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Research article

Effects of an Injury Prevention Program on Anterior Cruciate Ligament Injury Risk Factors in Adolescent Females at Different Stages of Maturation

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Abstract

The ideal timing to implement anterior cruciate ligament injury prevention programs with respect to maturation is unclear. The purpose of this study was to investigate the effects of an injury prevention program on knee mechanics in early-, late-, and post-pubertal females. In the study, 178 adolescent female basketball players were assigned to six groups: early-pubertal training, early-pubertal control, late-pubertal training, and late-pubertal control, post-pubertal training, and post-pubertal control. The training groups performed an injury prevention program for six months. Medial knee displacement, knee flexion range of motion, and the probability of high knee abduction moment were assessed before and after the training period. After the six-month training period, medial knee displacement was significantly increased in the early-pubertal control group whereas it was unchanged in the early-pubertal training group. Knee flexion range of motion was significantly decreased in the early-pubertal control group whereas it did not change in the early-pubertal training group. The probability of high knee abduction moment was increased in the early-pubertal control group whereas it was unchanged in the earl-pubertal training group. The probability of high knee abduction moment was also decreased in the post-pubertal training group whereas it did not change in the post-pubertal control group. The program limited the development of high-risk movement patterns associated with maturation in early puberty while improving the knee mechanics in post-pubertal adolescents. Therefore, an injury prevention program should be initiated in early puberty and continue through the post-puberty years.

Key words: Knee injuries, landing, neuromuscular control, puberty.

Introduction

The incidence of anterior cruciate ligament (ACL) injury significantly rises in females after the onset of puberty and peaks around 15-19 years-of-age (Renstrom et al., 2008). With an increasing enrollment in organized sports at younger ages, the incidence of ACL injuries is rising in children and adolescents (Werner et al., 2016). Injury to the ACL in children and adolescents is problematic, as studies have confirmed that ACL injury in youth will increase the risk of developing osteoarthritis (Caine and Golightly, 2011; Lohmander et al., 2007; Myklebust et al., 2003).

Multiplanar loading, namely, knee abduction and internal tibial rotation, as well as anterior tibial translation accompanied by reduced knee flexion, are considered to be mechanisms of ACL injury (Quatman and Hewett, 2009; Shimokochi and Shultz, 2008). These biomechanical features are commonly observed during actual injury situations (Koga et al., 2010; Krosshaug et al., 2007; Olsen et al., 2004), and have been investigated in cadaveric studies (DeMorat et al., 2004; Kiapour et al., 2016; Levine et al., 2013; Oh et al., 2012). Prospective studies have identified increased knee valgus (Hewett et al., 2005) and decreased knee flexion (Leppanen et al., 2017) as biomechanical risk factors for ACL injuries which seem to develop during maturation in females (Ford et al., 2010; Hewett et al., 2004; 2015; Schmitz et al., 2009; Yu et al., 2005). Several studies have identified that females demonstrate heightened knee valgus motion following the onset of pubertal growth spurts compared to males (Ford et al., 2010; Hewett et al., 2004; 2015; Schmitz et al., 2009). In addition, females land with decreased knee flexion during a stop-jump task as they mature (Yu et al., 2005). These biomechanical changes might be because female adolescents do not demonstrate sufficient neuromuscular adaptation to rapid skeletal growth like their male counterparts (Hewett et al., 2004). Coinciding with the appearance of these biomechanical characteristics, ACL injury rates start to rise in females during puberty (Renstrom et al., 2008; Shea et al., 2004).

To prevent this devastating injury, many prevention programs have been developed and are gradually being tested for their effectiveness. These programs can be effective in reducing the rate of ACL injuries according to a recent meta-analysis (Webster and Hewett, 2018). Furthermore, Myer et al. (2013) and Sugimoto et al. (2016) evaluated the effectiveness of the injury prevention programs for different age groups. They found that the programs were more effective in the mid-teen years (14-18 years) than in the late-teen (18-20 years) or early adult years (older than 20 years), (Myer et al., 2013; Sugimoto et al., 2016).

