Change with advancing age in the control of lower limbs during jump-landing in adolescents: A 5-year prospective study

Running title: Drop-jump test in adolescents

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Abstract

Background: The discrepancy of anterior cruciate ligament (ACL) injury incidence in males and females appears after puberty, however, little is known about the changes that occur in the control of lower limb during jump-landing in adolescents.

Methods: Twenty-five males and 29 females of the 5th grader students at the beginning of study participated and were followed for 5 consecutive years. Control of lower limbs during jump-landing was evaluated by drop-jump test using 2-dimensional video analysis. K/H ratio which was determined by dividing the knee separation distance by the hip separation distance was calculated at initial contact (IC) and maximum knee flexion (MKF) phase.

Results: Female subjects showed significantly lower K/H ratio at both IC and MKF than male subjects in all grades. Although no statistically significant difference in K/H ratio between age categories was shown at either IC or MKF in male subjects, K/H ratio at IC and MKF was significantly decreased between the 5th grader and the 9th grader female subjects.

Conclusion: This study suggests that adolescent females demonstrate lower K/H ratio during jump-landing compared with male subjects of same age and decrease K/H ratio accompanying with age advancing longitudinally. Gender difference in ability to control lower limbs in jump-landing task, which is suggested by our prospective study, may relate to the difference of ACL injury incidence between males

and females after puberty.

Background

Most anterior cruciate ligament (ACL) injuries occur in noncontact mechanism including landing from a jump, cutting, pivoting or deceleration during sports participation **[1,2]**. The dynamic knee biomechanics at the time of noncontact ACL injury have been described using the advanced video analysis technologies. The prospective study conducted by Hewett et al **[3]** demonstrated that knee valgus angle and moment during a jump-landing task are predictors of ACL injury risk in female athletes. In this way, it seemed that knee valgus motion is a key contributing factor of noncontact ACL injury. However, there is still much controversy about the actual mechanism at the time of ACL injury. The incidence of ACL injury has increased even in late childhood **[4]**. The distribution of ACL injury in males and females dramatically changes around the peripubertal period **[5,6]**, and skeletally matured female athletes suffer ACL injuries at a 4- to 6-fold greater incidence than male athletes participating in the same sports **[7,8]**. Lack of prospective study for lower limb kinematics accompanying age and development, however, makes it difficult to understand the changes of dynamic lower limb alignment around puberty and its relationship to the gender disparity in ACL injury. In addition, it is important to determine when and how a preventive intervention should be implemented to achieve the best effects of ACL injury prevention. It is essential to prospectively evaluate the changes in ability to control lower limbs in pubertal children accompanying with age. If there is a gender difference in change of ability to control lower limbs with advancing age, it is important to determine what factors affect its gender difference.

The primary purpose of this study was to evaluate the ability to control lower limbs during jump-landing maneuver in adolescents by using 2-dimensional (2D) video analysis, and analyze the change with advancing age longitudinally. A secondary purpose of this study was to determine what factors that change with advancing age affect a control of lower limbs in the coronal plane. We hypothesized that there are no significant differences in the ability to control lower limbs between males and females in younger children; however, females increase poor control of lower limbs with advancing age compared with males of the same age.

