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博士（スポーツ科学）

Prevention of Anterior Cruciate Ligament  
Injury in Female Athletes during Maturation

成長期女子選手における  
膝前十字靭帯損傷予防法の検討

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## **CHAPTER 1: INTRODUCTION**

### **1.1 INTRODUCTION AND PROBLEM STATEMENT**

Anterior cruciate ligament (ACL) injuries are frequently seen in the athletic population, especially among female athletes (Louw, Manilall, & Grimmer, 2008; Renstrom et al., 2008; Shea, Grimm, Ewing, & Aoki, 2011). Although great progress in surgery and rehabilitation has made possible a faster and safer return to sport, ACL injuries are still recognized as one of the most devastating sport-related injuries. ACL injuries usually require surgery and extensive rehabilitation for at least 6 months. In addition, an ACL injury can triple the risk of osteoarthritis development regardless of the management (Caine & Golightly, 2011; Lohmander, Englund, Dahl, & Roos, 2007; Myklebust, Holm, Mæhlum, Engebretsen, & Bahr, 2003). Therefore, the risk management of ACL injuries in female athletes is critical.

During the last several decades, many researchers have made efforts to understand ACL injury. The research area covered the epidemiology, etiology, risk factor, treatment, and prevention of ACL injury. Especially in the last decade, the trend of research has shifted toward the prevention of this devastating injury. Recently, several intervention studies indicated that training programs for ACL injury prevention might be effective in reducing the number of these injuries (Heidt Jr, Sweeterman, Carlonas, Traub, & Tekulve, 2000; Hewett, Lindenfeld, Riccobene, & Noyes, 1999; Kiani et al., 2010; LaBella et al., 2011; Mandelbaum et al., 2005; Myklebust, Engebretsen, et al., 2003; Olsen, Myklebust, Engebretsen, Holme, & Bahr, 2005; Steffen, Myklebust, Olsen, Holme, & Bahr, 2008; Waldén, Atroshi, Magnusson, Wagner, & Häggglund, 2012). In contrast, Agel, Arendt, and Bershadsky (2005) reported that the rate of ACL injury had not been declining in high-risk sports,



such as basketball and soccer. Also, others reported that low participant compliance to injury prevention programs resulted in the low effectiveness of ACL injury prevention (Emery, Rose, McAllister, & Meeuwisse, 2007; Soligard et al., 2009; Steffen et al., 2008). Therefore, at this point, it is necessary to investigate how to effectively implement an ACL injury prevention program.

In this dissertation, it was first investigated when an injury prevention program should be initiated. The occurrence of ACL injuries significantly increases after the onset of growth spurt in female athletes (Granan, Bahr, Steindal, Furnes, & Engebretsen, 2008). Around the same time, female athletes start to demonstrate high-risk movement patterns (Ford, Shapiro, Myer, Van Den Bogert, & Hewett, 2010; Hewett, Myer, & Ford, 2004; Schmitz, Shultz, & Nguyen, 2009), probably owing to their rapid physical development. It is reasonable to modify the risk factor during or prior to the period when the number of ACL injury actually increases. Furthermore, learning proper movement skills might be easier for young athletes than for adults because pre-adolescents undergo significant developmental changes in the neural system (Malina, Bouchard, & Bar-Or, 2004). It is ideal for young athletes to learn proper movement skills as they learn other sport-specific skills. To date, no consensus has been reached on when to initiate an ACL injury prevention program for young female athletes. Therefore, the first study evaluated the ACL injury risk across the different maturational stages. Evaluation by maturational stage rather than by chronological age was performed because the development of structure and motor function depends more on physiological age (Malina et al., 2004). These developmental changes in structure and motor function might increase the risk of ACL injury (Ford, Shapiro, et al., 2010; Hewett et al., 2004). ACL injury risk was investigated by using an ACL injury prediction algorithm that was developed to

estimate the probability of demonstrating high-risk movement patterns (Myer et al., 2010).

Second, in this dissertation, it was investigated what the focus of training should be to effectively reduce the risk of ACL injury. ACL injury prevention programs are multi-component programs that typically incorporate strength, plyometric, balance, skill, and flexibility training (Heidt Jr et al., 2000; Hewett et al., 1999; Kiani et al., 2010; LaBella et al., 2011; Mandelbaum et al., 2005; Myklebust, Engebretsen, et al., 2003; Olsen et al., 2005; Petersen et al., 2005; Steffen et al., 2008; Waldén et al., 2012). Although those programs seem effective, the important elements in an ACL injury prevention program are unknown. Furthermore, the volume of multi-component training might hinder the participants' adherence to the program. To improve the efficacy of an ACL injury prevention program, a more targeted strategy is needed. The program should be refined to include elements that modify the injury risk. Recent studies have identified that ACL injuries are likely to occur with excessive knee valgus motion within 40 ms after ground contact (Koga et al., 2010). Thus, the prevention training program should be aimed at reducing this high-risk movement during this critical period. In the second study, it is investigated what factors influence the knee valgus motion at 40 ms after ground contact. The muscle strength, preparatory muscle activities, and landing skills were specifically examined, as these were considered the most influential factors on the knee valgus motion at 40 ms after ground contact. Preparatory muscle activity was examined rather than reflexive muscle activity. It was shown that reflexive muscle activity occurs at approximately 95 ms after a stimuli to the ACL, with an electro-mechanical delay about 40 ms (Dyhre-Poulsen & Krogsgaard, 2000). Therefore, the reflex response would not be fast enough to provide necessary constraint to stabilize the joint at 40 ms

after ground contact. Rather than the reflexive muscle activity, the preparatory muscle activity might be responsible for the control of the knee joint during dynamic activity. Previous studies have demonstrated that the tensile stiffness of muscle was linearly proportional to the active tension developed by the muscle before perturbation (Dhafer, Tsoumanis, Houle, & Rymer, 2005; Zhang & Rymer, 1997). Also, it was shown that an increase in pre-activation level provides additional excitatory input to the motor pool and causes more motor neurons to fire (Fuglevand, Winter, & Patla, 1993). Therefore, the preparatory muscle activity might help reduce the strain on the ACL. The second study investigated how much of the knee valgus motion at 40 ms after ground contact could be explained by muscle strength, preparatory muscle activities, and landing skills.

Finally, on the basis of the findings of the first and second parts of the dissertation, a training program that focused on improving landing mechanics during the critical time period was developed and implemented in pubertal female athletes. The third study evaluated, in a laboratory setting, whether the training program would improve landing mechanics and what changes in strength, preparatory muscle activity and landing skill would be observed. In the last study, this training program was implemented for 6 months in pubertal female athletes to determine whether the training program could limit the movement changes associated with pubertal growth in young female athletes.

## **1.2 OBJECTIVES**

The objectives of this study are as follows:

1. To evaluate when ACL injury risk increases in pubertal female athletes

2. To identify the factors (strength, muscle activity, skill) that affect biomechanical ACL injury risk
3. To evaluate whether these factors are modifiable through a training program
4. To evaluate whether the training program could limit the changes in movement patterns associated with pubertal growth and reduce the risk of developing ACL injury

### **1.3 HYPOTHESES**

The following hypotheses were investigated in the study:

1. ACL injury risk, measured with an ACL injury risk prediction algorithm, would increase after the onset of puberty in female athletes
2. The knee abduction angles at 40 ms after ground contact during a drop vertical jump would be affected by preparatory muscle activity and lower-extremity motion
3. Lower-extremity motion and preparatory muscle activity could be changed with a training program
4. The training program would be effective in limiting the movement changes associated with pubertal growth in female athletes and reducing the risk of ACL injury

### **1.4 LIMITATIONS**

1. The results of this study are limited to female junior high school basketball players.

2. Pubertal stages were estimated by using a pubertal development scale. Other evaluations (e.g., skeletal age or time from peak height velocity) were not performed to determine pubertal stages.
3. Movement tasks were limited to the drop vertical jump. Single-leg landing or cutting tasks were not evaluated.
4. Other risk factors, such as morphological or hormonal factors, were not evaluated in this study.

### **1.5 DELIMITATIONS**

1. The participants consisted of female junior basketball players between the ages of 10 and 14 years.
2. All participants were members of school basketball teams and had similar performance level.
3. ACL injury risk was evaluated by using an ACL injury prediction algorithm, which was shown to be valid and reliable.

### **1.6 ETHICAL CONSIDERATIONS**

This project was approved by the Academic Research Ethical Review Committee of Waseda University (application no.: 2012-242, 2012-068(1)). Informed consent was obtained from the participants and their guardians before enrollment in the study. Complete privacy and confidentiality was ensured throughout the study. The names or other identifying information were removed from all test data. All data were kept in a safe area. The names of the subjects will never be used in any presentation or publication related to the study results. All procedures were non-

invasive, and there was minimal risk of injury or harm with the measurements done according to a standardized protocol.

## **1.7 DEFINITIONS OF TERMS**

### **Contact injury:**

A contact injury refers to an injury resulting from physical contact with other athletes, a moving object (e.g., ball), or a static object (e.g., goalpost).

### **Non-contact injury:**

A non-contact injury refers to an injury sustained without contact with another athlete or object.

### **Athlete-exposure (AE):**

The injury rate was reported as one athlete participating in one practice or competition.

### **Knee valgus:**

The frontal plane angular deviation of the tibia away from the midline of the body relative to the femur (same as knee abduction).

### **Knee abduction:**

The frontal plane angular deviation of the tibia away from the midline of the body relative to the femur (same as knee valgus).

**Maturation stages:**

Maturation stages were determined by using the self-administered rating scale for pubertal development (Carskadon & Acebo, 1993) in this study (Appendix).

**Probability of high knee abduction moment (pKAM):**

pKAM is the probability that a subject demonstrates a high knee abduction moment ( $> 21.74$  Nm of knee abduction) during a drop vertical jump, which was shown to be a risk of ACL injury. The pKAM was obtained by using an ACL injury prediction algorithm (Myer et al., 2010). pKAM was used to assess the risk of ACL injury.

**Initial contact:**

The point at which the subject's foot comes into contact with the ground and vertical ground reaction force exceed 10 N during the first landing of the drop vertical jump.

**Preparatory muscle activity:**

EMG activity for a period of a 200ms prior to initial contact during the drop vertical jump (Carcia & Martin, 2007; Zazulak et al., 2005).

**Dominant leg:**

The leg used to kick a ball for maximal distance.

## CHAPTER 2: LITERATURE REVIEW

### 2.1 EPIDEMIOLOGY

Several national registries have been established to collect information on ACL surgeries. In Norway, the annual population incidence of ACL reconstruction surgeries was 34 per 100,000 citizens (Granan et al., 2008). The incidence in the age group of 16-39 years was 85 per 100,000 citizens (Granan et al., 2008). In Germany, the incidence of ACL injuries in the active population was 70 per 100,000 citizens (Renstrom et al., 2008). In Sweden, the incidence in the age group of 10-64 years was 81 per 100,000 citizens. However, in Japan, there has been no nation-wide registry for monitoring the incidence of ACL injuries.

#### 2.1.1 Sex

The rate of ACL injuries differs between the sexes. In a study including all age groups, the incidence of ACL injuries was found to be higher in males than in females (Granan et al., 2008). However, in the young population, females had a higher rate of ACL injuries than males (Granan et al., 2008). On the basis of the data from the National Collegiate Athletic Association (NCAA) Injury Surveillance System in the United States, the rate of ACL injuries were 2.8-3.4 times higher in female than in male soccer and basketball players (0.27 vs. 0.08/1000 AE in basketball; 0.31 vs. 0.11/1000 AE in soccer) (Agel et al., 2005). Similarly, the data from an American high school injury surveillance system demonstrated that the rate of ACL injuries was 3.4 times higher in girls than in boys in sex-comparable sports (0.089 and 0.026/1000 AE, respectively) (Joseph et al., 2013). In Japanese junior and senior high schools, the rate of ACL injuries was 2.7 times higher in girls than in boys (Okuwaki, 2012).



Although female athletes seem to have a higher rate of ACL injuries, when looking at the overall injury rate of ACL injuries, male athletes in certain sports such as football are at a higher risk of developing ACL injuries (Agel et al., 2005; Joseph et al., 2013).

### **2.1.2 Age**

ACL injuries are frequently seen in young athletes. In female athletes, the rate of ACL injury seems to increase after puberty. In Norway, the highest number of ACL injuries is seen between the age of 15 and 19 years in females (Granan et al., 2008). In Japan, the number of ACL injuries gradually increases around the age of 14 years and peaks at the age of 17 years (Okuwaki, 2012).

### **2.1.3 Sports**

The NCAA injury surveillance system reported the rate of ACL injuries in 15 sports. Women's gymnastics (0.33/1000AE), women's soccer (0.28/1000AE), women's basketball (0.23/1000AE), and men's spring football (0.33/1000AE) produced many ACL injuries (Hootman, Dick, & Agel, 2007). In high school, women's soccer (0.117/1000AE), women's gymnastics (0.114/1000AE), women's basketball (0.107/1000AE), and men's football (0.117/1000AE) demonstrated a high rate of ACL injuries. Japanese data also showed that women's basketball, women's soccer, and women's gymnastics pose a high risk of ACL injuries among junior and senior high school sports (Okuwaki, 2012).

## **2.2 MECHANISMS OF ACL INJURY**

### **2.2.1 Playing situations**

Many of the ACL injuries are non-contact injuries. Boden, Dean, Feagin Jr, and Garrett Jr (2000) reported that 72% of all ACL injuries were non-contact. Arendt and Dick (1995) showed that non-contact ACL injuries accounted for 73% in women's basketball, 55% in women's soccer, 61% in men's basketball, and 40% in men's soccer. In soccer, 63% of the injured players were changing direction, while 25% were landing at the time of injury (Arendt & Dick, 1995). In basketball, 59% of ACL injuries occurred during landing and 10% were performing cutting movements at the time of injury (Arendt & Dick, 1995).

### **2.2.2 Video analysis**

A systematic video analysis of ACL injury situations was performed in team handball (Olsen, 2004). The common mechanisms of non-contact ACL injuries involved a forceful valgus collapse with the knee close to full extension combined with some tibial rotation (Olsen, 2004). Similarly, a video analysis of ACL injury in basketball showed that valgus collapse of the knee was observed in many cases (Krosshaug et al., 2007). Koga et al. (2010) performed a more detailed analysis of injury situations by using a model-based image-matching technique. They found that the main mechanisms of ACL injury involved increased knee valgus motion combined with internal tibial rotation (Koga et al., 2010). A reduced knee flexion was also commonly observed (Koga et al., 2010). The authors considered that ACL injuries most likely occurred approximately 40 ms after the initial ground contact (Koga et al., 2010). In addition to the lower-extremity motion, Hewett, Torg, and Boden (2009) reported that lateral trunk motion toward the injured side was

commonly observed at the time of ACL injury. The lateral motion of the trunk shifts the ground reaction force vector laterally; as a result, it might increase the knee abduction moment (Hewett et al., 2009). Sheehan, Sipprell, and Boden (2012) also reported that ACL injuries occurred with the center of mass far posterior to the base of support.

### **2.2.3 Cadaveric study**

Several researchers have investigated the mechanisms of ACL injury by using human cadavers. The hypothesized mechanisms of injury in these studies were anterior tibial translation with excessive quadriceps contraction, knee valgus, tibial internal rotation, combination of knee valgus and tibial rotation, and impingement under the femoral intercondylar notch. Recently, ACL strain was evaluated in physiologically relevant multi-planar loading conditions during high-risk activities (Levine et al., 2013). ACL failure was generated with a combination of anterior tibial shear force, and knee abduction and internal tibial rotation moments under axial impact. Furthermore, Kiapour et al. (2014) investigated the timing sequence of multi-planar knee kinematics and ACL strain during a simulated landing task. They reported that anterior tibial translation and ACL strain increased with quadriceps contraction before initial contact (Kiapour et al., 2014). Knee flexion, anterior tibial translation, knee abduction, and ACL strain were initiated and reached their maximum almost simultaneously (Kiapour et al., 2014). Approximately 40 ms later, internal tibial rotation was initiated and peaked (Kiapour et al., 2014). These findings suggested that the primary mechanism of ACL injury involved the anterior tibial translation and knee abduction moment. Internal tibial rotation might be a secondary mechanism of ACL injury.

## **2.2.4 Bone bruises**

Bone bruises on the femoral condyle or tibia are commonly observed in ACL injuries. Large impacts between the femoral and tibial articular cartilage during ACL injuries result in bone bruises. As the distribution of the bone bruises provides critical information on how injury occurred, several studies have investigated the location of bone bruises. A systematic review reported that the most common locations were the lateral femoral condyle and the posterior lateral tibial plateau (Patel, Hageman, Quatman, Wordeman, & Hewett, 2014). Quatman et al. (2011) investigated the distributions of articular cartilage pressure similar to the bone bruise patterns in ACL injury by using a finite element knee model. Knee abduction combined with anterior tibial translation or internal or external tibial rotation resulted in increased articular cartilage pressure on the lateral femoral condyle and posterior lateral tibial plateau (Quatman et al., 2011). Therefore, bone bruises on the lateral femur and tibia might be the result of lateral joint compression induced by knee abduction motion, whereas the bone bruises on the posterior tibial plateau might occur as a result of anterior tibial translation or internal tibial rotation.