However, the biomechanical changes related to the risk of an ACL injury start to develop in early puberty (Ford et al., 2010; Hewett et al., 2004; 2015; Schmitz et al., 2009; Yu et al., 2005); therefore, the program may need to be introduced even earlier than mid-teens years. Our previous study investigated the effects of an injury prevention program on knee mechanics in pubertal females and found that the program limited the undesirable changes in knee mechanics during puberty (Otsuki et al., 2014). There is a need for further investigation when during puberty the intervention training should begin to be the most effective. The purpose of this study was to determine if an injury prevention program would be effective in altering knee mechanics in early-, late-, and post-pubertal females. We hypothesized that an ACL injury prevention program would limit the undesirable changes in movement mechanics associated with pubertal growth in early- and late-puberty females as they would demonstrate physical growth,

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while the program would improve the biomechanics in post-puberty females.

Methods

Participants

In the study, 178 female basketball players from five junior high schools and six senior high schools were recruited to participate. Female basketball players were recruited as the rate of ACL injury in female basketball is the highest among junior and senior high school sports in Japan. All teams trained six days per week and competed at a regional level. Participants were excluded from the study if they had a history of an ACL injury, a lower extremity injury within the prior six weeks that prevented full participation in basketball games, any medical or neurological pathology, or had previously participated in an injury prevention program. The participants and their parents were informed about the nature of the study and were required to provide written consent to participate in the study. The study was approved by the Academic Research Ethical Review Committee of Waseda University.

The study was a non-randomized controlled trial. Two junior high schools and three senior high schools that were able to participate in an injury prevention program were assigned to the training groups. The other three junior high school and three senior high school teams were assigned to the control groups. All teams had never participated in an injury prevention program prior to the study and were instructed not to participate in any additional training or conditioning that could influence their jump landing performance outside of the prescribed regime during the study period. The maturational stage was evaluated using a self-administered rating scale for pubertal development (Carskadon and Acebo, 1993) which can evaluate maturational status in setting where a direct examination is not possible. As all the measurements were performed in each school's gym, this tool was selected. Participants were categorized into three maturational stages: early-puberty (equivalent to Tanner stage 2 and 3), late-puberty (equivalent to Tanner stage 4), and post-puberty (equivalent to Tanner stage 5). Based on the training and maturation status, participants were further divided into six groups: early-pubertal training (ET), early-pubertal control (EC), late-pubertal training (LT), late-pubertal control (LC), post-pubertal training (PT), and post-pubertal control (PC).

Within these groups, two participants who were categorized at a pre-pubertal stage were excluded as this study focused on pubertal and post-pubertal athletes. Additionally, two participants in the PT group and one participant in the PC group were unable to participate in the post-training testing session, as they ceased participation with the team during the study period. One participant in the LT group, one participant in the LC group, four participants in the PT group, and six participants in the PC group had injuries at the post-testing session. Among those injured, three subjects in the PC group sustained non-contact ACL injury. Two participants from the ET group, two participants from the LT group, four participants from the PT group, and one participant from the PC group were unable to participate in the post-testing session due to other personal reasons. As such, 154 participants (ET = 18, EC = 17, LT = 28, LC = 22, PT = 33, PC = 36) completed the study (Table 1).

Injury prevention training program

An injury prevention training program was developed based upon previous literature (Hewett et al., 1999; Mandelbaum et al., 2005; Olsen et al., 2005). This program included skills that were specific to basketball, such as pivoting and cutting (Table 2). The focus of this program was to ensure proper movement patterns, in particular, avoiding knee valgus motion and encouraging knee flexion during landing and cutting. The program was approximately 20 minutes long and was implemented as a warm-up routine. A certified athletic trainer conducted the initial training session. To ensure that the exercises were correctly performed, the trainer followed up and provided direct guidance to the participants every two weeks. The coaches were also trained on how to instruct the athletes on each skill at the initial training session. To monitor team compliance with the program, the coaches recorded whether the program was carried out at each practice session. All training teams completed the program three times per week during the study period. The control teams performed their regular training routine for six months.

