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Sex Differences in Muscle Activity During Drop-Jump Landing Motion

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Abstract
This study investigated the effect of hip joint muscles' activity on dynamic knee-joint valgus angle during one-leg drop-jump landing motion in male and female subjects. Twenty-four healthy university students (11 males and 13 females) participated in the study. Surface electromyography was used to measure muscle activity during a one-leg landing motion. A gender difference was observed: males showed greater activity in the gluteus medius muscle compared to the adductor magnus muscle, whereas females showed greater activity in the rectus femoris muscle. A correlation between lower limb muscle activity and knee-joint valgus angle was found in male subjects but not in female subjects, suggesting that factors other than muscle activity are necessary for controlling knee joint valgus in females. Therefore, factors other than muscle activity should be investigated in the future to prevent female anterior cruciate ligament injuries.

Keywords: Anterior Cruciate Ligament Injuries, One-Leg Drop-Jump Landing, Sex Difference, Adductor Magnus Muscle, Gluteus Medius Muscle, Injury Prevention

1. Introduction

Anterior cruciate ligament (ACL) injuries are among the most common sports injuries and disorders, and the etiology of these injuries has been reported in a variety of ways (Montalvo, A. M., etc., 2019, Larwa J., etc., 2021). An ACL injury is categorized by its cause, contact or noncontact. According to many reports, contact injury is more common in male athletes and noncontact injury in females (Larwa J., etc., 2021, Yu B., etc., 2007). Notably, contact injuries are more likely to occur in female athletes than in males (Montalvo, A. M., etc., 2019). In either case, prevention of ACL injuries in the female athletes is extremely important.

Although many theories exist whether knee joint or lower leg rotation is involved in female noncontact ACL injuries (Yu B., etc., 2007), a consensus exists that valgus movement of the knee during landing and cutting on one leg is the primary mechanism of the injury (Bisciotti G. N., etc., 2019, Hewett T. E., etc., 2009, Olsen O. E., etc., 2004, Hewett T. E., etc., 2005), probably because females tend to have a larger physiological knee valgus angle and less muscle activity in the hamstrings than males and are likelier to be in a slightly flexed external knee joint position. Studied have shown that females have an increased dynamic knee valgus (DKV) angle during landing motions and are likely to be more at risk (Wilczyński B., etc., 2020, Collings T. J., etc., 2022, Nilstad A., etc., 2015, Myer G. D., et al., 2009, Myer G. D., et al., 2005). While it is questionable whether static alignment (female greater knee valgus angle than male) is a factor in this risk (Nilstad A., etc., 2015), some reports have suggested that muscle contraction or neuromuscular control is involved in stabilizing the knee (Wilczyński B., etc., 2020, Myer G. D., et al., 2009, Myer G. D., et al., 2005).
Many studies have focused on a single-leg jump landing motion (Ugalde V., etc., 2014, Nilstad A., etc., 2014, Ekegren C. L., etc., 2009), which is considered to have highest injury rate among the ACL injuries and has been validated under various names and methods, such as single-leg squat test (Ugalde V., etc., 2014), vertical drop-jump landing (Nilstad A., etc., 2014, Ekegren C. L., etc., 2009), single-leg jump-landing (Boey D., & Jc Lee M., 2020). Notably, its significance as an evaluation method is high.

From the viewpoint of muscle activity, excessive anterior subluxation of the tibia caused by the quadriceps muscle and decreased hamstring muscle activity that controls the anterior withdrawal of the tibia are the cause of ACL injury (Hewett T. E., etc., 1999). In addition, hip adduction and internal rotation are associated with increased external rotation of the knee joint, and the activity of the vastus medialis muscle, which prevents hip adduction, plays an important role in single-leg landing (Olsen O. E., etc., 2004, Myer G. D., et al., 2009). The importance of the gluteus medius (GM) during landing on one leg has been reported in males (Collings T. J., etc., 2022), but only a few reports exist for females. Although many studies have explored the relationship between the quadriceps and hamstrings, only a few have considered the coordination of the GM with the adductor magnus (AM) - the GM antagonist - and no comparative study of the characteristics of their activities between males and females exists.