## **2.3 RISK FACTORS OF ACL INJURY**

### **2.3.1 Anatomical risk factors**

#### **Body mass**

Increased body mass index (BMI) might be a risk factor of ACL injury in females. A prospective study by Uhorchak et al. (2003) reported that female army recruits with a BMI >1 standard deviation above the mean had 3.5 times greater risk of ACL injury than did those with a lower BMI.

## **ACL structure**

According to Chaudhari, Zelman, Flanigan, Kaeding, and Nagaraja (2009), ACL-injured subjects had smaller ACL volume than the non-injured controls in both men and women. When comparing by sex, the ACL in women was smaller in length, cross-sectional area, volume, and mass (Chandrashekar, Slauterbeck, & Hashemi, 2005). In addition, the ACL in women had lower mechanical properties, such as strain and stress at failure and modulus of elasticity, when compared with the ACL in men (Chandrashekar, Mansouri, Slauterbeck, & Hashemi, 2006). Furthermore, the ACL in women had lower fibril concentration and lower percentage area occupied by collagen fibrils (Hashemi, Chandrashekar, Mansouri, Slauterbeck, & Hardy, 2008). These differences in geometry, mechanical properties, and ultrastructure might contribute to the sex difference in ACL injury.

## **Intercondylar notch**

Smaller intercondylar notch width or index seems to be a risk factor of ACL injury. Large prospective studies have generally reported that subjects with a smaller intercondylar notch were more likely to sustain an ACL injury (LaPrade, Burnett II, & Daniel, 1994; Shelbourne, Davis, & Klootwyk, 1998; Souryal, Freeman, & Daniel, 1993; Uhorchak et al., 2003). Some researchers speculated that persons with narrower intercondylar notches had smaller, and thus weaker, ACLs (Dienst et al., 2007). In contrast, others reported that the size of the ACL did not vary in proportion to the size of the intercondylar notch (Anderson, Dome, Gautam, Awh, & Rennert, 2001; Muneta, Takakuda, & Yamamoto, 1997). They suggested that normal-sized ACLs were impinged in stenotic notches with rotational or translational movements.

## **Tibial slope**

Tibial slope, the posterior inclination of the tibial plateau, contributes to sagittal plane laxity. An increased tibial slope produces anterior shear force during a quadriceps contraction. Biomechanical studies indicated that anterior tibial translation and ACL loading increased as the tibial slope increases during standing, walking and squatting (Shelburne, Kim, Sterett, & Pandy, 2011). Furthermore, posterior tibial slope was correlated with both peak anterior tibial acceleration and peak anteromedial bundle strain during simulated landing (McLean et al., 2011). Several retrospective studies reported that a steeper tibial slope was observed in subjects with ACL injury compared with the control group (Hohmann, Bryant, Reaburn, & Tetsworth, 2011; Todd, Lalliss, Garcia, DeBerardino, & Cameron, 2010). In addition, some studies with magnetic resonance imaging evaluated the geometry of both the lateral and medial tibial plateau. The lateral tibial slope was associated with ACL injury, whereas the medial tibial slope showed no difference between subjects with and those without ACL injury (Hashemi et al., 2010; Simon, Everhart, Nagaraja, & Chaudhari, 2010; Stijak, Herzog, & Schai, 2008). These findings suggested that a steeper lateral tibial slope might cause the lateral femoral condyle to slide posteriorly over the lateral tibial plateau during joint loading. As a result, the femur externally rotates relative to the tibia, which increases the strain on the ACL.

## **Joint laxity and static alignment**

Increased general joint laxity (Ramesh, Von Arx, Azzopardi, & Schranz, 2005), anterior knee laxity (Uhorchak et al., 2003; Woodford-Rogers, Cyphert L Fau - Denegar, & Denegar, 1994), genu recurvatum (Loudon, Jenkins, & Loudon, 1996; Myer, Ford, Paterno, Nick, & Hewett, 2008; Ramesh et al., 2005), and tibial internal

rotation laxity (Branch et al., 2010) were reported to be risk factors of ACL injuries. Increased quadriceps angle (Q-angle) may place increased dynamic knee valgus stress. A study has shown that female basketball players with knee injuries had increased Q-angle when compared with non-injured players (Shambaugh, Klein, & Herbert, 1991). However, others did not find the Q-angle to be a predictor of ACL injuries (Söderman, Alfredson, Pietilä, & Werner, 2001). There is not enough evidence to support the hypothesis that the Q-angle is a risk factor of ACL injuries. Foot pronation or an increased navicular drop might be associated with ACL injuries. Several retrospective studies have found that subjects with an ACL injury had an increased subtalar pronation or navicular drop (Allen & Glasoe, 2000; Loudon et al., 1996; Woodford-Rogers et al., 1994). However, other studies did not find increased subtalar pronation in ACL-injured subjects (Jenkins, Killian, Williams Iii, Loudon, & Raedeke, 2007; Smith, Szczerba, Arnold, Martin, & Perrin, 1997). To date, no consensus has been reached on whether foot pronation is a risk factor of ACL injury.

### **2.3.2 Hormonal risk factors**

Sex differences in ACL injury might be partly explained by sex hormones. However, the link between ACL injury and fluctuations of sex hormones during the menstrual cycle remains controversial. It seems that more studies have indicated that the preovulatory phase of the menstrual cycle poses an increased risk of ACL injury (Hewett, Zazulak, & Myer, 2007). A prospective study by Dragoo et al. (2011) found that female athletes with higher serum relaxin level were more likely to tear their ACL. These studies have directly associated the level of sex hormones with ACL injury.

Several studies have investigated the effects of sex hormones on ACL injury risks. Decreased collagen formation was observed with increased concentrations of estradiol, thereby reducing the mechanical properties of the ligament (Liu, Al-Shaikh, Panossian, Finerman, & Lane, 1997; Yu, Liu, Hatch, Panossian, & Finerman, 1999). Changes in sex hormones influence the knee joint laxity across the menstrual cycle (Eiling, Bryant, Petersen, Murphy, & Hohmann, 2007; Heitz, Eisenman, Beck, & Walker, 1999; Shultz, Kirk, Johnson, Sander, & Perrin, 2004); however, a large variability might exist among individuals. Furthermore, changes in joint laxity were reported to be associated with changes in knee kinematics during the menstrual cycle (Park, Stefanyshyn, Ramage, Hart, & Ronsky, 2009; Shultz et al., 2012).

### **2.3.3 Neuromuscular risk factors**

#### **Strength**

A prospective study by Myer et al. (2009) showed that female soccer and basketball players who sustained ACL injuries had increased relative quadriceps strength and decreased relative hamstring strength. Wild, Steele, and Munro (2013) reported that female adolescents with reduced hamstrings strength had significantly increased knee abduction alignment and decreased hip abduction moments. Weak hamstrings might be a risk factor of ACL injury.

#### **Muscle activity**

Many researches have investigated how muscle activation patterns around the knee joint are associated with ACL injury. Quadriceps contraction produces anterior translation of the tibia, and places strain on the ACL when knee flexion is  $< 30^\circ$  (Renstrom, Arms, Stanwyck, Johnson, & Pope, 1986; Withrow, Huston, Wojtys, &



Ashton-Miller, 2008). Therefore, co-contraction of the quadriceps and hamstrings is important in maintaining dynamic stability. Hamstrings recruitment limits the anterior drawer of the tibia and reduces the load on the ACL (Fleming et al., 2003; Li et al., 1999; More et al., 1993). During cutting or landing, high quadriceps activation occurs just before the foot strike and peaks in mid-eccentric motion (Colby et al., 2000). On the other hand, hamstrings activation was submaximal at and after the initial contact (Colby et al., 2000). Padua, Garcia, Arnold, and Granata (2005) found that female athletes demonstrated increased quadriceps and soleus activation and decreased hamstrings-to-quadriceps ratio. Moreover, several studies have investigated preparatory muscle activation, as reflective or voluntary muscle activation is too slow for ACL injuries that occur approximately 40 ms after ground contact (Chappell, Creighton, Giuliani, Yu, & Garrett, 2007; Hanson, Padua, Blackburn, Prentice, & Hirth, 2008; Palmieri-Smith, Wojtys, & Ashton-Miller, 2008). Female athletes typically prepare landing with increased quadriceps activation and decreased hamstrings activation when compared with male athletes (Chappell et al., 2007). Similarly, female athletes demonstrated greater quadriceps to hamstrings co-activation ratio than male athletes during the preparatory and loading phases of a side-step cutting maneuver (Hanson et al., 2008). In addition to the amount of muscle activation, a slower response of the hamstrings to the anterior tibial translation load was observed in female athletes (Huston & Wojtys, 1996).

Decreased joint compression on the medial side might contribute to an increase in dynamic knee valgus. Rozzi, Lephart, Gear, and Fu (1999) have shown that female athletes demonstrated increased lateral hamstrings activation during landing. Myer, Ford, and Hewett (2005) found that female athletes had a decreased ratio of medial-to-lateral quadriceps activation during high-risk maneuvers. Similarly, Palmieri-Smith

et al. (2008) reported that higher knee valgus angles in females were associated with increased preparatory muscle activity in the lateral hamstrings and vastus lateralis, whereas lower knee valgus angles were associated with increased preparatory activity of the vastus medialis muscle. Furthermore, Palmieri-Smith, McLean, Ashton-Miller, and Wojtys (2009) calculated the medial-to-lateral quadriceps-to-hamstrings co-contraction ratio. Female athletes had decreased medial-to-lateral quadriceps-to-hamstrings activation and increased external knee abduction moment (Palmieri-Smith et al., 2009).

The gluteus medius and maximus play an important role in controlling the hip kinematics. Insufficiency of these muscles might increase hip adduction and internal rotation, thereby increasing the strain on the ACL. Several studies have investigated sex differences in gluteus medius and maximus activities (Carcia & Martin, 2007; Hanson et al., 2008; Zazulak et al., 2005; Zeller, McCrory, Kibler, & Uhl, 2003). Surprisingly, only one study found that females demonstrated decreased activity of the gluteus maximus (Zazulak et al., 2005). Other studies did not find sex differences in gluteus medius or maximus activities (Carcia & Martin, 2007; Zeller et al., 2003). Hanson et al. (2008) showed that female athletes demonstrated increased preparatory gluteus medius activity during side step cutting in contrast to their hypothesis.

All these studies on muscle activity were sex comparisons and were not tested on subjects with actual ACL injury. Sufficient activation of the hamstrings during landing might be important in ACL injury.

#### **2.3.4 Biomechanical risk factors**

A prospective study by Hewett et al. (2005) reported that ACL-injured athletes had increased knee abduction angle, knee abduction moment, and ground reaction

force during a drop vertical jump when compared with uninjured subjects. In sex comparison studies, female athletes demonstrated increased knee abduction angle during bilateral landing (Chappell, Yu, Kirkendall, & Garrett, 2002; Ford, Myer, & Hewett, 2003; Hewett et al., 2005; Kernozek, Torry, Van Hoof, Cowley, & Tanner, 2005), unilateral landing (Pappas, Hagins, Sheikhzadeh, Nordin, & Rose, 2007) and cutting (Ford, Myer, Toms, & Hewett, 2005; McLean, Huang, & Van Den Bogert, 2005; McLean, Lipfert, & van den Bogert, 2004; Sigward, Pollard, Havens, & Powers, 2012) compared with male athletes. The knee abduction moment was also increased in female athletes (Kernozek et al., 2005; Landry, McKean, Hubley-Kozey, Stanish, & Deluzio, 2007; McLean et al., 2005; Sigward et al., 2012).

Concerning the sagittal plane, no consensus has been reached. Some reported that a smaller knee flexion was observed in females during landing (Lephart, Ferris, Riemann, Myers, & Fu, 2002; Schmitz, Kulas, Perrin, Riemann, & Shultz, 2007; Yu et al., 2005). Female athletes also showed decreased knee flexion during the preparation of the landing compared with male athletes (Chappell et al., 2007). A decreased knee flexion angle increases the anterior tibial shear force generated by the quadriceps, thereby straining the ACL. In addition, female athletes with decreased knee flexion angle during landing demonstrated an increased knee abduction angle and knee abduction moment, which increases the risk of ACL injury (Pollard, Sigward, & Powers, 2010). On the other hand, during cutting maneuvers, no sex difference in knee flexion angle was observed (Ford et al., 2005; Landry et al., 2007; Pollard, Davis, & Hamill, 2004; Sigward et al., 2012)

Proximally, a prospective study identified significantly increased hip flexion and adduction moment in ACL injured subjects, but they were not significant predictors of ACL injury (Hewett et al., 2005). In sex comparisons, no consensus has

been made in hip kinematics and kinetics. A prospective study by Zazulak, Hewett, Reeves, Goldberg, and Cholewicki (2007) reported that lateral trunk displacement after perturbation was greater in ACL-injured athletes than in uninjured athletes. Also, Dempsey et al. (2007) found that lateral trunk lean or rotation over the stance limb might increase the knee abduction load. Thus, the stability of the hip and trunk have a great effect on knee kinematics.

### **2.3.5 Developmental risk factors**

Female adolescents develop increased knee valgus motion after the onset of the pubertal growth spurt. Hewett et al. (2004) investigated, in a cross-sectional study, whether musculoskeletal changes that accompany maturation were associated with reduced control of the knee joint. In the prepubertal and early pubertal stages, females and males were shown to have similar landing mechanics; however, in the late and post pubertal stages, females displayed more knee valgus motion than males (Hewett et al., 2004). This study also found that males, but not females, had increased leg strength after the growth spurt (Hewett et al., 2004). Therefore, biomechanical changes associated with maturation might be due to the changes in muscular development. Ford, Shapiro, et al. (2010) conducted a longitudinal study investigating the changes in biomechanical risk factors during maturation. They found that pubertal females had increased knee abduction angle from the first year to the second year, whereas pubertal males did not show a similar change (Ford, Shapiro, et al., 2010).

The knee flexion angle also was reported to change during maturation. Yu et al. (2005) investigated the age and sex effects on the lower-extremity kinematics of young soccer players in a stop-jump task. They found that female soccer players had reduced knee flexion angles at the initial foot contact and during the landing of the

stop-jump task compared with their male counterparts (Yu et al., 2005). This sex difference were observed after the age of 12 years, and increased until before age 16 years (Yu et al., 2005). The appearance of these high-risk movement patterns might influence the risk of ACL injury.

## Summary

Although many studies have investigated the risk factors of ACL injuries, some were limited by their small sample sizes or retrospective design. Also, some factors were evaluated only with sex comparisons and were not directly tested on ACL-injured subjects. Table 2-1 summarizes the significant risk factors to date on the basis of prospective studies.

Table 2-1 Summary of risk factors of ACL injury

		Significant risk factors
Anatomical factors	BMI	Increased BMI
	ACL structure	Smaller ACL volume
	Intercondylar notch	Smaller intercondylar notch
	Tibial slope	Increased tibial posterior slope
	Joint laxity	Increased general joint laxity Increased anterior knee laxity Increased genu recurvatum Increased tibial internal rotation laxity
Hormonal factors	Menstrual cycle	Preovulatory phase
	Relaxin level	Increased serum relaxin level
Neuromuscular factors	Strength	Decreased 22relative hamstrings strength
Biomechanical factors	Knee abduction	Increased knee abduction angle/moment
	Ground reaction force	Increased ground reaction force
	Trunk motion	Increased lateral trunk displacement

## **2.4 PREVENTION OF ACL INJURY**

### **2.4.1 Effects on biomechanical and neuromuscular functions**

Several studies have evaluated the effect of injury prevention training on lower extremity mechanics. Hewett et al. (1999) investigated the effect of a jump-training program on the landing mechanics in female adolescents. Female athletes had significantly decreased peak landing force and knee abduction and adduction moments after the training period (Hewett et al., 1999). Lephart et al. (2005) evaluated the effect of an 8-week plyometric and resistance training and found that increased hip and knee flexion angles and decreased hip and knee flexion moments were observed in both training groups. Myer, Ford, McLean, and Hewett (2006) investigated the effect of a 6-week neuromuscular training on the lower-extremity biomechanics in female adolescents. Their study showed that the neuromuscular training decreased the knee valgus and varus torques compared with the control group (Myer et al., 2006). Pollard, Sigward, Ota, Langford, and Powers (2006) investigated the influence of in-season injury prevention training, by using the Prevent Injury and Enhance Performance (PEP) program, on hip and knee kinematics during a landing task. After the season, the subjects demonstrated decreased hip internal rotation and increased hip abduction; however, there were no differences in knee valgus or knee flexion angles (Pollard et al., 2006). Lim et al. (2009) evaluated the effects of an 8-week injury prevention training in female high school basketball players. The training group showed increased knee flexion angle and inter-knee distances, and decreased maximum knee extension torques during the rebound-jump task after the training period (Lim et al., 2009).

