown to increase performance [63], we consider further research on preventive programs in elite, semi-professional, or amateur male soccer teams recommendable to potentially decrease non-contact ACL injuries, thus, decreasing the athlete's individual suffering and the economic impact on the athlete's respective team.

Future research is needed in many topics of this article. More research on the exact role of weather conditions, shoe selection, shoe–surface interaction, and knee braces with respect to non-contact ACL injury prevention in soccer is warranted. There are no studies to date modifying ground characteristic to prevent injuries, and the role of shoes and knee braces in the prevention of injuries has been proposed for sports other than soccer. It is also necessary to better define the precise role of playing surface on non-contact ACL injuries in soccer (i.e., gravel, field turf, and natural grass).

While many studies discussed the biomechanical risk factors for non-contact ACL injuries, preventive programs emerged to correct or compensate this risk factor, and thus reduce the number of injuries. Prevention programs were created to decrease the rate of injuries and address the faulty biomechanical risk factors of different general sport tasks. However, more biomechanical studies of specific actions in soccer are also needed: trapping the ball, tackling, falling behavior after jumping with contact with an opponent, running, sprinting, starting, stopping and changing direction following unanticipated actions of an opponent.

Many prevention programs studied the impact of the quadriceps to hamstrings ratio and emphasized muscle balance with neuromuscular training. It is necessary to further investigate other muscular groups involved in trunk, hip, and ankle movements. Soccer is a sport that mainly requires closed-kinetic chain movements involving all segments of the body as a whole. Although the body acts in a holistic manner, it is first necessary to understand joint kinetics and kinematics in isolation, and from there going to the understanding of the whole body in a macroscopic way. Also, understanding neural fatigue at both the central (i.e., central nervous system) and peripheral levels (i.e., neuromuscular junction and muscles) will further afford elucidation of the non-contact ACL injury mechanism, and hence more successful prevention strategies [45].

As reviewed in P1A [1], athletes with decreased neuromuscular control of the body's core and trunk musculature are at increased risk of knee injury [79]. Zazulak et al. [79] proposed that athletes may be evaluated for deficits in core stability before competition and prophylactically treated with dynamic neuromuscular training targeted toward their specific deficits in core motor control. The implementation of interventions that incorporate core stability training, including proprioceptive exercise, perturbation, and correction of body sway, has the potential to reduce knee, ligament, and non-contact ACL injury risk in both female and male athletes [79]. The authors further recommended future research on controlled, prospective longitudinal studies of defined populations of athletes who are followed through multiple sport seasons to correlate core stability profiles with injury risk [79].

Myer et al. [51] proposed the tuck jump exercise to identify neuromuscular imbalance, which was reviewed to be one of the modifiable risk factors. The use of the tuck jump assessment to identify neuromuscular imbalances may provide direction for targeted treatment for those at high risk for non-contact ACL injury. Also, the authors considered that improvement in neuromuscular techniques may be assessed and continually monitored with repeated measurement using the tuck jump assessment.

Many preventive programs are targeted toward athletes aged from 15 to early twenties. Is it possible that the implementation of injury prevention programs in younger athletes would integrate proper biomechanics and neuromuscular control at an earlier age that would further reduce future injury rates? Future clinical research, focusing on the 8–12-year-old cohort and following them longitudinally through pubescence, will shed light on this prospect [70].

As reviewed in P1A [1], females soccer players exhibit a higher number of risk factors compared to their male counterparts. Hence, single-component preventive programs may not provide the ideal therapeutic dosage to significantly impact the non-contact ACL injury rates in female soccer players. Instead, programs including multiple components would act more broadly and diversely on a number of risk factors. This may explain why other authors found satisfactory results in female soccer players undergoing multi-component preventive programs [20, 27, 34, 44]. In other words, isolated proprioceptive training would only improve agonist–antagonist muscle contraction and joint stiffness, whereas multi-component programs would also act on decreasing the peak ground reaction force and the dynamic valgus collapse at landing, and, in general, modifying the performance of high risk dynamic positioning. The more modifiable risk factors that are corrected or addressed in female and male soccer players, the greater the potential to reduce the non-contact ACL injury incidence in the sport. Finally, maybe the most salient area of needed research is to understand the best mechanisms to influence athlete compliance with the effective neuromuscular training programs. As stated before, a highly organized prevention training investigation oriented toward reducing non-contact ACL injuries in female athletes demonstrated a compliance rates as low as 28% [54]. One factor which limits both the potential for implementation and compliance is that the inclusion of preventive programs throughout the entire season in professional and semi-professional soccer teams is not yet completely accepted by some coaches as ACL injury may not be considered as a high priority concern (especially with male teams). Compliance may in fact be the limiting factor to the overall success of ACL injury interventions targeted to athletes regardless of gender. Thus, interventional research must also consider techniques to improve compliance especially at the elite levels which will likely influence trickle down effects to sub-elite levels. Ultimately, this acceptance may help achieve the desired impact from interventional training aimed to decrease ACL injury rates in soccer.

Conclusions

- No standardized intervention programs have been established for soccer to prevent non-contact ACL injuries.
- Neuromuscular training appears to be effective to reduce non-contact ACL injury risk factors and to prevent non-contact ACL injuries in both male and female soccer players.
- Lower extremity plyometrics, dynamic balance and strength, and targeted core and trunk control appear to be successful components to reduce non-contact ACL injury risk factors and to prevent non-contact ACL injuries in soccer players, especially in female athletes.
- Pre-season injury prevention combined with an in-season maintenance program may be advocated to prevent injury.
- Future research is needed for male soccer athletes to better elucidate the risk factors for non-contact ACL injuries and to help determine the most effective intervention to prevent non-contact ACL injury in this high-risk group. In addition, further research is indicated to establish the potential prophylactic effects of cleat modification and bracing to prevent non-contact ACL injuries in soccer.

It has been demonstrated that the preventive programs for non-contact ACL injuries address both neuromuscular/biomechanical risk factors and successfully reduce non-contact ACL injury rates. In addition, most of the training protocols are time efficient and allow ease of incorporation into regular training programs in soccer teams. Multi-component programs show better results than single-component preventive programs to reduce the risk and incidence of non-contact ACL injuries in soccer players. Indeed, plyometric training combined with other training exercises (proprioception, strengthening, body awareness, stretching, or decision-making) have been found to decrease landing forces, decrease varus/valgus moments, and increase effective muscle activation. Multi-component programs should be targeted toward performance enhancement and non-contact ACL injury prevention. It is crucial to conduct more studies in male soccer players, as it has also been earlier demonstrated that male soccer players may benefit from preventive programs.

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