In this study, we focused on a one-leg drop-jump landing (ODL) motion and aimed to calculate the muscle output and coordination of hip joint muscles and the timing of the onset of muscle activity while verifying their effects on the DKV angle in females and males. Knowing the characteristics of the above muscle activities will help elucidate the causes of noncontact ACL injuries, which are more common in females.

2. Method

2.1 Subjects

The subjects were 24 healthy university students (11 males; 20.2 ± 0.9 years old, 172.2 ± 3.6 cm, 65.8 ± 10.1 kg, and 13 females; 19.9 ± 0.7 years old, 158.5 ± 3.9 cm, 51.4 ± 5.8 kg). Subjects with current pain or a history of orthopedic disease in the lower limbs were excluded. The dominant leg was examined, the leg was used to kick the ball.

2.2 Measurement Items

2.2.1 Static knee joint valgus (SJV) angle (Shultz S. J., etc., 2006)

The angle between the superior anterior iliac spine, the midpoint connecting the center of the medial and lateral knee joint spaces, and the midpoint connecting the medial and lateral malleolus were measured using an SJV angle on a goniometer. The measurement was performed in the one-leg standing posture, with the dominant leg supporting the subject not to lose balance.

2.2.2 Joint Angles and Muscle Activities during One-leg Drop-jump Landing (ODL) Motion

The subjects were instructed to jump down from a 30-cm-high platform to a 20-cm-forward fall, land on one leg, and maintain a static posture. They were also instructed to jump forward and were careful not to jump up during the motion. The upper limbs were fixed in front of the chest, with the elbows flexed. The subjects practiced twice before, and the number of measurements was one time.

2.2.2.1 DKV and Dynamic Knee Flexion (DKF) Angles

The angle between the superior anterior iliac spine, the midpoint connecting the center of the medial and lateral knee joint clefts (just on the patella), and the midpoint connecting the medial malleolus and lateral malleolus were designed as a DKV angle in the frontal plane. In addition, the angle between the greater trochanter, lateral knee joint cleft, and lateral malleolus was designed as a DKF angle in the sagittal plane. Two digital video cameras (Casio EX-FC100) were used to capture images at 210 frames per second. The height of the cameras was 1 m from the floor and the distance was set to capture whole-body movements. Each joint angle was photographed and calculated using Image J (1.53j, National Institutes of Health, USA). Motion was initiated by a light cue, and the two cameras were synchronized based on that timing.

2.2.2.2 Muscle Activity during Motion

Ultium electromyography (EMG, Noraxon EM-U810MM) was used to measure muscle activity. The target muscles were the rectus femoris, biceps femoris, GM, and AM muscles. The electrodes were applied to the rectus femoris muscle at the center of a line drawn from the superior anterior iliac spine to the center of the patella, the biceps femoris at the distal one-third of a line drawn from the sciatic tubercle to the fibular head, the GM at the center of a line connecting the middle iliac crest and adductor pollicis major, and the AM at the proximal one-fourth of a line drawn from the pubic sub-tubercle to the tuberosity of adductor pollicis brevis. Maximum voluntary contraction (MVC) was measured in advance in a fixed position on the BIODEX (Biodex Medical Systems) using the amount of muscle activity during the maximum voluntary isometric contraction of each muscle. Measurements were taken once for 5 s. After rectification and smoothing, the MVC was calculated as the average of the values obtained during the 3 s before and after the 5 s, excluding the 1 s before and after the 5 s.