The effects of injury prevention training on neuromuscular functions were also reported. Hewett et al. (1999) found that a jump-training program increased the

hamstrings-to-quadriceps muscle peak torque ratio on both dominant and non-dominant sides. Lim et al. (2009) also reported that an injury prevention program improved the strength of hip abductors, hip extensors, and knee flexors. Wojtys, Huston, Taylor, and Bastian (1996) investigated the effects of isokinetic, isotonic, and agility training on the muscle reaction time against the tibial anterior translation stimulus. Agility training improved the spinal reflex times of the medial and lateral quadriceps (Wojtys et al., 1996). Also, the cortical response time in the agility training group was improved in the gastrocnemius, medial hamstrings, and lateral quadriceps (Wojtys et al., 1996). Chimera, Swanik, Swanik, and Straub (2004) investigated the effects of plyometric training on muscle activation strategies in the lower-extremity. Plyometric training increased the preparatory hip adductor activity and adductor-to-abductor co-activation during landing (Chimera et al., 2004). Lephart et al. (2005) also evaluated the effect of plyometric or resistance training on muscle activation. Their results showed that both types of training improved the preparatory muscle activity of the gluteus medius during landing (Lephart et al., 2005).

As the methods of injury prevention training are different among studies, the results were not consistent. However, most of the studies have demonstrated that an injury prevention program was effective in improving the biomechanical and neuromuscular functions associated with ACL injury.

#### **2.4.2 Effects on ACL injury rates**

Several studies have investigated the effect of an injury prevention program on the incidence of ACL injury (Heidt Jr et al., 2000; Hewett et al., 1999; Kiani et al., 2010; LaBella et al., 2011; Mandelbaum et al., 2005; Myklebust, Engebretsen, et al., 2003; Olsen et al., 2005; Petersen et al., 2005; Pfeiffer, Shea, Roberts, Grandstrand, &

Bond, 2006; Söderman, Werner, Pietilä, Engström, & Alfredson, 2000; Steffen et al., 2008; Waldén et al., 2012). Table 2-2 presents a summary of these studies. Although some studies had methodological issues, an injury prevention training seems to be effective in reducing the number of ACL injuries.



Table 2-2 Summary of ACL injury prevention intervention studies

Author (Year)	Study Design	Sports	Age	No. of Subjects (Intervention vs Control)	Strength	Flexibility	Balance	Plyometrics	Agility	Skill	No. of ACL Injury (Intervention vs Control)
Hewett et al. (1999)	Prospective non-randomized cohort	Soccer, volleyball, basketball	14-18	366 vs 463	○	○		○			2 vs 5 0.12 vs 0.43/1000AE
Soderman et al. (2000)	Prospective randomized controlled	Soccer	20.4/20.5 (mean)	62 vs 78			○				4 vs 1
Heidt et al. (2000)	Prospective randomized controlled	Soccer	14-18	42 vs 258	○	○		○	○	○	1 vs 8 2.4% vs 3.0%
Myklebust et al. (2003)	Prospective non-randomized crossover	Handball	21-22 (mean)	942 vs 855 (1 <sup>st</sup> year)			○	○	○	○	10 vs 18 0.03 vs 0.09/1000AE
Mandelbaum et al. (2005)	Prospective non-randomized cohort	Soccer	14-18	1885 vs 3818	○	○		○	○		6 vs 67 0.49 vs 0.99/1000AE RR = 0.18
Olsen et al. (2005)	Prospective cluster randomized controlled	Handball	15-17	958 vs 879	○		○			○	3 vs 9 RR = 0.2
Petersen et al. (2005)	Prospective non-randomized cohort	Handball	19.4/19.8 (mean)	134 vs 142			○	○		○	1 vs 5 0.04 vs 0.21/1000AE
Pfeiffer et al. (2006)	Prospective non-randomized cohort	Soccer, volleyball, basketball	14-18	577 vs 862				○			3 vs 3 0.167 vs 0.078/1000AE
Steffen et al. (2008)	Prospective cluster randomized controlled	Soccer	13-17	1073 vs 947	○		○	○			4 vs 5
Kiani et al. (2010)	Prospective cluster non-randomized cohort	Soccer	13-19	777 vs 729	○		○	○			0 vs 5
Lebella et al. (2011)	Prospective cluster randomized controlled	Soccer, basketball	16.2 (mean)	737 vs 755	○		○	○	○		2 vs 6 0.07 vs 0.26/1000AE RR = 0.20
Walden et al. (2012)	Prospective cluster randomized controlled	Soccer	12-17	2479 vs 2085	○		○	○			7 vs 14 RR = 0.36

## **CHAPTER 3**

### **Study 1: ACL Injury Risk in Female Athletes during Maturation**

#### **3.1 INTRODUCTION**

The incidence of ACL injury starts to increase after puberty in female athletes (Granán et al., 2008). It is important to understand why this trend occurs during this period. As physical growth greatly influences movement strategy, this study investigated the changes in biomechanical risk factors during puberty. Identifying when the risk for ACL injury increase would help determine when to initiate an ACL injury prevention training. The purpose of this study is to evaluate whether the biomechanical risk factors of ACL injury increase during puberty in female basketball players.

#### **3.2 METHODS**

##### **Subjects**

Ninety-two female basketball players were recruited from the local elementary school, and junior and senior high schools. Subjects were included if they were members of school basketball teams and practiced more than three times per week. Subjects were excluded from the study if they had a history of ACL injury, a lower extremity injury within 6 weeks that prevented full participation in basketball games, any medical or neurological pathology, or had previously participated in an injury prevention program. The maturational stage was evaluated by using the self-administered rating scale for pubertal development (Carskadon & Acebo, 1993). The development of body structure and muscular function depends more on maturational stages rather than chronological ages; thus, the ACL injury risk was compared among

the different maturational stages. Subjects were categorized into four maturational stages: early pubertal ( $n = 14$ , age  $11.1 \pm 1.2$  years), middle pubertal ( $n = 13$ , age  $13.1 \pm 1.0$  years), late pubertal ( $n = 43$ , age  $13.1 \pm 0.7$  years), and post-pubertal ( $n = 22$ , age  $15.5 \pm 1.1$  years). The early-, middle-, late-, and post-pubertal stages were equivalent to the Tanner stages 2 to 5, respectively (Carskadon & Acebo, 1993). Once it was determined that the subjects met the inclusion and were not excluded by the exclusion criteria, the subjects and their guardians were informed about the nature of the study, and were asked if they would like to participate. All subjects and their guardians were required to provide written consent to participate in the study. This study was approved by the Academic Research Ethical Review Committee of Waseda University.

### **Data collection**

An ACL injury prediction algorithm developed by Myer et al. (2010) was used to evaluate the knee mechanics and ACL injury risk. This algorithm was reported to have high sensitivity and specificity, and was able to identify female athletes who demonstrate a high knee abduction moment, which increases their risk of sustaining an ACL injury (Myer et al., 2010).

The height, weight, and tibia length were measured. Tibia length was measured the distance between the lateral knee joint line and the prominence of the lateral malleolus with the subjects standing with their knees extended. On the basis of the method described by Myer et al. (2010), the quadriceps-to-hamstrings (QH) strength ratio was obtained through surrogate calculations by multiplying the female athlete's body mass by 0.01 and adding the resultant value to 1.10.

Two-dimensional lower extremity kinematics measurements were conducted. Eight bilateral markers were placed on each subject in the following locations: the greater trochanter, lateral knee joint line, patella, and lateral malleolus. Frontal and sagittal plane images were simultaneously captured with three video cameras (30 Hz; CASIO EXILIM, Tokyo, Japan) (Figure 3-1). A basketball goal was used as an overhead target. The subjects performed a drop vertical jump (DVJ), as described previously (Myer et al., 2010). The subjects stood on a box (31 cm high) with their feet positioned 35 cm apart. They were instructed to jump off the box and then immediately perform a maximum vertical jump, raising both arms toward the target. Before testing, the subjects were allowed to perform one to three practice trials to familiarize themselves with the test maneuver. Once they were able to perform the test maneuver, each subject performed three DVJ trials. No feedback was provided between the trials.

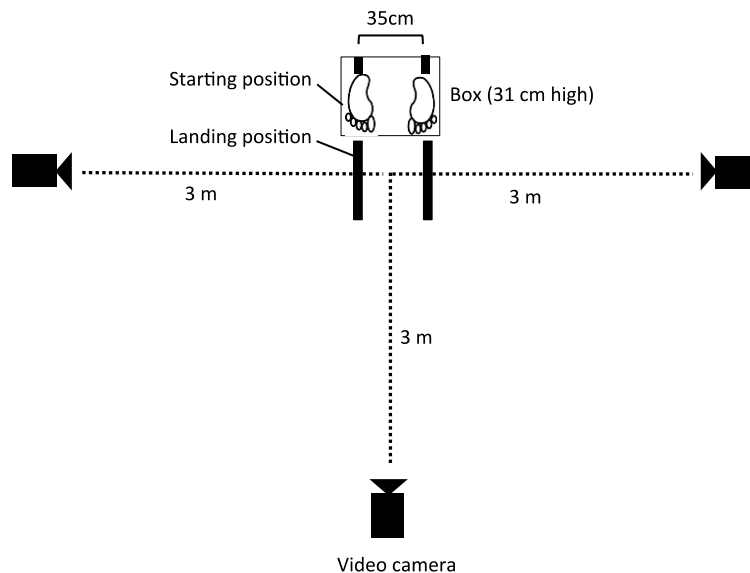


Figure 3-1 Experiment setup

## **Data analysis**

Frontal and sagittal images of the first DVJ landing were analyzed. The video files were first de-interlaced by using VirtualDub software (Avery Lee, GNU general public license). Then, the data were imported into ImageJ software (National Institute of Health, USA) to measure the knee valgus motion and knee flexion range of motion. The knee valgus motion was defined as the displacement between the patellar markers at the frame before initial contact and at the frame with a maximum medial position (Figure 3-2) (Myer et al., 2010). The displacement measurements were calibrated by using a known distance. The knee flexion angle was measured 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 at the frame before initial contact and maximum knee flexion (Figure 3-2) (Myer et al., 2010). With the tibia length, body mass, QH ratio, knee valgus motion, and knee flexion range of motion as variables, the ACL injury prediction algorithm was used to obtain the probability of a high knee abduction moment (pKAM), which was defined as the measure of ACL injury risk in this study (Figure 3-3). Only the left leg was analyzed, as previous studies have found that female athletes were more likely to tear their left ACL more frequently than the right (Brophy, Silvers, Gonzales, & Mandelbaum, 2010; Negrete, Schick, & Cooper, 2007; Ruedl et al., 2012).

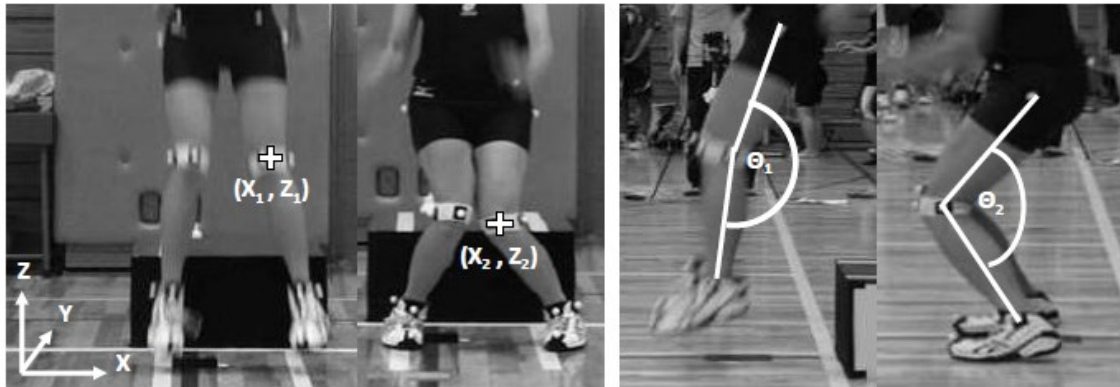


Figure 3-2 Calculations of knee valgus motion and knee flexion range of motion  
 Left: The displacement measure between the two marked knee alignments ( $X_2 - X_1$ ) is representative of the amount of knee valgus motion. Right: The displacement measure between the two knee flexion angles ( $\Theta_1 - \Theta_2$ ) is representative of the amount of knee flexion range of motion.

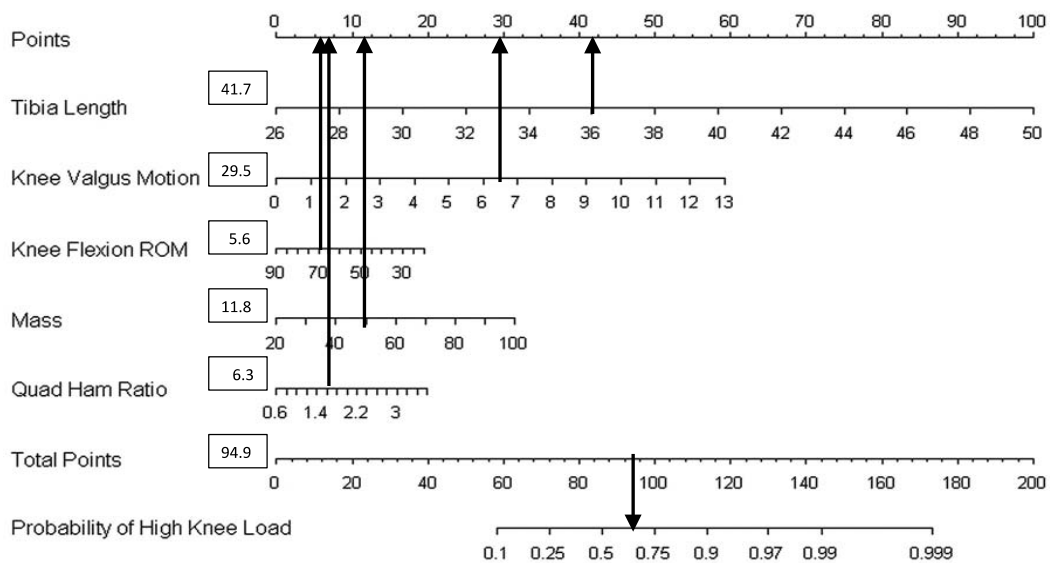


Figure 3-3 Example of use of the ACL injury prediction algorithm  
 (modified from Myer, Ford, Khoury, Succop, and Hewett (2010))

With 36.0 cm in tibia length, 6.5 cm in knee valgus motion, 70.0° in knee flexion range of motion, 50.0 kg in weight, and 1.6 in QH ratio, this athlete would have a 66% chance of demonstrating high knee abduction moment (> 21.74 Nm).

## Statistical analysis

The mean and standard deviation of the knee valgus motion, knee flexion range of motion, and pKAM were calculated for each group. A one-way analysis of variance was used to compare the means among the four groups for each dependent variable. When there were significant differences, a post hoc test was performed with a Bonferroni least significant test. The alpha level was set at 0.05. SPSS ver. 21 (SPSS Inc., Chicago, IL, USA) was used to perform the statistical analysis.

## 3.3 RESULTS

Table 3-1 presents the mean and standard deviation of age, height, tibia length, and weight by group. The height, weight, and tibia length were significantly larger in the middle-, late-, and post-pubertal stages than in the early-pubertal stage ( $p < 0.001$ ). However, there were no significant differences among the middle-, late-, and post-pubertal stages.