Data collection

Pre-training data were collected prior to the initial training session and post-training data were obtained within a week after the six-month training period for all subjects. An ACL injury prediction algorithm, which was developed to identify athletes at risk for ACL injury in the clinical setting (Myer et al., 2011a; Myer et al., 2011b; Myer et al., 2010a; Myer et al., 2010b), was used to evaluate knee mechanics and ACL injury risks. This algorithm estimates the probability of a high knee abduction moment (pKAM), using the measured values of weight, tibia length, quadriceps-hamstring ratio, medial knee displacement, and knee flexion range of motion (Myer et al., 2010b). This clinical assessment tool is reported to have 84% sensitivity and 67% specificity in predicting the status of high knee abduction moments, which is a major biomechanical risk factor for an ACL injury (Myer et al., 2011a; Myer et al., 2010b). Tibia length was measured as the distance between the lateral knee joint line and the prominence of the lateral malleolus while the participants stood with their knees extended. The quadriceps-hamstrings strength ratio was obtained using surrogate calculations by multiplying the female athlete's body mass by 0.01 and adding the resultant value to 1.10, as reported previously (Myer et al., 2010b). This assessment tool was used since it clinically evaluates how each biomechanical risk factor (medial knee displacement and knee flexion range of motion) was altered after an implementation of a training program. Also, this tool accounts for tibia length and weight; thus, it was appropriate to evaluate growing adolescents.

Reflective markers were placed on each participant over the greater trochanter, lateral knee joint line, patella, and lateral malleolus of both legs. Frontal and sagittal plane two-dimensional images were simultaneously captured with three video cameras (30 Hz; CASIO EXILIM, Tokyo, Japan). The participants stood on a box (31 cm high) with their feet positioned 35 cm apart. A basketball goal located directly in front and above the participants was used as an overhead target to enhance jump height (Wulf et al., 2007). The target height was not adjusted for each participant. Participants were instructed to drop off the box and immediately perform a maximum vertical jump, raising both arms in an attempt to reach the target. Prior to testing, the participants were allowed to perform one to three practice trials to familiarize themselves with the drop vertical jump test maneuver. During the practice trials, examiners ensured that participants jumped up immediately after landing and performed a maximal vertical jump. No additional feedback was provided between the trials.

Table 1. Subjects' demographics. Values are mean (± standard deviation).

		n	Age (years)	Height (cm)	Weight (kg)	BMI
Early-puberty Training	Pre	18	12.9 (0.7)	150.8 (5.4)	41.9 (4.6)	18.4 (1.5)
	Post			152.8 (5.3)	44.8 (4.7)	19.1 (1.5)
Early-puberty Control	Pre	17	12.6 (0.6)	151.4 (5.4)	40.1 (4.6)	17.5 (1.3)
	Post			152.7 (5.2)	42.5 (4.9)	18.2 (1.4)
Late-puberty Training	Pre	28	13.8 (1.0)	160.9 (6.4)	52.6 (6.7)	20.3 (2.1)
	Post			162.3 (6.4)	54.9 (5.7)	20.9 (1.7)
Late-puberty Control	Pre	22	14.0 (0.9)	161.4 (5.1)	51.7 (5.7)	19.8 (1.8)
	Post			162.3 (5.2)	54.3 (6.1)	20.6 (1.9)
Post-puberty Training	Pre	33	15.9 (0.7)	161.4 (7.2)	54.4 (6.9)	20.8 (1.4)
	Post			162.4 (7.3)	55.4 (6.8)	20.9 (1.4)
Post-puberty Control	Pre	36	16.0 (0.6)	161.5 (4.1)	55.6 (5.4)	21.3 (1.6)
	Post			161.8 (4.4)	56.1 (5.1)	21.4 (1.8)

n = number of participants. BMI = body mass index.

Table 2. ACL injury prevention program.

Exercises	Repetitions	Instructions
Two-legged squats	2 x 10 reps	Keep the feet, knees, and hips in a straight line. Do not let the knees fall inward. Bend the knees and hips.
One-legged squats	10 reps/side	Keep the feet, knees, and hips in a straight line. Do not let the knees fall inward. Bend the knees and hips. Keep the pelvis level.
Squat jumps	10 reps	Drop into a squat position and perform a maximal vertical jump. Upon landing, return to the starting position and repeat. Keep the feet, knees, and hips in a straight line. Make a soft landing.
Tuck jumps	10 reps	Leap up in the air, tucking the knees into the chest. Land softly and immediately explode back up. Keep the feet, knees, and hips in a straight line.
180° jumps	10 reps/side	Jump into the air and rotate 180°. Land softly, keeping the feet, knees, and hips in a straight line. Bend the knees and hips.
Contact jumps	10 reps/side	Jump towards a partner to make a shoulder-to-shoulder contact. Land softly, keeping the feet, knees, and hips in a straight line. Bend the knees and hips.
Lateral hops	10 reps/side	Stand on one leg and jump to the side. Land softly on the other foot, keeping the feet, knees, and hips in a straight line. Bend the knees and hips. Keep the pelvis level.
Pivoting	20 reps/side	Stand on the balls of the feet with the knees bent. Turn on the balls of the feet approximately 45° to the right and left. Keep the feet and knees pointing in the same direction.
Two-legged plant and cut	10 reps/side	Sprint for 4−5 steps and plant on both legs. Pivot on the feet and cut to change direction. Keep the feet, knees, and hips aligned.