EMG measurements during the ODL motion were performed, initiated by the light cue described above, and synchronized with motion capture. The sampling frequency was set at 2000 Hz, band-passed at low (50 Hz) and high frequency (500 Hz), and then filtered. The EMG waveform was converted to the root mean square every 10 ms. Muscle activity during ODL was analyzed in three intervals: pre-landing, post-landing, and during maximal valgus of the knee joint (hereinafter defined as "maximal valgus"). "Pre-landing" was the mean value calculated from 100 ms before toe-ground to the timing of toe-ground, "post-landing" was from toe-ground to the timing of maximal valgus of the knee joint after landing, and "maximal valgus" was from 50 ms before the timing of maximal valgus of the knee joint. Each muscle activity value of the three intervals for each subject was calculated as %MVC, devided by the value of the MVC. The ratio of rectus femoris to biceps femoris (hamstrings/quadriceps: H/Q ratio) and the ratio of AM muscle to GM muscle (AM/GM ratio) were calculated from the mean values for each interval.

2.3. Analysis Method

Each data was compared between the sexes; SJV, DKF, and DKV angles, and each muscle %MVC, H/Q ratio, and AM/GM ratio in the three intervals (pre-landing, post-landing, and maximal valgus). IBM SPSS Statistics Version 24 was used for statistical analysis. All data were checked for normality using the Shapiro-Wilk test, and when normality was present, a two-sample unpaired *t*-test was used, and when not normal, a Mann-Whitney test was used. Correlations between the maximum knee valgus angle and the other items were calculated separately for each gender and analyzed using Pearson's correlation coefficient for normality and Spearman's rank correlation coefficient for non-normality. The significance level was set at 5%.

2.4. Ethical Considerations

This study was designed and conducted following the Declaration of Helsinki. This study's aim and the measurement details were explained to the subjects orally and in writing in advance, and measurement was conducted after their written consent was obtained. The measurement was started after obtaining the consent of the faculty member in charge of the ethical review at the Department of Physical Therapy, Faculty of Health Care, Takasaki University of Health and Welfare.

3. Results

3.1. Gender Differences in Each Joint Angle and Muscle Activity (Table 1)

The SKV angle was significantly bigger in females than in males, but no gender difference in the DKV angle was found during the ODL motion. For muscle activity, only the rectus femoris muscle at a maximum valgus angle was significantly greater in females. The AM/GM ratio was significantly lower in males across all periods, but the H/Q ratio did not differ between sexes.

Table 1: Gender Differences in Each Joint Angle and Muscle Activity

		Male (n=11)	Female (n=13)	p value
Static knee valgus angle (deg)		1.55±1.44	6.08±2.56	<0.01*
Dynamic knee valgus angle (deg)		10.7±7.7	11.6±9.36	0.807
Maximal knee flexion angle (deg)		60.5(57.9,68.3)	60.2(57.9,69.6)	0.191
Pre-landing %MVC (%)	RF	39.9(27.7,63.9)	63.2(51.0,78.4)	0.063
	BF	40.7(27.3,53.4)	36.7(24.3,71.0)	0.910
	GM	46.8(30.9,94.3)	73.4(54.9,153.9)	0.106
	AM	37.5(19.4,49.8)	74.7(37.0,115.2)	0.119
	H/Q ratio	130.6(104.9,231.8)	106.1(91.4,126.4)	0.106
	AM/GM ratio	29.1(21.2,32.4)	88.4(47.6,121.4)	0.026*
Post-landing %MVC (%)	RF	56.8±61.8	95.4±50.8	0.054
	BF	40.1(26.1,64.4)	55.0(26.4,71.7)	0.649
	GM	55.0(42.2,74.3)	93.7(42.2,18.1)	0.106
	AM	61.4(37.9,92.6)	91.6(59.0,94.6)	0.228
	H/Q ratio	49.6(42.1,105.2)	58.8(50.8,76.8)	0.865
	AM/GM ratio	42.6(31.4,77.4)	107.8(97.0,141.6)	0.009*
Maximal valgus %MVC (%)	RF	36.0(18.6,47.8)	71.1(40.1,90.9)	0.035*
	BF	39.5(26.8,64.2)	43.2(29.5,53.1)	0.820
	GM	50.8(25.5,66.7)	86.2(51.6,97.6)	0.106
	AM	41.9(29.2,85.7)	83.8(46.1,132.6)	0.865
	H/Q ratio	91.0(71.6,208.3)	57.2(42.9,141.5)	0.167
	AM/GM ratio	67.4±45.6	138.0±81.4	0.018*