The knee valgus motion was significantly different among the groups ( $F(3,88) = 3.57, p = 0.017$ ). The middle- and post-pubertal groups demonstrated significantly larger knee valgus motion than the early pubertal group (early =  $2.0 \pm 4.1$  cm vs. middle =  $5.6 \pm 3.2$  cm,  $p = 0.046$ ; early =  $2.0 \pm 4.1$  cm vs. post =  $5.3 \pm 4.1$  cm,  $p = 0.030$ ) (Figure 3-4a). There were no significant differences in knee valgus motion among the other groups. The knee flexion range of motion was also significantly different among groups ( $F(3,88) = 8.91, p < 0.001$ ). The knee flexion range of motion was significantly smaller in the late- and post-pubertal groups compared with the early-pubertal group (early =  $73.2 \pm 14.3^\circ$  vs. late =  $58.3 \pm 11.8^\circ$ ,  $p = 0.001$ ; early =  $73.2 \pm 14.3^\circ$  vs. post =  $54.1 \pm 12.2^\circ$ ,  $p < 0.001$ ) (Figure 3-4b). Also, the knee flexion range of motion was

significantly smaller in the post-pubertal group than in the middle-pubertal group (middle =  $67.6 \pm 11.6^\circ$  vs. post =  $54.1 \pm 12.2^\circ$ ,  $p = 0.013$ ) (Figure 3-4b). There were also significant differences in the pKAM among groups ( $F(3,88) = 12.03$ ,  $p < 0.001$ ). The pKAM was significantly higher in the middle-, late-, and post-pubertal groups when compared to the early-pubertal group (early =  $5.9 \pm 12.2\%$  vs. middle =  $49.6 \pm 26.5\%$ ,  $p < 0.001$ ; early =  $5.9 \pm 12.2\%$  vs. late =  $46.3 \pm 26.8\%$ ,  $p < 0.001$ ; early =  $5.9 \pm 12.2\%$  vs. post =  $57.2 \pm 30.8\%$ ,  $p < 0.001$ ) (Figure 3-4c). No other significant differences were observed in pKAM among the groups.

Table 3-1 Subject demographics. Data are shown as mean  $\pm$  standard deviation.

Maturational Stage		Age (year)	Height (cm)	Tibia Length (cm)	Weight (kg)
Early pubertal	n = 14	11.1 $\pm$ 1.2	140.4 $\pm$ 6.6	31.5 $\pm$ 2.4	31.8 $\pm$ 3.6
Middle pubertal	n = 13	13.1 $\pm$ 1.0	156.5 $\pm$ 5.9	35.6 $\pm$ 1.9	46.3 $\pm$ 6.9
Late pubertal	n = 43	13.1 $\pm$ 0.7	157.9 $\pm$ 7.0	35.7 $\pm$ 2.1	49.0 $\pm$ 6.6
Postpubertal	n = 22	15.5 $\pm$ 1.1	157.4 $\pm$ 5.6	35.3 $\pm$ 2.1	48.2 $\pm$ 5.6



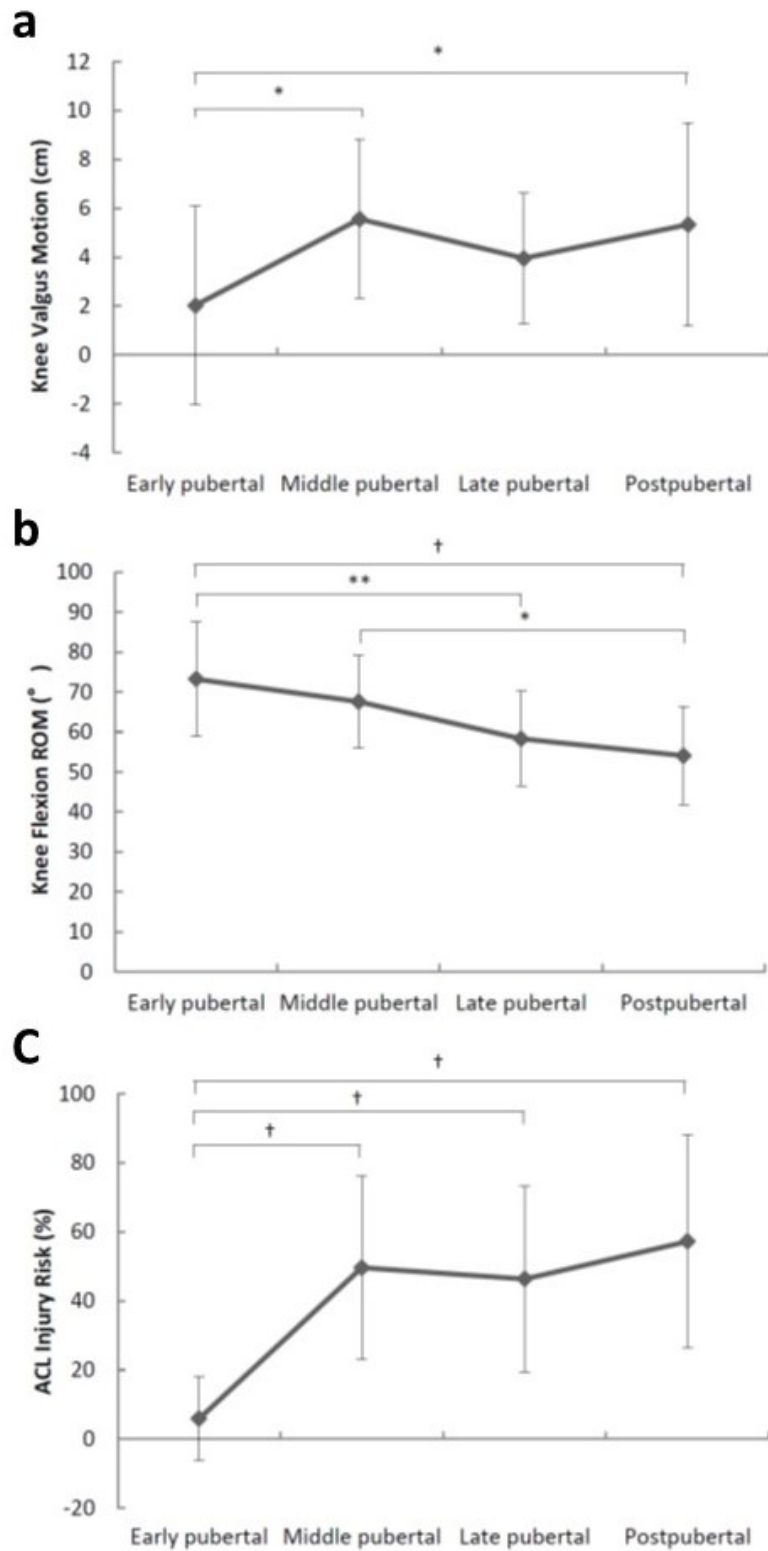


Figure 3-4 Comparison of knee valgus motion (a), knee flexion range of motion (b), and pKAM (c) among maturational stages \*:p<0.05, \*\*:p<0.01, †:p<0.001

### 3.4 DISCUSSION

Knee valgus motion is one of the risk factors of ACL injury. It was identified, through analysis of videos of ACL injury situations, that the main mechanisms of ACL injury involved increased knee valgus motion combined with internal tibial rotation (Koga et al., 2010). Biomechanical studies with cadavers have also identified that the knee abduction moment is an essential factor that contributes to ACL injury (Kiapour et al., 2014; Levine et al., 2013). Furthermore, a large prospective study demonstrated that increased knee valgus angle and moment are significant predictors of future ACL injuries (Hewett et al., 2005). In this study, it was therefore investigated when an increase in this knee valgus motion is manifested during female maturation. The results of this study showed that the knee valgus motion significantly increased after the early-pubertal stage. Previous studies also reported that an increase in knee valgus angle was observed after girls reached puberty (Ford, Myer, & Hewett, 2010; Hewett et al., 2004; Schmitz et al., 2009).

Another risk factor of ACL injury, a decrease in knee flexion, was also observed in this study. The knee flexion range of motion was significantly reduced as girls mature. This result was in agreement with a previous study by Yu et al. (2005) that found that the knee flexion angle during landing was significantly decreased as age increased, especially after 14 years of age in female athletes. A decrease in knee flexion angle increases the anterior tibial shear force generated by the quadriceps, thereby straining the ACL. Reduced knee flexion angle was commonly observed in injury situations (Koga et al., 2010; Krosshaug et al., 2007).

These biomechanical changes seemed to occur between the early- and middle-pubertal stages. As shown in Table 3-1, the height, weight, and tibia length were

significantly increased between the early- and middle-pubertal stages. During this period, the height, weight, and tibia length increased by 16.0 cm, 14.5 kg, 4.2 cm, respectively. The peak height velocity in Japanese girls was  $10.2 \pm 1.9$  cm/year, and the mean age at peak height velocity was  $11.5 \pm 1.4$  years (Satake, Kikuta, & Ozaki, 1993). The peak weight velocity was  $8.0 \pm 1.8$  kg/year, and the mean age at peak weight velocity was  $12.6 \pm 1.4$  years (Satake et al., 1993). The mean ages in the early- and middle-pubertal stages were 11.1 and 13.1 years; therefore, the peak height and weight velocity might have occurred between the early- and middle-pubertal stages. These significant changes in structure might affect their movement patterns. A rapid increase in height and weight was reported to increase the torque around the knee joint (Quatman, Ford, Myer, & Hewett, 2006); therefore, female adolescents might have demonstrated changes in movement patterns. Moreover, it was reported that female adolescents do not have a significant “neuromuscular development” during puberty compared with male adolescents (Hewett et al., 2004). Male adolescents increased their quadriceps and hamstrings peak torque with increasing maturity, whereas female adolescents did not (Hewett et al., 2004). Therefore, female adolescents might have reduced neuromuscular control of the knee joint during puberty. With a combination of structural and neuromuscular changes, girls develop high-risk movement patterns as they mature.

These changes in structure and movement patterns increased the overall risk of ACL injury, as measured by pKAM. The pKAM was significantly increased between the early- and middle-pubertal stages. Okuwaki (2012) reported that the number of ACL injury starts to increase at around the age of 13-14 years, and peaks at around the age of

16-17 years. This period seems to be in agreement with the period of pKAM increase observed in this study.

The difference in knee valgus motion between the early- and middle-pubertal stages was about 4 cm. Also, the difference in the knee flexion range of motion between the early- and late-pubertal stages was about 15°. It was indicated that a decrease in the knee flexion angle by about 15° might result in increased activation of the quadriceps (Malinzak, Colby, Kirkendall, Yu, & Garrett, 2001). Moreover, a decrease in the knee flexion angle was reported to increase the force in the ACL (Mesfar & Shirazi-Adl, 2005). Therefore, the difference of 15° in the knee flexion angle might be clinically meaningful. Although these differences in the knee valgus motion and knee flexion range of motion seem small, the pKAM, which accounts for both biomechanical and structural factors, was increased by 44% between the early- and middle-pubertal stages. This change in pKAM seems clinically important. When evaluating maturing subjects, it might be necessary to take into account both the changes in structure and the biomechanics.

One of the limitations of this study was its cross sectional nature which did not allow determining changes over time. Another limitation was that the knee kinematics were evaluated by using two-dimensional measurements in this study. Although a good correlation between two-dimensional and three-dimensional analysis was reported in previous studies (Myer et al., 2010), two-dimensional measures might not represent the complex movements of the knee. In addition, the use of the pKAM might not be as accurate as the laboratory-based assessment in evaluating the risk of ACL injury. However, this assessment tool is less costly and easier to apply; thus, it is more

clinically relevant. Also, the number of subjects in each group was not balanced; therefore, it might have affected the results of this study.

### **3.5 CONCLUSION**

The knee valgus motion, knee flexion range of motion, and pKAM were significantly changed during pubertal growth in female athletes; the period between the early- and middle-pubertal stages seemed especially critical. Therefore, intervention for ACL injury prevention should be initiated during this period to reduce the risk of ACL injury.

## CHAPTER 4

### Study 2: Factors Affecting Knee Abduction Angle during a Drop Vertical Jump

#### 4.1 INTRODUCTION

ACL injury prevention programs were reported to be effective in reducing the rate of ACL injury. However, recently it has been recognized that the adherence to the program is poor (Keats, Emery, & Finch, 2012). Several studies have failed to demonstrate the effectiveness of a prevention program owing to the lack of adherence among participants (Emery et al., 2007; Soligard et al., 2009; Steffen et al., 2008). One of the reasons for this might be the burden of the lengthy prevention program. ACL injury prevention programs are typically multi-component programs that incorporate strength, plyometric, balance, skill, and flexibility training (Heidt Jr et al., 2000; Hewett et al., 1999; Kiani et al., 2010; LaBella et al., 2011; Mandelbaum et al., 2005; Myklebust, Engebretsen, et al., 2003; Olsen et al., 2005; Petersen et al., 2005; Steffen et al., 2008; Waldén et al., 2012). The volume of a multi-component training program might hinder the participants' adherence. To improve participant adherence to an ACL injury prevention program, a more targeted strategy might be needed.

Another issue with ACL prevention programs is that it is unknown what element of the program is important to successfully prevent ACL injuries. Although ACL injury prevention programs seem effective, it is necessary to understand the underlying mechanisms. Koga et al. (2010) reported, in their video analysis of ACL injury situation using a model-based image-matching technique, that significant knee abduction loading within 40 ms of ground contact was contributing to ACL injury. Furthermore, a cadaveric study demonstrated that the maximum knee abduction and ACL strain

occurred almost simultaneously within 40 ms after simulated landing (Kiapour et al., 2014). Strategies to reduce the load during this critical period are necessary and should be included in the prevention program. This study was aimed at identifying the factors affecting the knee abduction angle at 40 ms after ground contact. Specifically, muscle strength, preparatory muscle activities, and landing kinematics were evaluated as these were considered to influence the kinematics at 40 ms after ground contact. Preparatory muscle activity was examined rather than reflexive muscle activity because the reflex response would not be fast enough to provide necessary constraint to stabilize the joint at 40 ms after ground contact. The control of the knee joint during dynamic activity might be modulated by the preparatory muscle activity rather than the reflexive muscle activity (Dhaer et al., 2005; Zhang & Rymer, 1997). A study by Zebis, Andersen, Bencke, Kjaer, and Aagaard (2009) demonstrated that female athletes with reduced preparatory muscle activity of the semitendinosus and increased preparatory activity of the vastus lateralis were at an increased risk of future ACL injury. Therefore, the preparatory muscle activity might be associated with the risk of ACL injury. The purpose of this study is to investigate how much of the variance in the knee abduction angle at 40 ms after ground contact would be accounted for by strength, preparatory muscle activities and landing kinematics during a DVJ.

## **4.2 METHODS**

### **Subjects**

Eleven female basketball players (age  $12.6 \pm 0.5$  years; height  $153.9 \pm 6.0$  cm; weight  $44.1 \pm 4.6$  kg) were recruited from a local junior high school. Subjects were included if they were members of school basketball teams and practiced six times per

week. Subjects were excluded from the study if they had a history of an ACL injury, a lower-extremity injury within 6 weeks that prevented full participation in basketball games, any medical or neurological pathology, or had previously participated in an injury prevention program. Once it was determined that the subjects met the inclusion and were not excluded by the exclusion criteria, the subjects and their guardians were informed about the nature of the study, and were asked if they would like to participate. All subjects and their guardians were required to provide written consent to participate in the study. This study was approved by the Academic Research Ethical Review Committee of Waseda University.

## **Data collection**

### **Isokinetic strength measurement**

The isokinetic concentric strength of the knee extension/flexion, hip extension/flexion, and hip abduction/adduction were measured with the BIODEX System3 (Biodex Medical System, New York, NY, USA). A 5-min warm-up was performed on a stationary bike at light resistance. Figure 4-1 shows the subjects' positioning for the knee extension/flexion measurement. Knee extension/flexion were tested in a seated position with the knees and hips flexed to 90°. The subjects were stabilized in the test position with straps around the trunk, pelvis, and thigh. The lever arm was secured to the shin 3 cm superior to the lateral malleolus. The axis of the dynamometer was aligned with the lateral femoral condyle. Knee extension/flexion was performed through a range of 0° to 90° of flexion. Figure 4-2 shows the subjects' positioning for the hip extension/flexion measurement. The subjects were positioned with the trunk flexed to approximately 60° and the pelvis was fixed with a strap. The



axis for the dynamometer was aligned with the greater trochanter of the femur on the test leg. The lever arm was attached on the posterior thigh just superior to the knee. Hip extension/flexion was performed through a range of 90° to 60° of hip flexion. Figure 4-3 shows the subjects' positioning for the hip abduction/adduction measurement. The subjects were positioned lying on the side. The pelvis and the non-tested leg were fixed with straps. The lever arm of the dynamometer was attached with a strap, just above the knee. To provide additional stabilization, the subject held onto the plinth with the uppermost arm during testing. The dynamometer axis was aligned medial to the anterior superior iliac spine at the level of the greater trochanter on the test leg. Hip abduction/adduction was performed through a range of 0° to 30° of hip abduction. Hip strength testing was performed in accordance with a previous study; this test was reported to be reliable (Boling, Padua, & Creighton, 2009). The subjects were allowed five submaximal practice repetitions before testing. The researcher monitored the torque curve on the screen to ensure that the subjects were performing correct and smooth contractions. If the subjects were incorrectly performing the movement being tested, they were asked to continue practicing until they could perform the movement correctly. After completing the practice session, five maximal repetitions for knee extension/flexion, hip extension/flexion, and hip abduction/adduction were collected for each strength test. All strength tests were performed at 60°/sec. The examiner monitored the torque curve on the screen, and if subjects were not performing correct and smooth contractions, the testing was repeated. A standardized verbal feedback was provided to encourage maximum effort. A 2-min rest was provided between each test.