Materials and Methods

Preliminary analysis for correlation between 2D and 3D motion analysis

Before the starting of this study, we conducted a preliminary analysis involving 14 female and 13 male college athletes (18-24 years) to validate the availability of 2D video analysis. All subjects signed an informed consent document and the study design was approved by the ethics committee of our institution. Dynamic control of the lower limb was evaluated by the drop jump screening test (DJT) according to the protocol previously described by Noyes et al **[9]**. The subject was instructed to drop off a box with 35 cm height, land on both feet on the floor, and then immediately perform a maximum vertical jump. Each subject was allowed to practice the task until he or she felt comfortable performing it. No instructions regarding any other dropping, landing or jumping techniques were given to the subjects to avoid a coaching effect on their performance. The image data was simultaneously recorded with both 2D and 3-dimensional (3D) motion analysis systems. For the 2D motion analysis, reflective markers with a 25 mm diameter were secured with double-sided adhesive tape on the skin at the greater trochanter (hip marker) and the center of patella (knee marker) on both the right and left legs. The drop-jump sequence was recorded with a digital video camera (HDR-HC3, Sony, Japan), which was placed on a 100 cm height camera-stand and away 4 m from the frontal face of the box, at 30 Hz of sampling rate. The DJT video data were analyzed using computer software (Dartfish TeamPro 4.5, DARTFISH). Advancing the video frame by frame, 2 images at the following time points were captured as still photographs: (1) initial contact (IC) defined with the frame in which the subject's toes just touched the ground after dropping off the box; (2) maximum knee flexion (MKF) defined with the frame in which the subjects was at the deepest point. The separation distance between the 2 hip markers and that between the 2 knee markers were measured on the still images of IC and MKF. The knee separation distance was divided by the hip separation distance to assess the control of lower limbs in coronal plane, and it was defined K/H ratio in this study **(Figure1)**. In addition to 2D motion analysis, the kinematic data were collected by the 3D motion analysis system with seven infrared cameras (VICON, Oxford Metrics, London, England) at 120 Hz of sampling rate. Both static and dynamic calibrations were performed, and residuals of less than 2 mm from each camera were deemed acceptable. According to the VICON Clinical Manager Protocol, 25 mm diameter reflective markers were secured with double-sided adhesive tape on the skin positioned over the anterior superior iliac spine, posterior superior iliac spine, lateral midthigh, lateral femoral condyle, lateral midcalf, lateral malleolus, posterior calcaneus, and the second metatarsal head of each lower limb. The 3D marker trajectories were recorded and the kinematic variables were calculated with a VICON Workstation (version 4.6; Oxford Metrics, London, England). The kinematic variables of interest included the knee varus-valgus angle at IC and MKF. Spearman's rank correlation was used to determine whether significant correlations existed between the K/H ratio and the average of right and left knee valgus angles in 3D kinematic data. A statistical analyses were performed with the SPSS ver. 16.0 (SPSS Inc., Chicago, IL, USA), and p values < 0.05 were considered significant. There were significant correlations between the K/H ratio in the 2D motion analysis and the knee varus-valgus angle in the 3D motion analysis at IC ($p = 0.02$, $r = -0.51$) and MKF ($p < 0.001$, $r = -0.62$) (Figure 2).

Subjects

This prospective study was designed as a part of Iwaki Health Promotion Project which was conducted for 5 consecutive years from 2007 to 2011. Forty-one females and 31 males of the 5th grader students participated in this prospective study at the first year. Subjects who had a complaint or surgical history involving lower limbs were excluded. Ethical approval of this project was obtained from the internal review board of our institute, and the written informed consent was provided by the participants and their guardians in advance.

Anthropometric measurements

Height, body weight, body mass index (BMI), lower limb muscle mass and trunk muscle mass were measured using the body composition analyzer (Tanita MC-190, Tanita Corp, Tokyo, Japan) **[10] (Table 1)**. The lower limb muscle mass and the trunk muscle mass were normalized by dividing by body weight. Information about sports habit was acquired from a questionnaire. Those with a sports habit were defined as having continuous sports activities with the frequency of 4 times or more per week, and 2 hours or more per day.

Motion analysis

The DJT and 2D video analysis was performed in the same method as in preliminary study, except using a 23cm-height box for immature and smaller height subjects. Each subject performed 3 trials after practicing several times. After the completion of 3 trials, the most successful trial in which the subjects performed the highest vertical jump without breaking down the balance for each subject was selected.