average±standard deviation, central value (1st quartile, 3rd quartile) * : $p<0.05$
unpaired t-test or Mann-Whitney's U-test
RF : rectus femoris BF : biceps femoris
GM : gluteus medius muscle AM : adductor magnus muscle H/Q: hamstrings/quadriceps

3.2. Correlations to DKV Angle by Gender (Table 2)

The following results were observed in males: although no correlation existed between the DKV and SKV angles (r = -0.229) or DKF angle (r = -0.100), a negative correlation was found between the DKV angle and %MVC of the biceps femoris, GM, and AM muscles in the correlation of muscle activity before landing. In addition, a negative correlation was found between the DKV angle and %MVC of the biceps femoris muscle in muscle activity during post-landing and maximal valgus. Negative correlations were also found in the H/Q ratio after landing and during maximal valgus, and a negative correlation was found only after landing in the AM/GM ratio. In female subjects, no correlation was found in all data.

Table 2: Correlation with dynamic knee joint valgus angle in male subjects

		RF %MVC	BF %MVC	GM %MVC	AM %MVC	H/Q ratio	AM/GM ratio
male	Pre-landing	r=-0.451	r=-0.629*	r=-0.673*	r=-0.691*	r=0.181	r=-0.509
	Post-landing	r=-0.082	r=-0.745*	r=-0.364	r=0.518	r=-0.709*	r=-0.609*
	Maximal valgus	r=-0.188	r=-0.791*	r=-0.418	r=-0.327	r=-0.7*	r=-0.422
females	Pre-landing	r=0.148	r=-0.368	r=-0.374	r=0.093	r=-0.342	r=0.475
	Post-landing	r=0.454	r=-0.066	r=-0.305	r=0.255	r=-0.462	r=0.453
	Maximal valgus	r=0.563	r=-0.001	r=-0.028	r=0.379	r=-0.412	r=0.285

Pearson's correlation coefficient or Spearman's rank correlation coefficient * : $p<0.05$

RF : rectus femoris BF : biceps femoris

GM : gluteus medius muscle AM : adductor magnus muscle H/Q: hamstrings/quadriceps

4. Discussion

4.1. SKV angle by gender

The SKV angle was significantly larger in females than in males, similar to the results of a previous study (Nilstad A., etc., 2015). This suggests that this study's physiological knee valgus angle is greater in females than in males. However, because no relationship was found between the SKV and DKV angles, the SKV angle does not necessarily affect the DKV angle, and it cannot be said that an increase in the SKV angle causes ACL injury, which is similar to the results of Nilstad et al. (Nilstad A., etc., 2015). Although the incidence of ACL injury is lower in males than in females, suggesting that males may have a larger DKV angle that does not directly lead to ACL injury, it is also necessary to examine how the actual occurrence of trauma is related to an increase in the DKV angle.

4.2. Gender Differences in Muscle Coordination

The correlation results in male subjects showed that the DKV angle decreased with increased muscle activity of the biceps femoris, GM, and AM muscles before landing. In other words, the coordinated contraction of these three muscles before landing prevented excessive DKV, suggesting that male subjects might have had greater predictive postural control by muscle activity than females. Notably, predictive postural control ability to avoid the injured limb position before landing is necessary to prevent ACL injury (Hewett T. E., etc., 2013), and males can manage predictive postural control with cooperative lower limb muscle activity. The lack of correlation between muscle activities in females suggested that they might use physical functions other than muscle activity for postural control.