Figure 4-1 Knee extension/flexion testing position



Figure 4-2 Hip extension/flexion testing position



Figure 4-3 Hip abduction/adduction testing position

### **Three-dimensional kinematic measurement**

Each subject performed five trials of the DVJ (Figure 4-4). The subjects stood on a box (31 cm high) with their feet positioned 35 cm apart. They were instructed to jump off the box and then immediately perform a maximum vertical jump, raising both arms toward the target. Before testing, the subjects were allowed to perform one to three practice trials to familiarize themselves with the test maneuver. No feedback was provided between the trials.

Three-dimensional kinematic measurements were conducted (Figure 4-4). Thirty-six retro-reflective markers were attached bilaterally on the acromion, lateral epicondyle, radial styloid process, anterior superior iliac spine, posterior superior iliac spine, greater trochanter, thigh, medial and lateral knee joint lines, tibial tubercle, shank, distal shank, medial and lateral malleoli, heel, dorsal surface of midfoot, fifth metatarsal, and toe (between the second and third metatarsals) (Figure 4-5). The data were collected with EvaRT (Motion Analysis Corp., Santa Rosa, CA, USA) by using eight infrared cameras (Motion Analysis) at a sampling rate of 200 Hz. Ground reaction forces were simultaneously collected at 1000 Hz by using two force plates (AMTI, Watertown, MA, USA) to determine initial contact (vertical ground reaction force exceeds 10 N). The subjects landed on each force plate with each foot. Before the testing, a static trial was performed in which the subject was instructed to stand still in the anatomical position.

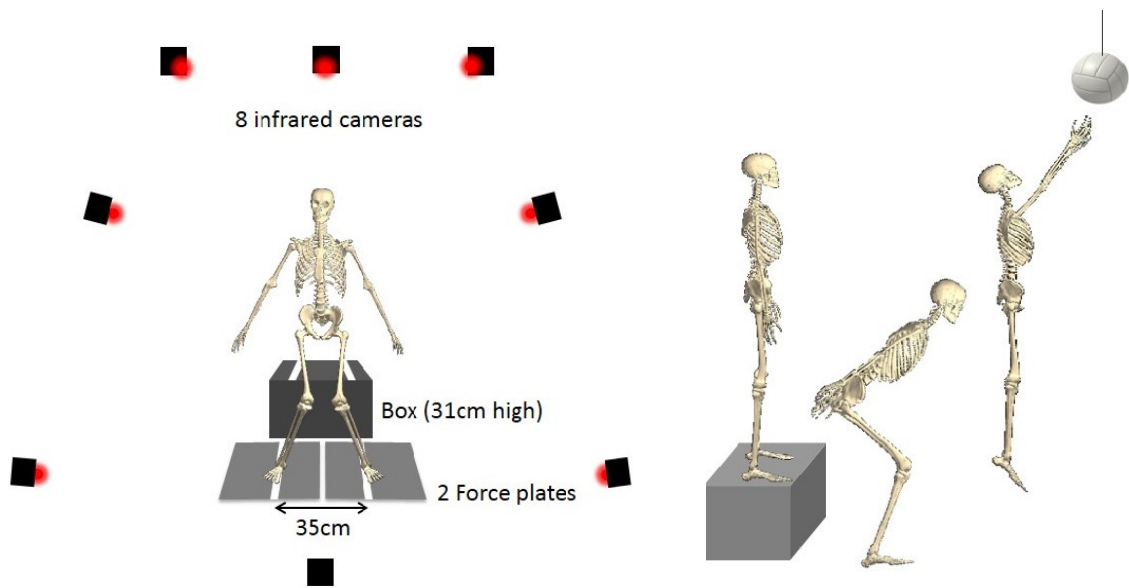


Figure 4-4 Experiment setup and drop vertical jump task

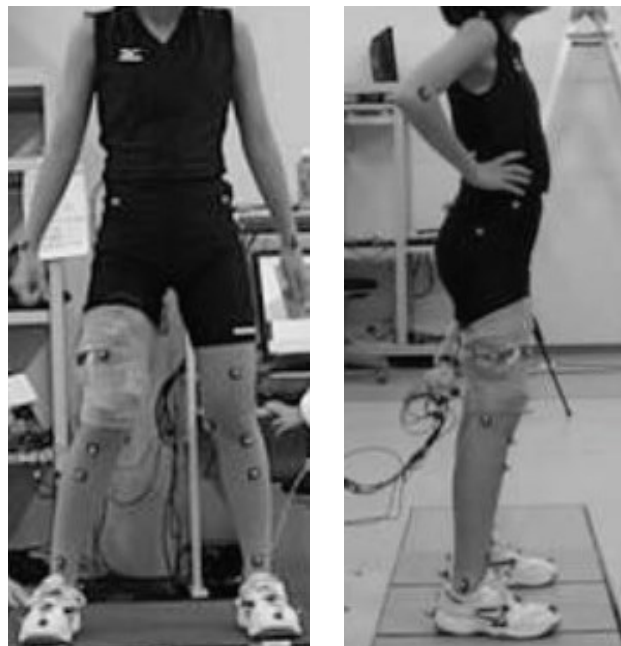


Figure 4-5 Marker placements

## **Electromyography (EMG) measurement**

EMG was measured on the dominant leg (i.e., the foot used to kick a ball for maximal distance) by using ME 6000 (Mega Electronics Ltd., Finland). The EMG data were collected at 1000 Hz and were synchronized with the motion analysis system. The subject's skin was shaved over the EMG sites and cleaned with an alcohol swab to reduce impedance. Ag–AgCl bipolar disposable surface electrodes (Ambu Inc., Denmark) with an inter-electrode distance of approximately 3.5 cm were used. Seven channels of EMG were collected from the biceps femoris (BF), semitendinosus (ST), rectus femoris (RF), vastus lateralis (VL), vastus medialis (VM), gluteus maximus (Gmax), and gluteus medius (Gmed). The placements of the electrodes were determined according to the previous guideline (Delagi, Perotto, Iazzetti, & Morrison, 2011). To minimize motion artifacts, electrodes and wires were secured with self-adhesive tape. Two trials of maximum voluntary isometric contractions (MVICs) were performed for each of muscle for 5 s. To obtain the MVICs for the quadriceps and hamstrings, the subjects assumed a sitting position with the knee flexed at 90°. The MVIC testing for the gluteus maximus was performed with the subjects in a prone position with the knee fully extended. The MVIC testing for the gluteus medius was performed with the subjects in a side-lying position. The hip of the subject's test limb was held in 10° of extension and the knee in full extension.

## **Data analysis**

The highest peak torque (Nm) of the five repetitions for each muscle group was determined. All torque data were normalized to body weight (Nm/kg). The hip, knee, and ankle joint angles were calculated by using Visual3D (C-Motion Inc., Rockville,

MD, USA). The procedures within Visual3D started with the development of a static model for each subject. The pelvis, thigh, shank and foot joint centers were determined on the basis of the reflective markers from the static trial. The subjects were positioned for the static trial in a standardized position in order to align the global coordinate system with each segment coordinate system. The pelvis coordinate system was considered aligned with the global laboratory coordinate system. The thigh, shank, and foot coordinate systems were defined by the proximal joint centers and laboratory-projected lateral marker of the proximal joint. The raw three-dimensional coordinates of the reflective markers were filtered with a fourth-order Butterworth low-pass filter with a cutoff frequency at 12 Hz. The joint angles were determined as the orientation of the distal segment with respect to the proximal segment according to the Cardan rotation sequence with flexion-extension as the first rotation, abduction-adduction as the second rotation, and internal-external rotation as the third rotation. The angular displacement of hip flexion/extension, hip adduction/abduction, knee flexion/extension, knee abduction/adduction, and ankle plantar flexion/dorsiflexion at 40 ms after initial contact, at initial contact, and at 100 ms before initial contact were obtained. The reference of these measurements was obtained during the static trial. EMG data were band-pass filtered at a low-pass cutoff frequency of 350 Hz and a high-pass cutoff frequency of 15 Hz. The root mean square of the EMG signal was obtained by using a 40 ms moving window. The average amplitude of the middle 2 s of two MVIC trials was used to normalize the data (%MVIC). The mean amplitude values at 200 ms before initial contact were calculated as the preparatory muscle activity. Several previous studies have used a similar time frame when evaluating preparatory muscle activity during drop vertical jumps (Carcia & Martin, 2007; Zazulak et al., 2005).

## **Statistical analysis**

A multiple linear regression analysis was used to determine the associations between the dependent and independent variables. The dependent variable was knee abduction angle at 40 ms after initial contact. The independent variables were isokinetic strength (knee extension, knee flexion, hip extension, hip flexion, hip abduction, and hip adduction), EMG preparatory activity (BF, ST, RF, VL, VM, Gmax, and Gmed), and kinematics (hip flexion, hip adduction, knee flexion, knee abduction, and ankle plantar flexion angles at initial contact and at 100 ms before initial contact). A regression model for strength, EMG, and kinematics were obtained. For the EMG and kinematics data, a total of 55 trials (5 trials  $\times$  11 subjects) were included in the analysis. This method was used on the basis of a previous study (Kristianslund, Faul, Bahr, Myklebust, & Krosshaug, 2014). A forced entry multiple regression was performed, in which all the selected predictors were forced into the model simultaneously. This method was chosen to observe the contribution of each independent variable to the model's ability to predict the dependent variable. The alpha level was set at 0.05. SPSS ver. 21 (SPSS Inc.) was used to perform the statistical analysis.

## **4.4 RESULTS**

The mean and standard deviations for the isokinetic strength, EMG, and kinematics are presented in Table 4-1. The isokinetic strength of knee extension, knee flexion, hip extension, hip flexion, hip abduction, and hip adduction were used in a regression analysis to predict the knee abduction angle at 40 ms after initial contact. No associations were found between the knee abduction angle at 40 ms after initial contact and isokinetic strength ( $p > 0.05$ ) (Table 4-2). For the preparatory muscle activity, the

BF, ST, RF, VL, VM, Gmax, and Gmed were used in a regression analysis. The prediction model was statistically significant and accounted for approximately 52.3% of the variance of the knee abduction angle at 40 ms ( $p < 0.001$ ;  $R^2 = 0.523$ ) (Table 4-3). Increased knee abduction angle was associated with increased BF and VL activities, whereas decreased knee abduction angle was associated with increased ST and VM activities (Table 4-3). The prediction models for the kinematics at initial contact and 100 ms before initial contact were statistically significant and accounted for approximately 97.0% and 94.7% of the variance of the knee abduction angle at 40 ms ( $p < 0.001$ ;  $R^2 = 0.970$ ; Table 4-4,  $p < 0.001$ ;  $R^2 = 0.947$ ; Tables 4-4 and 4-5). An increase in the knee abduction angle at 40 ms after initial contact was strongly associated with an increase in the knee abduction angle at initial contact and 100 ms before initial contact (Tables 4-4 and 4-5). Also, an increase in the knee abduction angle at 40 ms after initial contact was associated with a reduced hip flexion angle at initial contact (Table 4-4).



Table 4-1 Means and standard deviations of isokinetic strength, EMG, and kinematics

		Mean	SD
Strength (Nm/kg)	Knee extension	1.9	0.5
	Knee flexion	0.8	0.2
	Hip extension	1.6	0.4
	Hip flexion	0.9	0.2
	Hip abduction	1.0	0.3
	Hip adduction	0.8	0.3
EMG (%MVIC)	BF	18.8	7.3
	ST	30.2	18.8
	RF	36.0	25.6
	VL	29.4	20.0
	VM	37.3	22.9
	Gmax	13.6	10.6
	Gmed	27.5	19.0
Kinematics IC (deg)	Hip flexion	31.4	7.1
	Hip adduction	0.6	3.0
	Knee flexion	29.3	5.7
	Knee abduction	0.4	4.2
	Ankle plantar flexion	20.7	4.6
Kinematics -100ms (deg)	Hip flexion	33.1	7.8
	Hip adduction	1.6	3.9
	Knee flexion	28.7	13.0
	Knee abduction	-0.6	5.1
	Ankle plantar flexion	22.2	6.7

Table 4-2 Regression model for isokinetic strength

Model	b	SE-b	Beta	p value	Pearson r	sr <sup>2</sup>
Constant	-5.139	13.485				
Knee extension	7.310	6.958	0.650	0.353	0.459	0.186
Knee flexion	0.718	18.518	0.023	0.971	0.176	0.000
Hip extension	-5.196	13.423	-0.266	0.718	0.115	0.025
Hip flexion	-3.907	7.685	-0.220	0.638	-0.218	0.044
Hip abduction	-0.232	6.031	-0.022	0.971	0.148	0.000
Hip adduction	-2.971	15.440	-0.112	0.857	-0.093	0.006

The dependent variable was knee valgus angle at 40ms after initial contact.  
 $R^2 = 0.327$ , Adjusted  $R^2 = -0.683$ ,  $p = 0.895$ .  
 $sr^2$  is the squared semi-partial correlation.

Table 4-3 Regression model for preparatory muscle activity

Model	b	SE-b	Beta	p value	Pearson r	sr <sup>2</sup>
Constant	-3.767	1.889				
BF	0.336	0.086	0.473	<0.001*	0.475	0.154
ST	-0.107	0.036	-0.388	0.004*	-0.417	0.091
RF	-0.017	0.030	-0.083	0.585	-0.396	0.003
VL	0.123	0.049	0.477	0.016*	0.026	0.063
VM	-0.118	0.042	-0.527	0.006*	-0.130	0.082
Gmax	-0.038	0.076	-0.078	0.620	-0.163	0.003
Gmed	0.039	0.032	-0.143	0.261	0.068	0.013

The dependent variable was knee valgus angle at 40ms after initial contact.  
 $R^2 = 0.523$ , Adjusted  $R^2 = 0.452$ ,  $p < 0.001$ .  
 $sr^2$  is the squared semi-partial correlation.  
 \*  $p < 0.05$ .

Table 4-4 Regression model for knee abduction angle at initial contact

Model	b	SE-b	Beta	p value	Pearson r	sr <sup>2</sup>
Constant	-0.824	1.555				
Hip flexion	-0.073	0.031	-0.101	0.021 *	-0.127	0.004
Hip adduction	0.062	0.038	0.048	0.106	0.122	0.001
Knee flexion	0.062	0.045	0.068	0.174	0.402	0.001
Knee abduction	1.158	0.036	0.935	<0.001 *	0.978	0.629
Ankle plantarflexion	-0.036	0.047	-0.032	0.452	-0.279	0.000

The dependent variable was knee valgus angle at 40ms after initial contact.  
 $R^2 = 0.970$ , Adjusted  $R^2 = 0.966$ ,  $p < 0.001$ .  
 $sr^2$  is the squared semi-partial correlation.  
 \*  $p < 0.05$ .

Table 4-5 Regression model for knee abduction angle 100ms before initial contact

Model	b	SE-b	Beta	p value	Pearson r	sr <sup>2</sup>
Constant	2.331	1.721				
Hip flexion	-0.043	0.036	-0.066	0.240	-0.195	0.002
Hip adduction	-0.015	0.060	-0.011	0.806	0.138	0.000
Knee flexion	0.019	0.033	0.049	0.566	0.110	0.000
Knee abduction	0.995	0.042	0.975	<0.001 *	0.960	0.590
Ankle plantarflexion	-0.106	0.060	-0.137	0.084	0.039	0.003

The dependent variable was knee valgus angle at 40ms after initial contact.  
 $R^2 = 0.947$ , Adjusted  $R^2 = 0.942$ ,  $p < 0.001$ .  
 $sr^2$  is the squared semi-partial correlation.  
 \*  $p < 0.05$ .

## 4.5 DISCUSSION

Excessive knee valgus motion strains the ACL. Identifying the factors that affect the knee valgus motion would help in developing a strategy for the prevention of ACL injury. This study found that the knee abduction angles before and at initial contact were strong predictors of the knee abduction angle at 40 ms after initial contact. Moreover, the preparatory muscle activities of the BF, ST, VL, and VM might also be associated with the knee abduction angle at 40 ms after initial contact. The isokinetic strength in the hip and knee was not a predictor of the knee abduction angle at 40 ms after initial contact.

This study revealed that the knee abduction angles at initial contact and at 100 ms before initial contact were strong predictors of the knee abduction angle at 40 ms after initial contact. As ACL injuries occur approximately 40 ms after ground contact, the posture before ground contact might be important.