Statistical analysis

The comparison of height, body weight, body mass index (BMI), percent of body fat, lower limb muscle mass, trunk muscle mass, sports habit, and K/H ratio between females and males was performed using the Mann-Whitney U test. Analysis of covariance (ANCOVA) was performed to compare K/H ratio between each age categories in each gender group, and which was adjusted by BMI. The distribution of subjects according to K/H ratio (≦0.40, 0.41-0.60, 0.61-0.80, and >0.80) **[9]** was compared between female and male subjects using the χ^2 test. Examination of the factors which have an influence on the value of K/H ratio was performed by using multiple linear regression analysis. The dependent variable was K/H ratio at 9^{th} grader, and the independent variable was the amount of change in height, body weight, lower limbs muscle mass and trunk muscle mass from the first year to the last year during this study, and which was adjusted by either she or he had regular sports habit. All analyses were performed with the SPSS ver. 16.0 (SPSS Inc., Chicago, IL, USA), and P values < 0.05 were considered significant.

Results

Gender difference and longitudinal change in K/H ratio

Twenty-nine of 41 (71%) females and 25 of 31 (81%) males who participated at the first year of this study completed all annual measurements for 5 consecutive years, and the total follow-up rate was 75% **(Figure 3)**. None of the subjects suffered any severe lower limbs injury including ACL injury during this period.

For female subjects, K/H ratio at IC was 0.59 ± 0.09 in 5^{th} grader, 0.56 ± 0.11 in 6^{th} grader, 0.54 ± 0.08 in 7^{th} grader, 0.52 ± 0.11 in 8^{th} grader and 0.52 ± 0.09 in 9^{th} grader. That for male subjects was 0.68 ± 0.12 in 5^{th} grader, 0.62 ± 0.12 in 6^{th} grader, 0.65 ± 0.14 in 7^{th} grader, 0.70 ± 0.11 in 8^{th} grader and 0.67 ± 0.11 in 9^{th} grader. K/H ratio at MKF for female subjects was 0.42 ± 0.11 in 5^{th} grader, 0.39 ± 0.12 in 6^{th} grader, 0.36 ± 0.10 in 7th grader, 0.34 ± 0.09 in 8th grader and 0.32 ± 0.08 in 9th grader, and that for male subjects was 0.59 ± 0.22 in 5th grader, 0.53 ± 0.16 in 6th grader, 0.55 ± 0.16 in 7th grader, 0.57 ± 0.20 in 8th grader and 0.56 ± 0.21 in 9th grader. In all the school-grades for 5 years, the K/H ratio of females was significantly smaller than that of males at both IC (P = 0.004, 0.031, 0.003, < 0.001 and < 0.001, respectively) and MKF (P = 0.002, < 0.001, < 0.001, < 0.001 and < 0.001, respectively) **(Figure 4, 5)**. In female subjects, K/H ratio at IC in 9th grader (0.52 ± 0.09) was significantly lower than that in 5th grader (0.59 ± 0.09) (P = 0.036). Also, K/H ratio at MKF in JH3 (0.32 ± 0.08) was significantly lower than that in 5th grader (0.42 ± 0.11) and 6th grader (0.39 ± 0.12) (P < 0.001 and = 0.003, respectively). No statistically significant difference in K/H ratio between the school-grades was shown at either IC or MKF in male subjects **(Figure 4, 5)**.

Distribution of subjects according to K/H ratio

The distribution of female subjects who demonstrated smaller K/H ratio increased with age at both IC and MKF, however this change was not evident in male subjects. The female and male subjects who showed K/H ratio less than 0.60 at IC accounted for 55% and 36% in 5th grader, 58% and 44% in 6th grader, 75% and 44% in 7th grader, 90% and 20% in 8th grader, and 79% and 28% in 9th grader, respectively. There was significant gender difference in the distribution of subjects according to K/H ratio at IC in 8th and 9th grader (P < 0.001 and < 0.001, respectively), while significant difference was not found in 5th, 6th and 7th (P = 0.100, = 0.401 and = 0.051, respectively) **(Figure 6)**. Furthermore, the female and male subjects who showed K/H ratio less than 0.60 at MKF accounted for 90% and 52% in 5^{th} grader, 93% and 76% in 6^{th} grader, 97% and 72% in 7^{th} grader, 100% and 60% in 8^{th} grader, and 100% and 72% in 9^{th} grader, respectively. In all 5 school-grades, there was significant gender difference in the distribution of subjects according to the K/H ratio at MKF (P = 0.008, = 0.032, < 0.001, < 0.001 and < 0.001 respectively) **(Figure 7)**.