Data analysis

The data were imported into the ImageJ software (National Institute of Mental Health, Maryland, USA) to measure the medial knee displacement and knee flexion range of motion from the first drop jump, using the frontal and sagittal images, respectively. The displacement measurements were calibrated using a known distance (the length of the box that the participants stood on) in the image field. The medial knee displacement was defined as the displacement between the patellar markers within the frame prior to initial contact and within the frame with the maximum medial position of the analyzed leg. The knee flexion angle was measured in the sagittal view with the angle made by the greater trochanter, lateral knee joint line, and lateral malleolus. The knee flexion range of motion was defined as the difference in the knee flexion angles within the frame prior to initial contact and the maximum knee flexion. Using the values of the tibia length, body mass, quadriceps-hamstring ratio, medial knee displacement, and knee flexion range of motion, the ACL injury prediction algorithm was used to estimate pKAM. Only the left leg was analyzed since the left leg demonstrated a greater mean pKAM than the right leg at pre-test in all groups and literatures reported that females were more likely to tear their left ACL than the right (Brophy et al., 2010; Negrete et al., 2007; Ruedl et al., 2012). A single individual performed all of the data analysis. Intra-rater reliability of the repeated measures for the medial knee displacement and knee flexion range of motion of 16 females who were not included in this study indicated an intraclass correlation coefficients of 0.989 (95% confidence interval: 0.970, 0.996) and 0.987 (95% confidence interval: 0.965, 0.995), respectively.

Statistical analysis

The mean and standard deviation of the medial knee displacement, knee flexion range of motion, and pKAM were obtained for each group. To test the effect of an injury prevention program at each maturational stage, a 2 × 2 (training × time) analysis of variance (ANOVA) with a mixed-model design was conducted for each dependent variable in each maturational group. Further, a 2 × 2 × 3 (training × time × maturation) ANOVA with a mixed-model design was performed for each dependent variable to determine whether the effects of the training program differ among maturational stages. When there were significant interaction effects, a post hoc test was performed using a Bonferroni correction within the model. The alpha level was set at 0.05. An effect size (d = mean difference/pooled standard deviation) was calculated for post hoc comparisons. The magnitude of effect size was interpreted according to Cohen's criteria: small (d = 0.2 - 0.5), medium (d = 0.5 - 0.8), and large (d > 0.8) (Cohen, 1988). SPSS version 24 (IBM Inc., Armonk, NY, USA) was used to perform the statistical analysis.

Results

There were no differences between the control and training groups with respect to age, height, or weight within early-, late-, and post-pubertal groups, respectively (Table 1).

In early puberty, there were significant training × time interactions for the medial knee displacement ($F_{1,33}$ = 11.59, p = 0.002), knee flexion range of motion ($F_{1,33}$ = 8.12, p = 0.007), and pKAM ($F_{1,33}$ = 6.96, p = 0.01). After the six-month training period, the medial knee displacement was significantly increased in the EC group (p = 0.002, d = 0.68) whereas it was unchanged in the ET (p = 0.37, d = 0.16) (Figure 1). The knee flexion range of motion was significantly decreased in the EC group (p = 0.01, d = 0.53) whereas it was unchanged in the ET (p = 0.23, d = 0.26) (Figure 1). The pKAM was significantly increased in the EC group (p < 0.001, d = 0.89) but was unchanged in the ET (p = 0.13, d = 0.33) (Figure 1).