This study also found that an increased knee abduction angle at 40 ms after initial contact was associated with increased lateral muscle activity (BF and VL) and decreased medial muscle activity (ST and VM). This finding was in agreement with previous studies. Rozzi et al. (1999) found that female athletes demonstrated increased lateral hamstring activation during landing. Myer et al. (2005) reported that female athletes had a decreased ratio of medial-to-lateral quadriceps activation during a high-risk maneuver. Palmieri-Smith et al. (2008) also reported that higher knee valgus angles in females were associated with increased preparatory muscle activity in the lateral hamstrings and vastus lateralis, whereas lower knee valgus angles were associated with an increased preparatory activity of the vastus medialis muscle. These findings suggest that the lateral joint compression force might be increased by increased co-contraction

of the lateral hamstrings and quadriceps (Schipplein & Andriacchi, 1991), thereby causing the knee abduction. Unexpectedly, this study did not find that gluteus medius and maximus muscle activities were related to knee valgus angle. Some studies reported that increased knee valgus was related to decreased muscle activity of the gluteus medius (Hollman, Hohl, Kraft, Strauss, & Traver, 2013) and the gluteus maximus (Nguyen, Shultz, Schmitz, Luecht, & Perrin, 2011). Others found that increased knee valgus was associated with increased activity of the gluteus medius and maximus (Homan, Norcross, Goerger, Prentice, & Blackburn, 2013). Furthermore, several studies reported no associations between hip muscle activity and knee valgus motion (Palmieri-Smith et al., 2008). A study by Lloyd, Buchanan, and Besier (2005) suggested that the activation of the quadriceps and hamstrings was the most important in stabilizing varus and valgus moments. Therefore, the muscles directly acting on the knee joint, such as the BF, ST, VL, and VM, might be more important than the proximal hip muscles in controlling knee valgus motion.

Several studies have investigated the relations between strength and knee valgus motion (Claiborne, Armstrong, Gandhi, & Pincivero, 2006; Hollman et al., 2013; Homan et al., 2013; Sigward, Ota, & Powers, 2008; Thijs, Van Tiggelen, Willems, De Clercq, & Witvrouw, 2007; Wild et al., 2013). Some reported that increased knee valgus angle was associated with decreased strength in the hamstrings (Claiborne et al., 2006; Wild et al., 2013) and hip (Claiborne et al., 2006; Hollman et al., 2013). Others showed that the knee valgus angle was not associated with hip strength (Homan et al., 2013; Sigward et al., 2008; Thijs et al., 2007). This study also found that there were no relationships between knee abduction angle and strength around the knee and hip.

On the basis of the findings of this study, an ACL prevention training program

might need to address the proper techniques for landing preparation. Especially, controlling knee valgus before landing seems extremely important in order to reduce excessive loading during the critical time period when ACL injuries most likely occur. Some of the current ACL injury prevention programs incorporate instructions of proper landing techniques (Hewett et al., 1999; Kiani et al., 2010; LaBella et al., 2011; Mandelbaum et al., 2005; Myklebust, Engebretsen, et al., 2003; Olsen et al., 2005; Petersen et al., 2005; Pfeiffer et al., 2006; Steffen et al., 2008; Waldén et al., 2012). The emphasis should be placed on avoiding knee valgus before and at ground contact. This study also found that preparatory muscle activities might contribute to increased knee valgus motion. Specifically, reducing the activity of the BF and VL and increasing the activity of the ST and VM might reduce the risk of ACL injury. Unfortunately, it is unknown what kind of training could selectively increase or decrease the preparatory muscle activity. Future studies need to be done to identify the training methods that could change the amount of preparatory muscle activities.

One of the limitations of this study was that the isokinetic strength and EMG measurements were the only predictors of the muscle forces occurring during DVJs. Thus, the actual muscle forces affecting the knee joint were unknown. Another limitation was that the sample size for the regression analysis of isokinetic strength was small ( $n = 11$ ). With a large effect size  $R^2 = 0.35$ ,  $\alpha = 0.05$ ,  $\beta = 0.80$ , and six independent variables, 46 subjects were needed. Furthermore, the results of this study might be applicable only to female pubertal adolescents. Other age groups should be tested.

#### **4.6 CONCLUSION**

The results of this study indicated that increased knee valgus motion at 40 ms after ground contact is associated with increased knee valgus motion before and at ground contact. Moreover, the preparatory muscle activities of the BF, ST, VL, and VM might affect the knee valgus motion. An ACL injury prevention program might need to be focused on proper landing techniques, including the preparation posture, to reduce the risk of ACL injuries.

## **CHAPTER 5**

### **Study 3: Effect of Skill Training on Lower-extremity Kinematics and Muscle Function in Female Pubertal Athletes**

#### **5.1 INTRODUCTION**

ACL injuries most likely occur at approximately 40 ms after ground contact (Koga et al., 2010). The mechanisms of ACL injury include excessive knee valgus motion during landing (Hewett et al., 2009; Koga et al., 2010; Krosshaug et al., 2007). Study 2 has found that increased knee abduction angle at 40 ms after ground contact is associated with increased knee abduction angles at and before ground contact. Therefore, a training program aiming to control the amount of knee valgus motion at and before ground contact might be beneficial to reduce the risk of ACL injury. The purpose of this study is to investigate whether implementing a training program that focuses on landing preparation could improve the kinematics at 40 ms after ground contact. In addition, this study evaluated the effects of the training program on muscle strength, preparatory muscle activity, and kinematics.

#### **5.2 METHODS**

##### **Subjects**

The subjects of this study were 9 female basketball players from study 2 who were able to complete 12-week training sessions. The inclusion and exclusion criteria were as described in study 2. Once it was determined that the subjects met the inclusion and were not excluded by the exclusion criteria, the subjects and their guardians were informed about the nature of the study, and were asked if they would like to participate.



All subjects and their guardians were required to provide written consent to participate in the study. This study was approved by the Academic Research Ethical Review Committee of Waseda University.

### Data collection

Isokinetic strength, EMG, and kinematics measurements, as described in study 2, were performed. Table 5-1 shows the study protocol. The EMG and kinematics data were collected at three testing sessions: pre-test, post-test 1, and post-test 2. Isokinetic strength testing was performed at pre-test and post-test 2. Between the pre-test and post-test 1, verbal instructions were provided to evaluate the immediate effect of instructions on muscle activity and kinematics. After the instructions, the subjects were allowed three practice trials, and then post-test 1 was performed. After post-test 1, a 12-week training program was implemented. Post-test 2 was performed after the completion of the 12-week training sessions. The measurements of the isokinetic strength, EMG, and kinematics were as described in study 2.

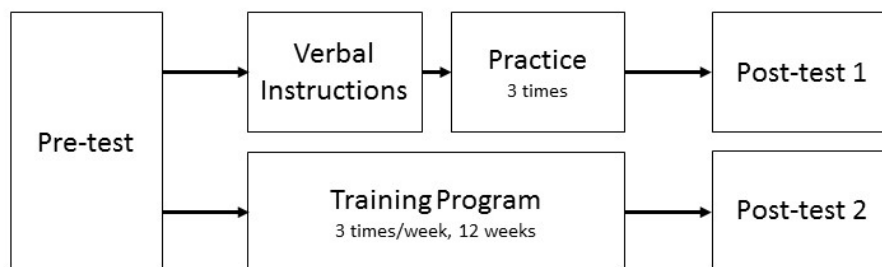


Figure 5-1 Flowchart of the study protocol

## **Interventions**

Standardized verbal instructions and a training program were developed on the basis of the findings of study 2 and previous studies. The focus of the instruction and training program was to ensure proper landing preparation, particularly avoiding knee valgus motion and encouraging knee flexion. Standardized verbal instructions were provided immediately after the pre-test. The subjects were instructed to “not let the knees fall inward” and “bend the knees and hips” before and at landing.

These landing techniques were trained based on the tasks required in basketball, such as jumping, stopping, cutting and pivoting (Table 5-1). The program was 15-min long and was implemented as a warm-up routine. The training group performed the program three times per week for 12 weeks. The initial training session was conducted by a physical therapist. To ensure that the exercises were correctly performed, the therapist followed the subjects every week. The coach was also trained on how to instruct athletes on each skill at the initial training session. The coach led the training between therapist follow-ups. The subjects did not perform any additional training or conditioning that may influence their landing performance.

Table 5-1 Skill training program

Exercise	Instruction	Repetitions
Two-legged squat	Keep the feet, knees, and hips in a straight line. Do not let the knees fall inward. Bend the knees and hips.	2 × 10 reps
One-legged squat	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.	10 reps/side
Squat jumps	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.	10 reps
Tuck jumps	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.	10 reps
180° jumps	Jump into the air and rotate 180°. Land softly, keeping the feet, knees, and hips in a straight line. Bend the knees and hips.	10 reps/side
Contact jumps	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.	10 reps/side
Lateral hops	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.	10 reps/side
Pivoting	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.	20 reps/side
Planting and cutting 1. Two-legged planting 2. One-legged planting	1. 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. 2. Sprint for 4–5 steps and plant on one leg. Pivot on the foot and cut to change direction. Keep the foot, knee, and hip aligned.	10 reps/side

## **Statistical analysis**

The means and standard deviations of strength (Nm/kg) of the knee and hip muscles; preparatory muscle activity (%MVIC); and kinematics of the knee, hip, and ankle were obtained at pre-test, post-test 1, and post-test 2. The Shapiro-Wilk test was performed to test for normality. When a normal distribution was observed, a paired t-test was used. When a nonnormal distribution was present, a Wilcoxon signed-rank test was used. The means of the peak torques between pre-test and post-test 2 were compared. The means of the muscle activity and kinematics were compared between pre-test and post-test 1, as well as between pre-test and post-test 2. The alpha level was set at 0.05. SPSS ver. 21 (SPSS Inc.) was used for the statistical analysis.

## **5.3 RESULTS**

Table 5-2 presents the means and standard deviations of height and weight in the pre-test and post-test 2. Height and weight were significantly increased after the 12-week training period (height:  $p = 0.01$ , weight:  $p = 0.01$ ). For the comparison between pre-test and post-test 1, the knee flexion angle at 40 ms after initial contact was significantly increased at post-test 1 ( $p = 0.01$ , Table 5-3). The preparatory muscle activity of the VM was significantly decreased at post-test 1 ( $p = 0.04$ , Table 5-4). For the comparison between pre-test and post-test 2, knee abduction angles at 40 ms after initial contact were significantly decreased at post-test 2 ( $p = 0.04$ , Table 5-5). The preparatory muscle activities of the RF, VM, and Gmax were significantly decreased at post-test 2 (RF:  $p = 0.04$ , VM:  $p = 0.01$ , Gmax:  $p = 0.02$ , Table 5-6). As the preparatory muscle activity of the quadriceps seemed greatly reduced relative to the activity of the hamstrings, the quadriceps-to-hamstrings (QH) ratio was evaluated. The QH ratio was

computed as the average of the quadriceps (VM, RF, and VL) EMG activity divided by the average of the hamstring (ST and BF) EMG activity. The QH ratio was reduced after the training period; however, the differences were not statistically significant (Table 5-6). The preparatory muscle activities of all the other muscles were also decreased after the 12-week training period; however, they were not statistically significant (Table 5-6). The isokinetic strength of knee flexion was significantly increased after the training period ( $p = 0.04$ , Table 5-7). The changes of the strength, muscle activity, and kinematics in three testing sessions are shown in Figures 5-1 to 5-3.

Table 5-2 Subject demographics

	Pre-test		Post-test 2		p
	Mean	SD	Mean	SD	
Height (cm)	152.9	6.1	153.7	5.7	0.01 *
Weight (Kg) <sup>a</sup>	44.2	5.0	45.7	5.5	0.01 *

<sup>a</sup> Wilcoxon signed-rank test was used.

\*  $p < 0.05$ .

Table 5-3 Comparison of kinematics between pre-test and post-test 1

Kinematics (deg)		Pre-test		Post-test 1		p
		Mean	SD	Mean	SD	
Hip flexion	-100ms <sup>a</sup>	34.2	7.7	32.5	7.7	0.21
	IC	31.9	7.5	32.6	7.6	0.33
	40ms	36.8	8.1	38.4	7.8	0.10
Hip adduction	-100ms	1.9	3.8	-0.6	4.0	0.13
	IC	0.7	4.2	-1.4	3.4	0.17
	40ms <sup>a</sup>	0.7	4.7	-0.3	4.1	0.37
Knee flexion	-100ms	30.8	13.4	29.2	11.4	0.42
	IC <sup>a</sup>	29.7	5.2	31.6	7.0	0.26
	40ms	50.2	5.0	53.2	5.6	0.01 *
Knee abduction	-100ms	-0.9	5.7	-0.8	5.0	0.84
	IC <sup>a</sup>	0.1	4.7	-0.1	4.8	0.44
	40ms	-1.9	5.8	-2.4	6.1	0.37
Ankle plantar flexion	-100ms <sup>a</sup>	21.4	6.8	22.1	5.7	0.72
	IC	21.0	4.0	20.0	4.6	0.31
	40ms	-11.3	4.1	-11.1	5.2	0.88

<sup>a</sup> Wilcoxon signed-rank test was used.

\*  $p < 0.05$ .

Table 5-4 Comparison of preparatory muscle activity between pre-test and post-test 1

EMG (%MVIC)	Pre-test		Post-test 1		p
	Mean	SD	Mean	SD	
BF	19.0	7.1	20.0	6.5	0.66
ST <sup>a</sup>	31.0	18.3	27.4	18.1	0.17
RF <sup>a</sup>	38.0	25.2	32.1	19.4	0.14
VL	29.7	19.5	22.5	12.4	0.06
VM	37.6	22.8	27.3	12.3	0.04 *
Gmax	13.8	9.2	12.0	6.2	0.50
Gmed	30.5	15.8	32.1	17.1	0.51
Q/H <sup>a</sup>	1.4	0.5	1.2	0.3	0.31

<sup>a</sup> Wilcoxon signed-rank test was used.

\*  $p < 0.05$ .

Table 5-5 Comparison of kinematics between pre-test and post-test 2

Kinematics (deg)		Pre-test		Post-test 2		p
		Mean	SD	Mean	SD	
Hip flexion	-100ms <sup>a</sup>	34.2	7.7	35.1	6.9	0.37
	IC	31.9	7.5	33.1	4.9	0.45
	40ms	36.8	8.1	38.2	4.6	0.47
Hip adduction	-100ms	1.9	3.8	0.0	4.7	0.16
	IC	0.7	4.2	-0.7	4.2	0.24
	40ms	0.7	4.7	-0.8	4.5	0.22
Knee flexion	-100ms	30.8	13.4	33.6	13.5	0.42
	IC <sup>a</sup>	29.7	5.2	30.6	8.3	0.59
	40ms	50.2	5.0	50.8	7.2	0.78
Knee abduction	-100ms	-0.9	5.7	-2.0	3.5	0.21
	IC <sup>a</sup>	0.1	4.7	-1.4	3.5	0.05
	40ms	-1.9	5.8	-4.5	3.8	0.04 *
Ankle plantar flexion	-100ms	21.4	6.8	18.8	5.9	0.16
	IC	21.0	4.0	19.5	4.0	0.34
	40ms	-11.3	4.1	-12.0	4.5	0.48

<sup>a</sup> Wilcoxon signed-rank test was used.

\*  $p < 0.05$ .

Table 5-6 Comparison of preparatory muscle activity between pre-test and post-test 2

EMG (%MVIC)	Pre-test		Post-test 2		p
	Mean	SD	Mean	SD	
BF	19.0	7.1	16.9	7.0	0.36
ST <sup>a</sup>	31.0	18.3	23.9	22.4	0.37
RF	38.0	25.2	21.5	7.7	0.04 *
VL	29.7	19.5	17.7	7.7	0.06
VM	37.6	22.8	23.0	13.1	0.01 *
Gmax	13.8	9.2	5.4	1.8	0.02 *
Gmed	30.5	15.8	24.5	10.8	0.22
Q/H <sup>a</sup>	1.4	0.5	1.1	0.4	0.14

<sup>a</sup> Wilcoxon signed-rank test was used.

\*  $p < 0.05$ .

Table 5-7 Comparison of strength between pre-test and post-test 2

Strength (Nm/kg)	Pre-test		Post-test 2		p
	Mean	SD	Mean	SD	
Knee extension	1.89	0.51	1.92	0.18	0.84
Knee flexion	0.83	0.18	0.94	0.10	0.04 *
Hip extension	1.00	0.30	1.20	0.30	0.13
Hip flexion	0.75	0.29	0.82	0.20	0.41
Hip abduction	1.58	0.37	1.85	0.51	0.26
Hip adduction	0.90	0.20	0.90	0.10	0.37

\* p < 0.05.