Factors which influenced the valgus alignment in female subjects

In female subjects, K/H ratio in both IC and MKF significantly decreased with pubertal maturation. In the multiple linear regression analysis, K/H ratio at MKF in 9^{th} grader showed a negative statistical correlation with the amount of change in height during 5 years (β = -0.576, P = 0.040), however, it was not found with the amount of change in body weight, lower limb muscle mass or trunk muscle mass **(Table 2)**. There was no significant correlation between K/H ratio at IC and any anthropometric measurements. On the other hand, there was no effect of pubertal maturation during 5 years on K/H ratio at IC or MKF in male subjects.

Discussion

Results of the current longitudinal study indicated that female subjects significantly increased poor control of lower limbs that is smaller K/H ratio during jump-landing accompanying with age, in contrast with male subjects. The distribution of female subjects who demonstrated abnormal knee separation distance increased with advancing age and was significantly higher than that of same age males, supporting a part of our starting hypothesis **(Figure 8)**. It has been reported that knee valgus motion was a key component of suffering ACL injury particularly in female athletes **[3,11,12]**. Hewett et al **[13]** performed a cross-sectional study of knee valgus with subjects of 81 boys and 100 girls, and reported that the girls had increased knee valgus after adolescence while the boys demonstrated no significant change around adolescence. Ford et al **[14]** reported that no gender difference in knee abduction angle and moment in pubertal males and females, however after puberty, females showed greater knee abduction angle and moment compared with males. Although it was unclear the actual knee valgus angle or moment in the subjects, the current longitudinal study reinforced the findings of that previous cross-sectional study. In addition, our results indicated that adolescent females showed smaller K/H ratio during jump-landing compared to the same age males in all school grades from 5th to 9th grader, and thus it failed to support our investigational hypothesis that there would be no significant gender differences in the control of lower limbs in younger adolescent children.

Most ACL injury occurs by non-contact mechanism **[1,2]**, and a lot of research has been conducted to identify internal risk factors of non-contact ACL injury. Although neuromuscular and biomechanical factors **[3,12]**, anatomical and structural factors **[15,16]** and hormonal factors **[17]** were considered to be risk factors of non-contact ACL injury, the mechanism how these factors affect the gender disparity of incidence of ACL injury after puberty is still a matter of controversy. During the pubertal maturation process, children undergo rapid skeletal growth and changing of physical and hormonal factors, for instance height, weight, muscle strength and first menstruation. Although these changes accompanying pubertal maturation in children may possibly produce the gender disparity in the incidence of ACL injury, there is little prospective study to identify the risk of ACL injury. In the current study, K/H ratio at MKF in the 9th grader female subjects was affected by the amount of change of height for 5 consecutive years, i.e. the larger increase in height brought about the greater valgus lower limb alignment. Myer et al **[18]** developed the prediction tool to determine high knee valgus moment, in which tibial length is one of the key criteria for evaluation of knee valgus moment. Because tibial length may be longer in association with increase in height, it seems to be reasonable that the amount of change in height affected K/H ratio in this study. Although the valgus moment which was actually generated during jump-landing in this study was not measured, growth in height appears to increase poor knee control in female subjects that may contribute to ACL injury. Adolescent female athletes demonstrate neuromuscular imbalance including ligament dominance, quadriceps dominance, leg dominance, and trunk dominance which lead to decrease dynamic knee stability and predispose them to ACL injury **[19-21]**. After the onset of puberty, female athletes may not have a neuromuscular spurt and the lack of natural adaptation strategies may lead to neuromuscular imbalances that increase the risk for ACL injury **[13,22]**.