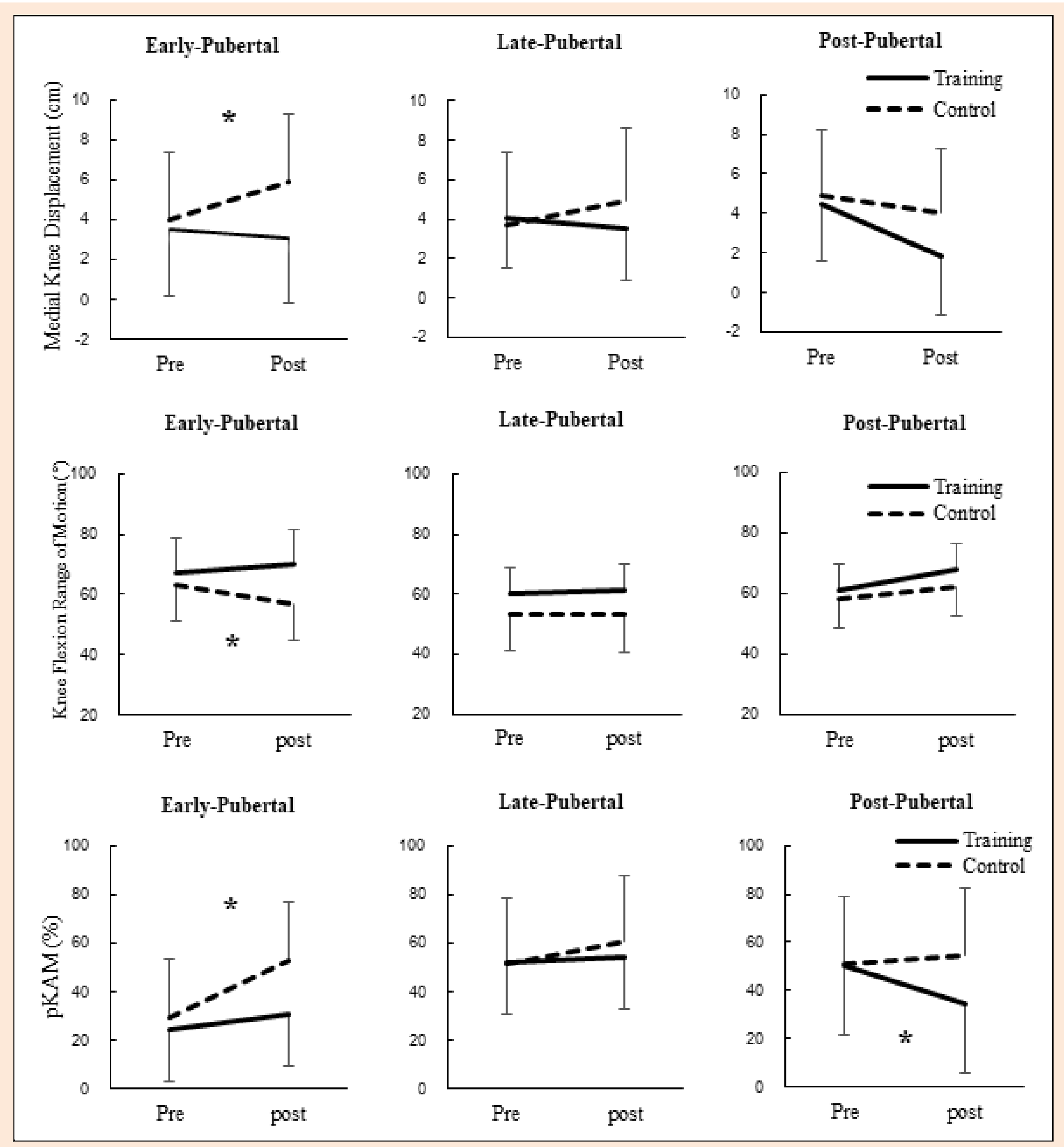

Figure 1. Changes in medial knee displacement, knee flexion range of motion, and probability of high knee abduction moment in training and control groups. pKAM = probability of high knee abduction moment. * Significant difference between pre- and post-test (p < 0.05)

In late puberty, there were no significant training × time interactions for the medial knee displacement ($F_{1,48}$ = 3.45, p = 0.07), knee flexion range of motion ($F_{1,48}$ = 0.35, p = 0.56), or pKAM ($F_{1,48}$ = 1.12, p = 0.30). The main effects of time were not significant for the medial knee displacement ($F_{1,48}$ = 0.39, p = 0.54), knee flexion range of motion ($F_{1,48}$ = 0.07, p = 0.79) or pKAM ($F_{1,48}$ = 2.86, p = 0.10) (Figure 1).