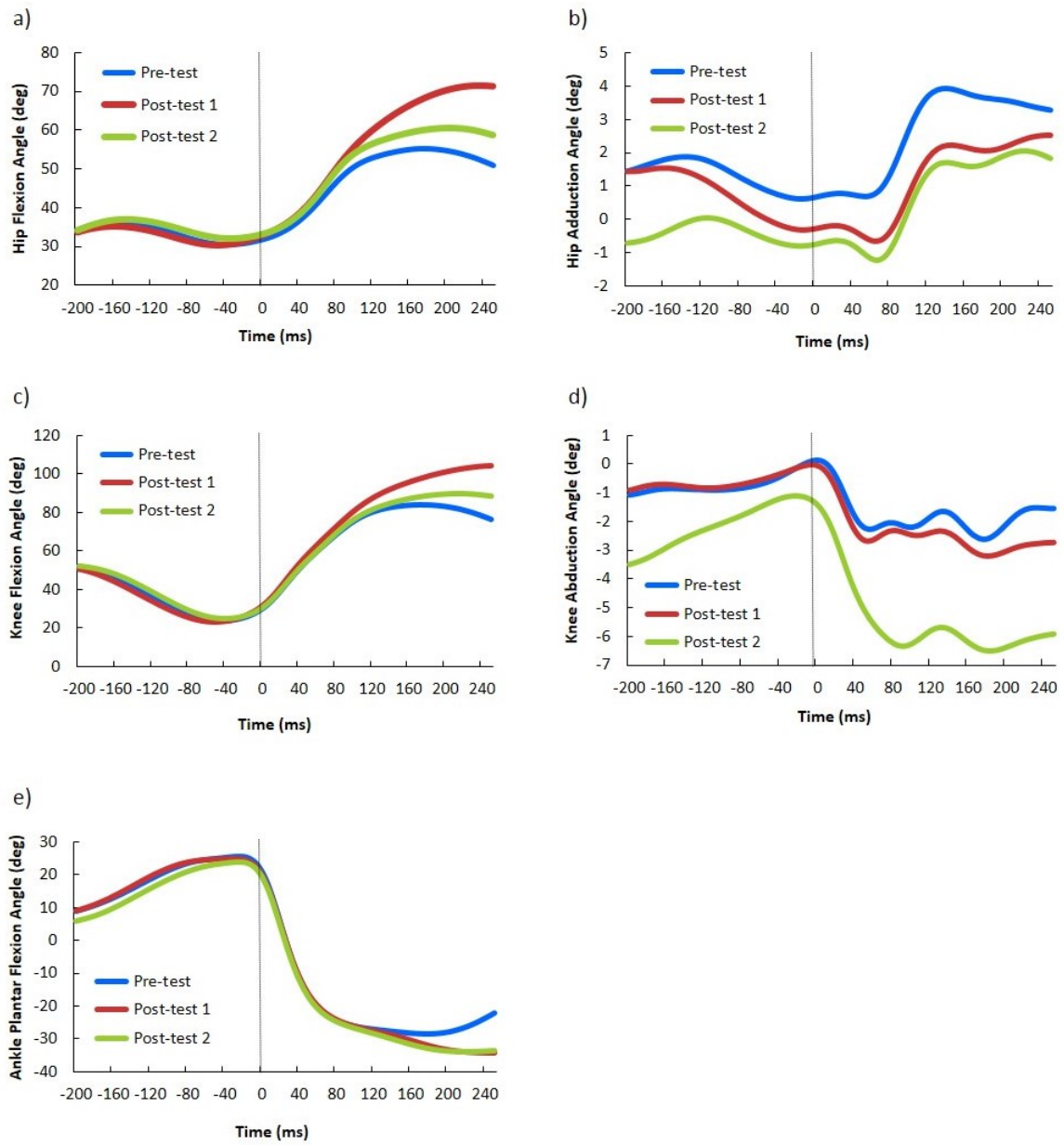


Figure 5-2 Kinematics in three testing sessions

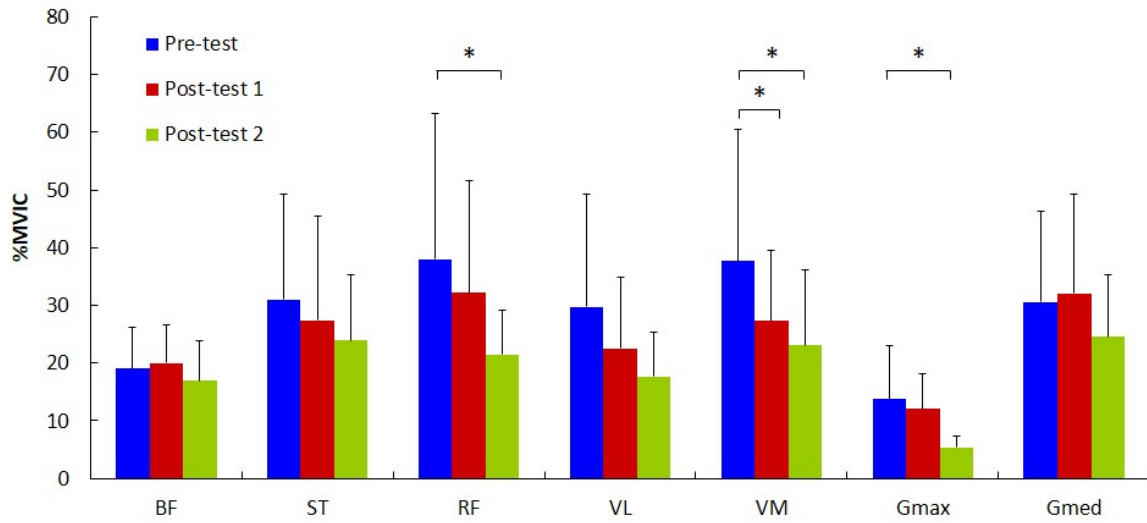


Figure 5-3 Preparatory muscle activities in three testing sessions  
\*p < 0.05

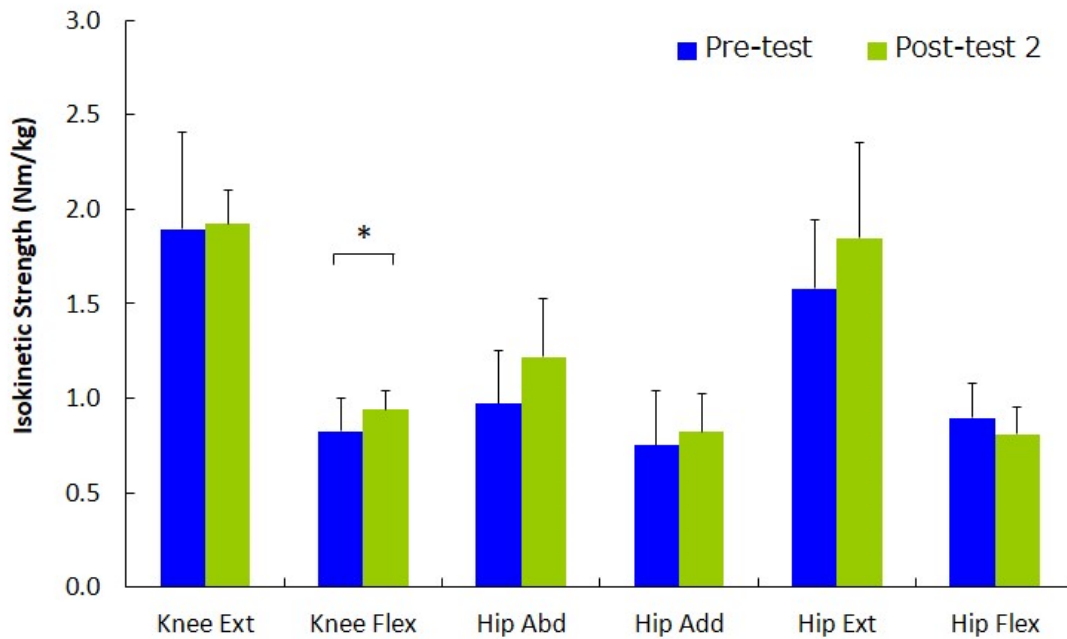


Figure 5-4 Strength in pre-test and post-test 2  
\*p < 0.05

## 5.4 DISCUSSION

Many previous studies have examined knee kinematics at initial contact or at maximum during landing. However, ACL injuries most likely occur at approximately 40 ms after initial ground contact, and it is necessary to avoid high-risk movements during this critical time period. This study, therefore, evaluated the effects of verbal instructions and a 12-week training program on lower-extremity kinematics at 40 ms after the initial ground contact.

The verbal instructions provided an immediate effect on the knee flexion angle at 40 ms after initial contact. The knee flexion angle 40 ms after initial contact was significantly increased after the verbal instructions. Decreased knee flexion angle during landing increases the anterior translation of the tibia, thereby increasing the risk of ACL injury. A simple verbal instruction might improve the knee mechanics in the sagittal plane and possibly reduce the risk of ACL injury.

A 12-week training decreased the knee abduction angle at initial contact and 40 ms after initial contact. Several studies have demonstrated that an ACL injury prevention program decreased the knee valgus motion at initial contact and at maximum (Hewett et al., 1999; Lim et al., 2009; Myer et al., 2006). Similarly, this study found that a 12-week training program improved the knee abduction angle at 40 ms after initial contact. In the sagittal plane, this study did not find any changes at initial contact or at 40 ms after initial contact. However, the maximum knee and hip flexion angles were significantly increased after the training period (Figure 5-1). This was in agreement with previous studies (Lephart et al., 2005; Lim et al., 2009).

The preparatory muscle activities generally decreased after the 12-week training period, in contrast to our hypothesis. Especially, the activities of the RF, VM, and Gmax

were significantly decreased. Decreased muscle activities might imply an improved proficiency in the performance of the landing task. In addition, the QH ratio was decreased after the training period, although it was not statistically significant. The training program might have improved the activity of the hamstrings in relation to the quadriceps, which is considered to be protective against ACL injury.

The isokinetic strength of knee flexion was significantly increased after the 12-week training period. In addition to the improvement in the activation of the hamstring muscles, the force production ability of the hamstrings was also improved. This suggests that the training program was effective in increasing the use of the hamstring muscles. Although not statistically significant, all the other muscle strength seemed to be increased. Twelve weeks might have been too short to observe a significant improvement in strength in some of the muscles. The significant increase in body weight during this period might have underestimated the changes in the muscle strength, as the muscle strength was normalized with the body weight in this study. Overall, this study demonstrated a decreased preparatory muscle activity and increased muscle strength after the 12-week training period. These results suggest that the force production per muscle activity might be improved after the training.

The difference in the knee abduction angle at 40 ms after initial contact between the pre-test and post-test 2 was  $2.6^\circ$ , and its effect size was Cohen's  $d = 0.53$ , suggesting a medium effect size. Therefore, it might not be able to determine how much the training program could reduce the risk of ACL injury on the basis of the findings of this study.

One of the limitations of this study is the small sample size. A post-hoc analysis revealed that with an effect size = 0.5,  $\alpha = 0.05$ ,  $\beta = 0.80$ , 33 subjects were needed.

Another limitation is that the results of this study might be applicable only to female pubertal adolescents. Other age groups should be tested.

## **5.5 CONCLUSION**

This study suggested that a simple verbal instruction changed the landing mechanics in the subjects; especially, it increased the knee flexion angle. Furthermore, a 12-week training program that focuses on proper landing skills might be effective in reducing the knee abduction angle at 40 ms after initial contact. The training program also changed the preparatory muscle activities of the rectus femoris, vastus medialis, and gluteus maximus and the isokinetic strength of the knee flexors. The 12-week training program might have improved not only the landing skills but also the neuromuscular system.

## CHAPTER 6

### Study 4: Effect of Skill Training on ACL Injury Risk in Female Pubertal Athletes

#### 6.1 INTRODUCTION

Although injury prevention training seems to be effective in reducing the number of ACL injuries in adolescents, there is a need to understand the underlying mechanisms of this phenomenon. There is a lack of knowledge regarding the relationship between the changes in knee mechanics associated with pubertal growth and injury prevention training. Several studies have evaluated the effect of injury prevention training on dynamic knee alignment in adolescents (Lephart et al., 2005; Lim et al., 2009; Myer et al., 2006; Pollard et al., 2006). However, it is still unknown whether injury prevention training is effective in limiting the movement pattern changes associated with pubertal growth in female adolescents.

To the best of our knowledge, no studies have investigated the effect of injury prevention training on knee mechanics, specifically during puberty. Thus, the purpose of this study was to evaluate the effect of injury prevention training on dynamic knee alignment in female basketball players specifically when the knee mechanics were changing during puberty. We hypothesized that implementation of injury prevention training in female basketball players during puberty could limit the loss of dynamic knee control.

## **6.2 METHODS**

### **Subjects**

Sixty-five female basketball players from five local junior high school basketball teams were recruited to participate in this study. All teams trained 6 days/week and had similar skill level. Subjects participated in the study during the first 6 months of a 12-month season. Two teams (n = 36; age, 13.1 ± 0.8 years) that were able to participate in the injury prevention training were assigned to the training group. The other three teams (n = 29; age, 13.1 ± 0.8 years) were assigned to the control group. A total of 60 subjects (training group: n=32; control group: n=28) completed the study and were analyzed. Four subjects from the training group and one subject from the control group were unable to participate in the post-training testing session for personal reasons. Subjects were excluded from the study if they had a history of ACL injury, a lower extremity injury within 6 weeks that prevented full participation in basketball, any medical or neurological pathology, or previously participated in an injury prevention program. Maturation stage was evaluated using the self-administered rating scale for pubertal development (Carskadon & Acebo, 1993). Subjects were categorized into five maturational stages: pre-pubertal, early pubertal, middle pubertal, late pubertal, and post-pubertal. To evaluate pubertal subjects, females who were categorized at a pre- or post-pubertal stage were excluded from the study. There were 2 pre-pubertal and 4 post-pubertal subjects.

### **Training program**

The ACL injury prevention training program shown in study 3 was used (Table 5-1). The focus of this program was to ensure proper landing preparation, particularly

avoiding knee valgus motion and encouraging knee flexion. These landing techniques were trained with the skills required in basketball, such as jumping, stopping, cutting and pivoting. The program was 15-min long and was implemented as a warm-up routine. The training group performed the program three times per week for 6 months. A 6-month training period was selected to observe the changes associated with growth. The initial training session was conducted by a physical therapist. To ensure that the exercises were correctly performed, the therapist followed the subjects every 2 weeks. The coach was also trained on how to instruct athletes on each skill at the initial training session. The coach led the training during the 2 weeks between therapist follow-ups. The control group performed their regular training routine for 6 months. Both groups did not perform any additional training or conditioning that may influence the landing performance.

### **Data Collection**

The pre-training data were collected prior to the initial training session and post-training data were obtained after the 6-month training period in all subjects. An ACL injury prediction algorithm was used to evaluate knee mechanics and ACL injury risk (Myer et al., 2010). The methods and procedure of the data collection were as described in study 1.

### **Statistical Analysis**

The mean and standard deviation of the knee valgus motion, knee flexion range of motion, and pKAM were calculated for each group. A  $2 \times 2$  (group  $\times$  time) analysis of variance with a mixed model design was conducted for each dependent variable. When



there were significant interaction effects, a post hoc test was performed with a Bonferroni least significant test. The alpha level was set at 0.05. SPSS ver. 21 (SPSS Inc.) was used to perform the statistical analysis.

### 6.3 RESULTS

No statistically significant differences were found between the training and control groups for age, height, or mass at the two testing sessions (Table 6-1). The data for the knee valgus motion and knee flexion range of motion are summarized in Table 6-2. A significant group  $\times$  time interaction was found for the knee valgus motion ( $p = 0.01$ ), knee flexion range of motion ( $p = 0.01$ ), and pKAM ( $p=0.02$ ). The post hoc analysis revealed that the knee valgus motion was significantly increased in the control group ( $p < 0.001$ ), whereas it did not change in the training group ( $p = 0.64$ ) (Table 6-2). Similarly, the knee flexion range of motion was significantly decreased in the control group ( $p < 0.001$ ); however, it did not change in the training group ( $p = 0.55$ ) (Table 6-2). The pKAM was significantly increased in the control group ( $p < 0.001$ ), but not in the training group ( $p = 0.06$ ) (Table 6-2).

Table 6-1 Subject demographics. Data are shown as mean  $\pm$  standard deviation.

	Pretest		Posttest	
	Training	Control	Training	Control
Age (years)	13.1 $\pm$ 0.8		13.1 $\pm$ 0.8	
Height (cm)	156.1 $\pm$ 6.8	157.0 $\pm$ 7.9	157.7 $\pm$ 6.7	158.0 $\pm$ 7.7
Weight (kg)	47.0 $\pm$ 7.0	46.7 $\pm$ 8.7	50.5 $\pm$ 6.5	49.4 $\pm$ 9.1

Table 6-2 Changes in the knee valgus motion, knee flexion range of motion, and pKAM. Data are shown as mean  $\pm$  standard deviation.