In this study, the AM/GM ratio was calculated to examine the coordination between the GM and AM muscles. The AM/GM ratio was significantly smaller in males than females in all the periods, suggesting that the GM muscle activity might be greater or the AM muscle activity smaller during the ODL motion. Notably, the GM muscle activity tends to increase during landing motion in males (Hewett T. E., etc., 1999), and Padua et al. reported that medial knee displacement appeared to be associated with increased hip-adductor activation. These reports suggested that GM muscle activity is important during the jump landing motion for the male subjects, and it may be used to control the hip joint's adduction and the abduction of the knee joint (Padua D. A., et al., 2012). However, the AM/GM ratio was higher in the female subjects, and the values increased after landing, suggesting that the greater activity of the AM muscle has the action in the female subjects might exert a hip adduction and relatively increase the knee valgus angle. Russel et al. reported that females tended to land in more knee valgus than males, but GM muscle activation did not differ between the sexes (Russell K. A., etc., 2006). Thus, GM did not appear to be responsible for the sex differences in knee valgus, suggesting that the adductor muscles, not the GM, might affect DKV. In addition, the AM muscle has the action of hip internal rotation, and when the hip internal rotation occurs, the lower leg anatomically tends to be in an externally rotated position. Notably, females tend to have hip adduction and internal rotation due to the excessive contraction of the AM muscle during the ODL motion, resulting in external rotation of the lower leg and knee joint. The increased muscle activity of the AM muscle, a characteristic of the female muscle activity, might result in external rotation of the lower leg - a phenomenon that should be noted from ACL injury viewpoint.

Notably, the dominance of the quadriceps muscle acts on ACL shearing forces, and the hamstring activity inhibits ACL tension (Myer G. D., et al., 2009, Withrow T. J., et al., 2006, Draganich L. F., & Vahey J. W., 1990). From this study, the female subjects had greater rectus femoris muscle activity than males, and in males, an increase in biceps femoris muscle activity was associated with a decrease in the DKV angle, whereas this relationship was not observed in females. Kernozek et al. reported that the female athletes who suffered an ACL injury had a combination of decreased hamstring strength but not quadriceps strength compared to males, suggesting that males can control external knee movement using the hamstring muscle activity, whereas females could not control forward movement of the tibia sufficiently and might thus be at risk for an ACL injury (Kernozek T. W., etc., 2005). However, the maximum knee flexion angle in this study was about 60 degrees, which might not have met the generally reported risk factors of mild flexion and valgus of the knee joint for an ACL injury. A previous report stated that "there is no problem at flexion angles greater than 60 degrees, but the risk is greater at flexion angles between 0 and 45 degrees" (Arms S. W., etc., 1984). Therefore, the flexion position in the present study was deep flexion as a risk factor for ACL injury.
As no significant relationship was found between the DKV angle and muscle activity in the female subjects, the muscle activity may not be the only cause of prevention for taking a risky position of ACL injury. Other factors besides the muscle activity, such as neuromuscular activation strategies (Padua D. A., et al., 2012), trunk movements (Hewett T. E., etc., 2009), and poor core stability (Larwa J., etc., 2021, Zazulak B. T., etc., 2007), may be related to taking such a jump landing position.

4.3. Limitations and Future Prospects

This study could not capture the motion of internal/external rotation of the hip joint and lower leg because the motion was analyzed in two dimensions using a digital video camera. It is expected to analyze the motion in the horizontal plane using a 3D motion analyzer and to examine the relationship between the hip and ankle joints and the dynamic knee external rotation angle in the future.

The study's results suggested that males could control the knee joint external rotation by the lower limb muscle activity, but females had difficulty controlling the external rotation by the lower limb muscle activity, and it might be difficult to prevent ACL injury by strength training alone. In addition, the external rotation of the knee joint was considered a passive change in angle caused by a sudden increase in load. In the future, it will be necessary to prevent ACL injury in females by focusing on the muscle activity, kinematics, and balance ability.

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