In post puberty, there was a significant training × time interaction for the pKAM ($F_{1,67}$ = 6.51, p = 0.01). After the training period, the pKAM was significantly decreased in the PT group (p < 0.001, d = 0.51), whereas it was unchanged in the PC group (p = 0.58, d = 0.13) (Figure 1). There were no interactions for the medial knee displacement ($F_{1,67}$ = 3.45, p = 0.07) or knee flexion range of motion ($F_{1,67}$ = 1.73, p = 0.19). The main effects of time were significant for the medial knee displacement ($F_{1,67}$ = 14.84, p < 0.001) and knee flexion range of motion ($F_{1,67}$ = 19.36, p < 0.001), indicating that both training and control groups decreased the medial knee displacement and increased knee flexion range of motion (Figure 1).

No significant effect of maturity status upon the magnitude of the effect of the training program was observed for either medial knee displacement ($F_{2,148}$ = 0.13, p = 0.88), knee flexion range of motion ($F_{2,148}$ = 1.98, p = 0.14), and the pKAM ($F_{2,148}$ = 0.78, p = 0.46).

Discussion

The present study investigated the effects of an injury prevention program on the knee mechanics of female basketball players at different stages of maturation. The results of the control groups suggested a natural progression of the measured outcomes during maturation. In the EC group, female athletes seemed to develop faulty movement patterns, as demonstrated by increased medial knee displacement, decreased knee flexion range of motion, and elevated pKAM. In the LC group, participants showed no changes in medial knee displacement, knee flexion range of motion, or pKAM over the study period. Despite an increase in knee flexion range of motion, pKAM in the PC group remained unchanged over the study period. The present injury prevention program seemed to alter this natural progression of the movement mechanics. In the ET group, medial knee displacement, knee flexion range of motion, and pKAM were unchanged after the training period, suggesting that the program limited the development of high-risk movement patterns. In the LT group, there were no significant training effects, as the medial knee displacement, knee flexion range of motion, and pKAM did not change over the training period. Concerning the post-pubertal athletes, the program improved their knee mechanics, as demonstrated by reduced pKAM. Although these changes were observed within each maturational stage, the patterns of the changes did not differ among three maturational stages for medial knee displacement, knee flexion range of motion, or the pKAM.

The difference in medial knee placement observed over the study period was 2.0 cm (d = 0.63) in the EC group. For the knee flexion range of motion, the difference was -6.4° (d = 0.52) in the EC group. Although these differences appear small, the effect sizes of these variables were medium; thus, the changes observed over the six-month period may be clinically important. Increased medial knee displacement and the small knee flexion angle are frequently observed at the time of ACL injuries (Koga et al., 2010; Krosshaug et al., 2007; Olsen et al., 2004), and previous studies have indicated that the knee is 5° - 12° abducted and 12° - 24° flexed when ACL injuries occurred (Kim et al., 2015; Koga et al., 2010).

To the best of our knowledge, only one study has investigated the effects of injury prevention programs in different age groups during adolescence. DiStefano et al. (2009) reported that the high-school age group (14 - 17 years old) sustained greater improvements in the Landing Error Scoring System from the injury prevention program compared to a pre-high-school age group (10 - 13 years old); our study agrees with these findings. DiStefano et al. (2009) speculated that the reason for this different training effect might be that the extensive program was not appropriate for younger participants, considering their stage of motor development. This study, which used control groups, was also able to identify that the changes in knee mechanics during maturation was one of the reasons for the different responses to the injury prevention program. It has been reported that the growth of the tibia and the femur leads to longer lever arms, resulting in increased torque around the knee (Quatman et al., 2006). An increase in height and weight also leads to a higher center of mass and a greater body mass, and this makes dynamic control more challenging. Therefore, the increase in height and weight observed in early-pubertal females may lead to the development of high-risk movements. The present training program limited these undesirable mechanical changes in early puberty. The late-pubertal athletes did not demonstrate significant changes as they might have suffered ill effects of having recently grown greatly. The late-pubertal athletes were about 10 cm taller than the early-pubertal and almost as tall as the post-pubertal athletes, but they were only 10 months older than the early-pubertal and about 2 years younger than the post-pubertal athletes. In post-puberty, on the other hand, without growth-related biomechanical changes, the training program did produce a significant improvement.