ACL tears are severe injuries; additionally, no conservative or surgical treatment has been established that guarantees perfect restoration of normal knee biomechanics **[23,24]** or complete avoidance of secondary osteoarthritis **[25]**. The limitation of these treatments has accentuated the need for ACL injury prevention in recent years. Our results indicated that female subjects in adolescent might already be at high risk for ACL injury compared with male subjects, and therefore any preventive interventions for school-children may decrease future injury risk. Although it was reported that ACL prevention training was effective for reducing the incidence of ACL injury in mature competitive athletes **[26-28]**, it was difficult to show the effects of injury prevention training in younger children **[29,30]**. It is considered that this adolescent period is valuable time to learn and refine movement skills for children, therefore, development of effective prevention program which corrects a risky movement pattern causing ACL injury is expected.

One of the limitations of this study was that the control of lower limbs alignment was evaluated only in the frontal plane by 2D motion analysis, thus neither the joint angle nor the moment which actually occurred could be evaluated. When analyzing the control of lower limbs during jump-landing task, it is favorable to use 3D motion analysis. However, the 2D motion analysis which was performed in this study was useful to screen the ability to control lower limbs in coronal plane for a large population. Although the subjects were grouped by school-grade age, it was not precisely clear which stage of the pubertal maturation process each student was in. Since the subjects in each school-grade were at various stage of pubertal maturation, an established staging system of pubertal maturation should be used rather than age and school grade alone. The third limitation was that this prospective study included a relatively limited number of subjects and was not adequately powered to perform all statistical analyses. It would be necessary to conduct a further extensive prospective study with larger sample size, in which the subjects are divided according to the maturation process in adolescence.

Conclusion

This study shows that female subjects in adolescence demonstrate poor control of lower limbs that is smaller K/H ratio during jump-landing compared with male subjects of same age and decrease K/H ratio accompanying age longitudinally. The smaller K/H ratio in 9^{th} grader female subjects is affected by the amount of change in height. Gender difference in the control of lower limbs in jump-landing with advancing age which is suggested by our prospective study may relate to the difference of ACL injury incidence between males and females after pubertal.

Acknowledgement

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Conflict of interest

None.

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Figure caption

Figure 1. The centimeters of distance between the hips (H1 to H2) and the knees (K1 to K2) were calculated. K/H ratio was determined by dividing the knee separation distance by the hip distance.

Figure 2. Correlation between 3D knee valgus/varus angle and 2D K/H ratio at IC (A) and MKF (B)

Figure 3. At the beginning of this study, 31 males and 41 females of the 5th grader students were enrolled in the study, and 75% of them (25 males and 29 females) were able to be followed for five consecutive years.

Figure 4. K/H ratio at IC

* indicates a significant difference between males and females at a level of less than 0.05.

† indicates a significant difference between age categories within gender at a level of less than 0.05.

Figure 5. K/H ratio at MKF

* indicates a significant difference between males and females at a level of less than 0.05.

† indicates a significant difference between age categories within gender at a level of less than 0.05.