		Pretest	Posttest	Difference	P Value	95% CI	
						Lower	Upper
Knee valgus motion (cm)	Training	3.63 $\pm$ 2.38	3.85 $\pm$ 2.36	0.22	0.64	-0.73	1.16
	Control	3.94 $\pm$ 3.00	5.68 $\pm$ 2.87	1.74	<0.001	1.06	2.43
Knee flexion ROM (°)	Training	61.67 $\pm$ 11.37	62.63 $\pm$ 11.98	0.96	0.55	-2.3	4.22
	Control	59.52 $\pm$ 12.74	53.15 $\pm$ 12.17	-6.37	<0.001	-9.22	-3.52
pKAM (%)	Training	38.91 $\pm$ 23.19	46.28 $\pm$ 23.10	7.36	0.06	-0.21	14.96
	Control	41.36 $\pm$ 26.83	61.43 $\pm$ 26.51	20.07	<0.001	12.81	27.33

## 6.4 DISCUSSION

The incidence of ACL injury increases after puberty in female athletes (Renstrom et al., 2008). Recent research suggests that the biomechanical changes associated with pubertal growth may contribute to the increased occurrence of ACL injury after puberty (Ford, Shapiro, et al., 2010; Hewett et al., 2004; Schmitz et al., 2009). Injury prevention strategies that minimize these biomechanical changes during puberty are necessary.

The results of this study support the hypothesis that the implementation of an injury prevention training is effective in limiting the loss of dynamic knee control in female basketball players during puberty. Although injury prevention training was able to limit the changes in knee mechanics, no improvement was observed. Previous studies evaluating high school female athletes found that injury prevention training improved knee mechanics in both the frontal and sagittal planes (Lim et al., 2009; Myer et al., 2006; Pollard et al., 2006). Although the methods of evaluating knee mechanics were different, it seems that the injury prevention training was not as effective in pubertal girls compared with post-pubertal girls. This may be due to the changes in landing

mechanics that pubertal girls naturally develop during this period. A rapid increase in height and weight might increase torque at the knee joint (Quatman et al., 2006). In addition, the width of the pelvis increases in girls during puberty. An increase in pelvic width might bring the hips to a more adducted position and therefore affecting dynamic knee alignment (Pantano, White, & Gilchrist, 2005). Moreover, it has been reported that female adolescents do not have a significant neuromuscular development during puberty compared with male adolescents (Hewett et al., 2004). With a combination of structural and neuromuscular changes, pubertal girls demonstrate changes in landing mechanics. Although a significant improvement might not be possible, limiting the changes in knee mechanics during this period might be necessary to prevent ACL injury.

Implementation of injury prevention training could potentially enhance the neuromuscular system in female adolescents. The effect sizes of the difference between the two groups in the knee valgus motion, knee flexion range of motion, and pKAM were Cohen's  $d = 0.70, 0.79,$  and  $0.61,$  respectively. With these medium to large effect sizes, we believe that the posttest differences between the two groups were clinically important.

The pKAM in the training group was increased following the training period, although it was not statistically significant. This may be due to the physical growth factors, as the algorithm includes the body weight and tibia length. During the 6-month period, the height and weight of the training group subjects increased by 1.6 cm and 3.5 kg, respectively. Similarly, the control group subjects gained 1.1 cm in height and 2.7 kg in weight. These physical growth factors might have played a role when evaluating ACL injury risk in female adolescents.

One of the limitations of this study was that the knee kinematics was evaluated using two-dimensional measurements. Although a good correlation between two-dimensional and three-dimensional analysis was reported in the previous studies (Myer et al., 2010), two-dimensional measures might not represent the complex movements of the knee. In addition, the use of the pKAM might not be as accurate as the laboratory-based assessment to evaluate the risk of ACL injury. However, the use of this assessment tool is less costly and easier to apply; thus, it is more clinically relevant. Another limitation was that the subjects in this study were junior high school students with an age between 12 and 14 years. This age group might not be representative of the entire stage of puberty, as many of the subjects were categorized in the middle or late pubertal stages. In addition, in this study, randomization during group allocation and blinding of the examiner were not achieved. This may have produced unintentional biases. Also, the generalizability of the results of the present study was limited due to the use of a convenience sample. Other factors such as ethnicity or position played were not considered. Since these factors could affect landing mechanics, they may have influenced the results of this study.

Future studies should focus on evaluation of factors that contribute to the changes in landing mechanics in girls during puberty such as physical composition, strength, and neuromuscular control. Further understanding of these factors would help identify what should be addressed in the injury prevention programs for maturing female athletes. In addition, a long-term follow-up and investigation of ACL injury rate after an injury prevention training for pubertal females are necessary.

## **6.5 CONCLUSION**

This study revealed that implementation of injury prevention training was effective in limiting the increase in the knee valgus motion and decrease in the knee flexion range of motion in female basketball players during puberty. Although a significant improvement in the landing technique was not observed, lowering the risk of ACL injury might be possible in this population.

## CHAPTER 7: GENERAL DISCUSSION AND CONCLUSION

### 7.1. GENERAL DISCUSSION

ACL injury is one of the biggest problems in sport orthopedics. Although many studies have demonstrated successful prevention programs, the incidence of ACL injury remains high. A recent report from the NCAA showed that the rate of ACL injury has not changed during an 8-year period (2004-2005 through the 2011-2012 season) (Agel & Klossner, 2014). In addition, more and more studies have revealed that the long-term consequence of ACL injury might be an osteoarthritis of the knee joint, regardless of the management (Barenius et al., 2014; Claes, Hermie, Verdonk, Bellemans, & Verdonk, 2013). More effective strategies are required to reduce the number of ACL injuries. This dissertation, therefore, presented strategies to improve the efficacy of ACL injury prevention.

The first study examined when to initiate an intervention to effectively prevent ACL injury. The rate of ACL injury increases just after puberty in females (Renstrom et al., 2008). To obtain the best preventative effect, an ACL injury prevention program might need to be initiated during this period. One of the risk factors of ACL injuries is poor lower-extremity kinematics. Recent studies reported that an increased knee valgus motion and a reduced knee flexion angle seem to be important factors associated with the occurrence of ACL injury (Hewett et al., 2005; Kiapour et al., 2014; Koga et al., 2010; Krosshaug et al., 2007; Levine et al., 2013). Therefore, this study evaluated these biomechanical risk factors in female adolescents at different maturational stages to identify when exactly the risk of ACL injury increases and when to initiate an ACL injury prevention program. In this study, significant changes in movements were

observed in female athletes between the early- and middle-pubertal stages. The female athletes in the middle-pubertal stage demonstrated significantly increased knee valgus motion and decreased knee flexion during landing. The height and weight were also significantly increased during this period. A rapid increase in height and weight might increase the torque at the knee joint (Quatman et al., 2006). These biomechanical and structural changes would increase the risk of ACL injury. This study suggested that an ACL injury prevention program might need to be initiated during this period to prevent the changes in movement patterns.

Study 2 investigated what kind of training is needed to effectively reduce the risk of ACL injury. Current ACL injury prevention programs typically incorporate strength, plyometric, balance, skill, and flexibility training. It is unknown what elements of an ACL injury prevention program are important. The training program should be a strategy to effectively avoid injury situations. As recent studies have started to reveal the mechanisms of ACL injury, the training programs might need to be re-evaluated. An excessive knee abduction within 40 ms after ground contact seems to cause ACL injury (Koga et al., 2010). To date, many studies have examined the maximum knee abduction angle during landing; however, the ACL is already torn when the knee abduction angle reaches the maximum. Therefore, this study examined what factors influence an increase in knee abduction angle at 40 ms after ground contact during landing. A training program should be developed to modify the identified factors. This study specifically examined muscle strength, preparatory muscle activities, and landing skills, as these were modifiable through training and were considered to be the most influential factors for knee valgus motion 40 ms after ground contact. The results of the study showed that knee abduction angle at 40 ms after ground contact was influenced by knee

abduction angle at initial contact and at 100 ms before initial contact. Also, the preparatory muscle activities of biceps femoris, semitendinosus, vastus lateralis, and vastus medialis were associated with knee valgus motion at 40 ms after ground contact. Specifically, this study found increased muscle activity in the lateral musculature (biceps femoris and vastus lateralis) and decreased activity in the medial musculature (semitendinosus and vastus medialis). These muscle activation patterns might contribute to a decrease in joint compression on the medial side, thereby increasing knee valgus motion. These results suggested that avoiding knee valgus motion during landing preparation seems important in order to reduce the risk of ACL injury.

Study 3 investigated, in a laboratory setting, the effect of a verbal instruction and a 12-week skill training program on the knee abduction angle at 40 ms after ground contact. Muscle strength, preparatory muscle activities, and landing kinematics were also compared before and after the training period. The training program was developed on the basis of the findings of the study 2. The main focus of the program was to ensure proper landing preparation, particularly avoiding knee valgus motion and encouraging knee flexion. The skills required in basketball, such as landing, pivoting, stopping, and cutting, were practiced with the instructions to use proper body mechanics. The results of the study demonstrated that a verbal instruction immediately increased the knee flexion angle during landing. Also, the verbal instruction changed the preparatory muscle activity of the vastus medialis. The 12-week training program was effective in decreasing the knee abduction angle at 40 ms after ground contact. The preparatory muscle activities of the rectus femoris, vastus medialis, and gluteus maximus were decreased after the training period in contrast to the hypothesis. Reduced muscle activities might imply an improved proficiency in performing the landing task. Also, the



strength of the knee flexion was increased after the 12-week training period. These results suggested that the 12-week training program focusing on the modification of landing patterns reduced the knee valgus motion during the critical time period. Moreover, the training program might have induced an adaptation in the neuromuscular function. Especially, the activity and strength of the hamstrings relative to the quadriceps were improved. Also, decreased muscle activities and increased muscle strength suggest that the force production per muscle activity might be improved with the training program.

Finally, study 4 investigated, in a real-life setting, the effect of the training program on the knee mechanics during maturation. The training program developed in study 3 was implemented in female junior high school basketball players for 6 months. This study examined whether this training program could modify the changes in movement patterns associated with pubertal growth that were observed in study 1. The results of the study showed that the athletes who performed the training program did not change the landing mechanics, whereas the athletes who did not undergo the training intervention demonstrated an increase in knee valgus motion and a decrease in knee flexion during landing, thereby increasing their risk of developing an ACL injury. This study suggested that the skill training program was able to limit the changes in landing mechanics; therefore, the implementation of the training program should be encouraged in female athletes during puberty to reduce the risk of ACL injury.

These studies suggested that intervention at a young age might be necessary to prevent ACL injury. A recent meta-analysis revealed that an injury prevention training was more effective in reducing ACL injury in the mid-teen years than in the late teen or early adult period (Myer, Sugimoto, Thomas, & Hewett, 2013). Starting early might be

one of the effective strategies for the prevention of ACL injury. The studies have also demonstrated that a program that focuses on acquiring proper movement skills might be beneficial for reducing the risk of ACL injury. The program not only improved the knee mechanics but also changed the muscle strength and activity. This suggested that skill practice could change muscle strength and activity as well as kinematics. Therefore, this simple skill practice might be useful for ACL injury prevention.

## **7.2 RELEVANCE TO THE SPORTS FIELD**

This study found that high-risk movement patterns emerged in female athletes between the early- and middle-pubertal stages. Although the significant increase in the actual number of ACL injury might occur a few years later, coaches, trainers, and parents need to be aware that the risk of ACL injury increases during puberty and an intervention to reduce this risk should be initiated at this stage.

Second, this study examined the contents of an ACL injury prevention program. As the participant adherence to injury prevention training programs seem low, this study attempted to simplify the program based on the understanding of ACL injury mechanisms. The results of the study implied that landing skill, especially the landing preparation, was the most influential factor on the mechanism of ACL injury. Therefore, a training program that focuses on proper landing preparation skills was developed. These skills were practiced with movements that are specific to basketball. As the focus of training is “skill development” rather than “injury prevention”, the athletes and coaches might be encourage to perform the training program with a high adherence.

Finally, this study evaluated the effect of this training program on the movement patterns. The results demonstrated that implementing the training program could limit

the changes in movement patterns associated with pubertal growth. Although the actual number of ACL injuries was not investigated in this study, it is important that young female athletes learn proper movement skills that have a low-risk of causing an ACL injury. Therefore, the implementation of this training program should be encouraged in pubertal girls in elementary and junior high school.

### **7.3 SUGGESTIONS FOR FUTURE INVESTIGATION**

A future study is needed to identify the causes of the change in movement patterns during puberty. Previous studies have implied that significant structural changes would influence the movement strategy as an increase in height and weight would change the torque around the knee joint (Ford, Shapiro, et al., 2010; Hewett et al., 2004). Also, female adolescents do not demonstrate an increase in quadriceps and hamstrings strength like male adolescents do; thus, female adolescents might have reduced knee joint control during puberty (Hewett et al., 2004). A longitudinal study is needed to further investigate what factors are responsible for the movement changes in female adolescents. This understanding will clarify what kind of training is needed in order to prevent an ACL injury. A future study should also evaluate the changes in knee mechanics over time after the training program. It is necessary to investigate how long the training effect will last after the intervention is discontinued. This will indicate whether a one-time training is sufficient or if the training needs to be continued for the modification of movement patterns. In addition, although it was assumed that young children were more capable of learning new skills, a study needs to investigate the ideal age group that would obtain the optimal training effects. Therefore, a comparison among different age groups is needed. Also, a future study needs to investigate whether

this training effect is applicable to the other high-risk tasks, such as single-leg landing and cutting. It should also be investigated whether the learned skill would be transferable to other tasks or if task-specific training would be needed. Furthermore, the mechanism of ACL injury is reported to include not only the knee valgus but also the tibial internal rotation (Kiapour et al., 2014; Koga et al., 2010; Levine et al., 2013). This dissertation focused on only the knee valgus motion; therefore, a future study should also investigate a strategy to avoid tibial internal rotation. Finally, a large prospective study investigating the number of ACL injuries with and without the training program is necessary to evaluate the actual effectiveness of the training program.

#### **7.4 CONCLUSION**

The biomechanical risk factors of ACL injury, the knee valgus motion and knee flexion range of motion were significantly changed during pubertal growth in female athletes, especially the period between the early- and middle-pubertal stages. As a result, the risk of ACL injury was significantly increased during this period. Therefore, an ACL injury prevention intervention should be initiated at this period to reduce the risk of ACL injury.

This study also revealed that increased knee abduction angle at 40 ms after ground contact was strongly associated with increased knee abduction angle before and at the ground contact. Furthermore, the preparatory muscle activities of the biceps femoris, semitendinosus, vastus lateralis, and vastus medialis might affect the knee abduction angle at 40 ms after ground contact. An ACL injury prevention program might need to focus on proper landing techniques, specifically the landing preparation to reduce the risk of ACL injuries.

This study also indicated that a 12-week training program that focuses on proper landing skills was effective in reducing the knee abduction angle at ground contact and at 40ms after ground contact. The training program also changed the preparatory muscle activities of the rectus femoris, vastus medialis, and gluteus maximus and the isokinetic strength of knee flexors. The 12-week skill training program improved the neuromuscular function as well as the landing skills.

Finally, this study revealed that the implemented training program was effective in limiting the increase in knee valgus motion and the decrease in the knee flexion range of motion that are associated with pubertal growth in females. Although a significant improvement in the landing technique was not observed, lowering the risk of ACL injury might be possible in this population.

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## APPENDIX

### Self-Administered Rating Scale for Pubertal Development (Carskadon & Acebo, 1993)

#### Introduction:

The next questions are about changes that may be happening to your body. These changes normally happen to different young people at different ages. If you do not understand a question or do not know the answer, just mark "I don't know".

Questions:	Response options	Point value
1. Would you say that your growth in height:	has not yet begun to spurt	1
	has barely started	2
	is definitely underway	3
	seems completed	4
	I don't know	
2. And how about the growth of your body hair? ("Body hair" means hair any place other than your head, such as under your arm)		
Would you say that your body hair growth:	has not yet begun to grow	1
	has barely started to grow	2
	is definitely underway	3
	seems completed	4
	I don't know	
3. Have you noticed any skin changes, especially pimples?	Skin has not yet started changing	1
	Skin has barely started changing	2
	Skin changes are definitely underway	3
	Skin changes seem completed	4
	I don't know	
4. Have you noticed that your breasts have begun to grow?	Have not yet started growing	1
	Have barely started growing	2
	Breast growth is definitely underway	3
	Breast growth seems completed	4
	I don't know	

5a. Have you begun to menstruate (started to have your period)?	Yes	4
	No	1

5b. If yes, how old were you when you started to menstruate?      Age in years:

**Rating:**

Pre-puberty = 2 and no menarche

Early puberty = 3 and no menarche

Middle puberty = > 3 and no menarche

Late puberty = < 7 and menarche

Post-puberty = 8 and menarche