Although the post-pubertal participants may appear to have greater improvement, injury prevention programs should be encouraged in early puberty since the program was able to limit the development of high-risk movement patterns. Without training, these younger females might continue to develop high-risk movements as they mature. In the present study, the pre-training pKAM in early-pubertal participants was 26.7% while that of late- and post-pubertal participants was 51.7% and 50.7%, respectively, suggesting natural development of high-risk movements patterns during maturation. In fact, three participants in the PC group sustained non-contact ACL injuries during the study whereas no one in the other groups sustained ACL injuries. In addition to these biomechanical changes, muscle strength and ACL geometry change considerably during maturation (Davidson and McLean, 2016). Knee extensor and flexor strength imbalance coincides with smaller ACL cross sectional area, especially in mid-pubertal females, implying that the ACL may be unable to withstand quadriceps-dominant loading (Davidson and McLean, 2016). Therefore, the prevention programs need to be introduced in early puberty and not wait until the risk factors emerge due to rapid pubertal growth.

One of the limitations of this study was that knee mechanics were evaluated using a two-dimensional measurement based on video image analysis. However, this clinically applicable approach has been validated against three-dimensional measurements and can be conveniently used outside of the laboratory, making it more accessible (Myer et al., 2011a; Myer et al., 2011b; Myer et al., 2010a; Myer et al., 2010b). The motions reported are useful for comparative, rather than the absolute measure of knee joint kinematics and, thus, are appropriate here. Another limitation was that randomization during group allocation was not achieved in this study, as the training teams voluntarily enrolled in the training program. This study design may have produced unintentional biases. This study also did not record individual participation rate to the training program, although the coaches recorded whether the team carried out the program at each session. Furthermore, while the changes we did observe have been associated with a reduction in ACL injury incidence (Hewett et al., 2016), we cannot extrapolate this from our study since a statistical analysis of injury rates with our cohorts was not conducted due to a limited sample size. Another important limitation is the lack of individualization of the program. This study used the same training program for all maturational groups, but the intensity of the training program would have varied between groups. The effects of the program on knee mechanics might have been even greater if the program was prescribed by maturity. In addition, there was no progression built in the program during the six-month training period. Athletes, regardless of maturity, might have reached a plateau in unloaded bodyweight activities as they performed the program three times per week for six months. Ideally, training program should be progressed according to athletes' technical competence. Finally, this study did not include pre-pubertal females, as it focused on the maturational stages when the risk of ACL injuries begins to develop (Ford et al., 2010; Hewett et al., 2004; Hewett et al., 2015; Schmitz et al., 2009; Yu et al., 2005). These programs may be more effective in pre-pubertal athletes because earlier intervention is ideal in terms of skill acquisition (Janacsek et al., 2012). Therefore, a future study is required to evaluate the training effects in pre-pubertal females. A longitudinal study is needed to determine whether females who are trained in the pre-pubertal period could mitigate injury risk throughout critical maturational stages.

Conclusion

Our findings indicate that, although the rate of ACL injuries peaks in late adolescence (Renstrom et al., 2008), the high-risk movement patterns associated with injury already develop in early puberty. Furthermore, in early-pubertal athletes, the program was effective in limiting the development of these undesirable movements associated with maturation. While the prevention program significantly improved knee mechanics in post-pubertal athletes, the biomechanical risk of ACL injury is already developed at this stage. Waiting until this time to introduce an intervention is reactive rather than proactive. Our findings, therefore, suggest initiation of injury prevention programs at earl-pubertal stage. This study also suggests that the coaches and trainers need to have different expectations regarding training effects for early-, late-, and post-pubertal athletes. In early and late puberty, an improvement through a program might not be obvious due to the natural development of the faulty movement patterns. On the other hand, since physical growth is mostly completed in post-puberty athletes, significant improvement through the training program can be expected.

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Key points

- An ACL injury prevention program limited the development of high-risk movement patterns associated with maturation in early puberty while it improved the knee mechanics in post-pubertal adolescents.
- An improvement through a program might not be obvious due to the natural development of the faulty movement patterns in early-pubertal adolescents, while significant improvement through the training program can be expected in post-pubertal adolescents.
- An ACL injury prevention program should be initiated in early puberty and continue through the post-puberty years.

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