Figure 6. Distribution of male and female subjects according to K/H ratio at IC

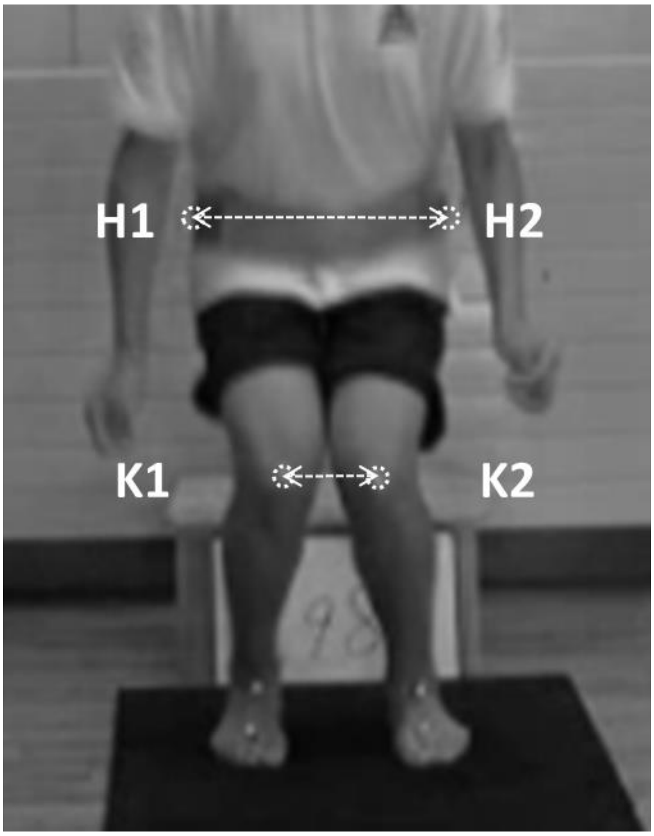
There was no significant difference between the distribution of female and male subjects in 5^{th}, 6^{th} and 7^{th} grader, but there was significant difference in 8^{th} and 9^{th} grader ($P < 0.001$, 0.001, respectively).

Figure 7. Distribution of male and female subjects according to K/H ratio at MKF

There was significant difference between the distribution of female and male subjects in all grades (P = 0.005, 0.033, < 0.001, < 0.001, < 0.001, respectively).

Figure 8. A female subject increased poor control of lower limb with advancing age.

A: K/H ratio was 0.72 in the 5^{th} grader, B: 0.42 in the 6^{th} grader, C: 0.39 in the 7^{th} grader, D: 0.38 in the 8^{th} grader, E: 0.24 in the 9^{th} grader.



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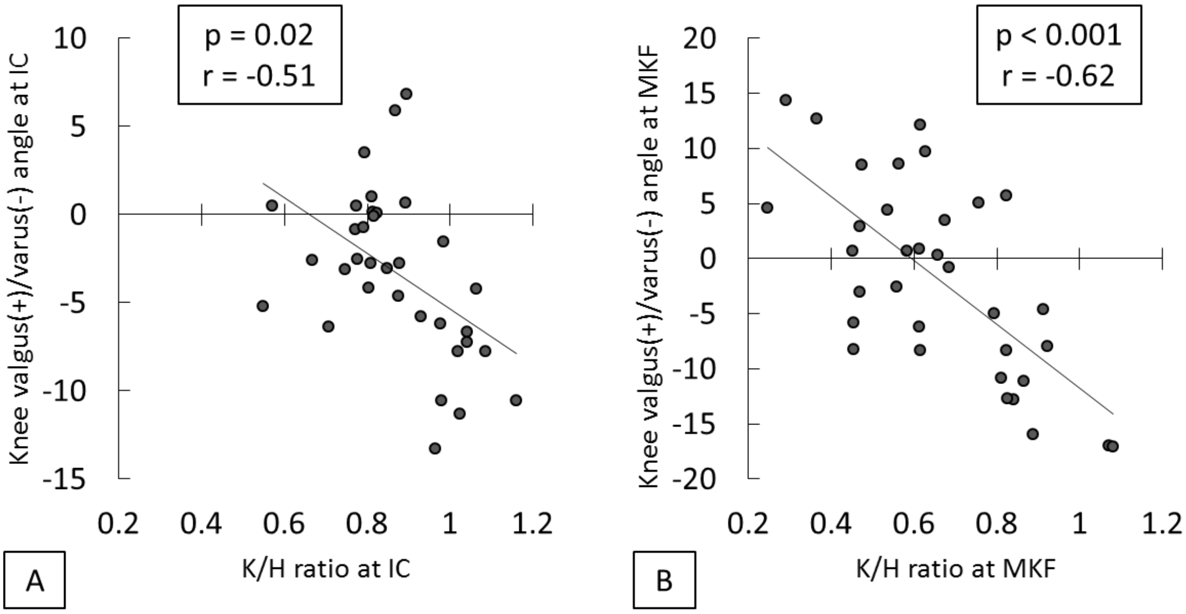

p = 0.02
r = -0.51
Knee valgus(+)/varus(-) angle at IC
K/H ratio at IC
A
p < 0.001
r = -0.62
Knee valgus(+)/varus(-) angle at MKF
K/H ratio at MKF
B

Figure 2

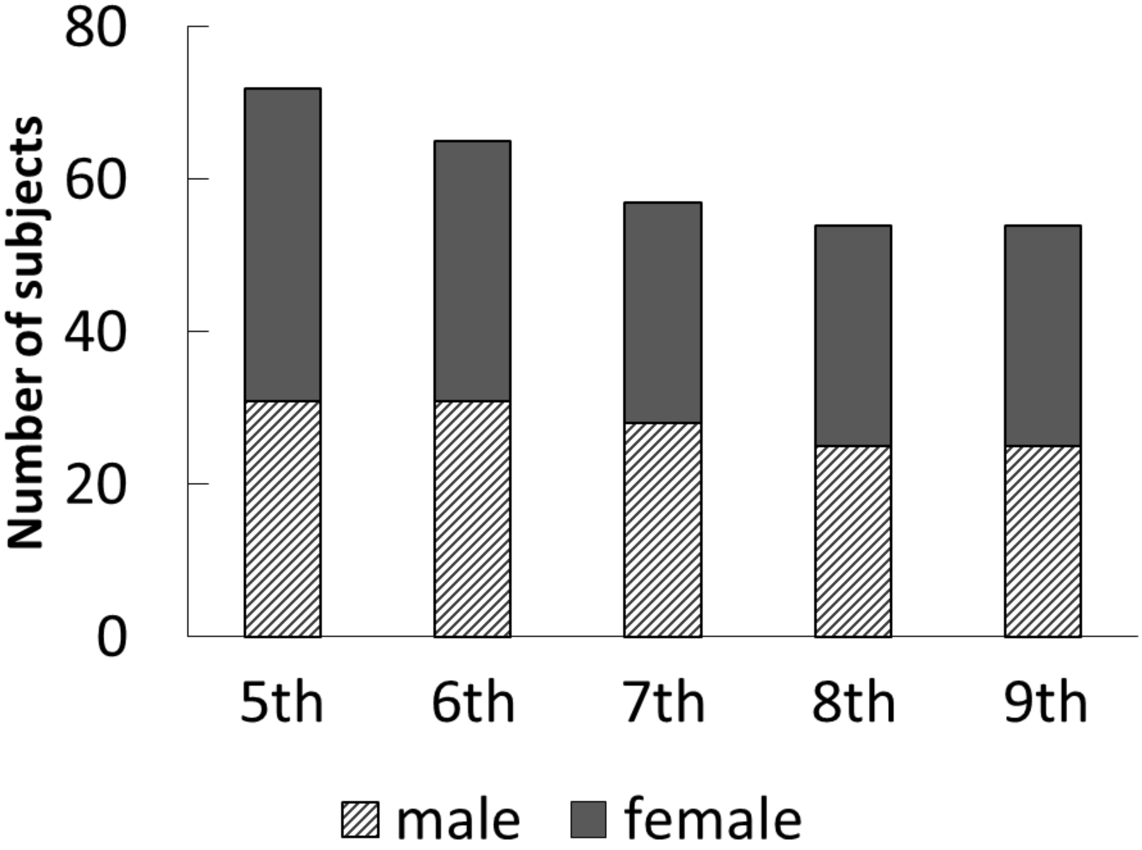
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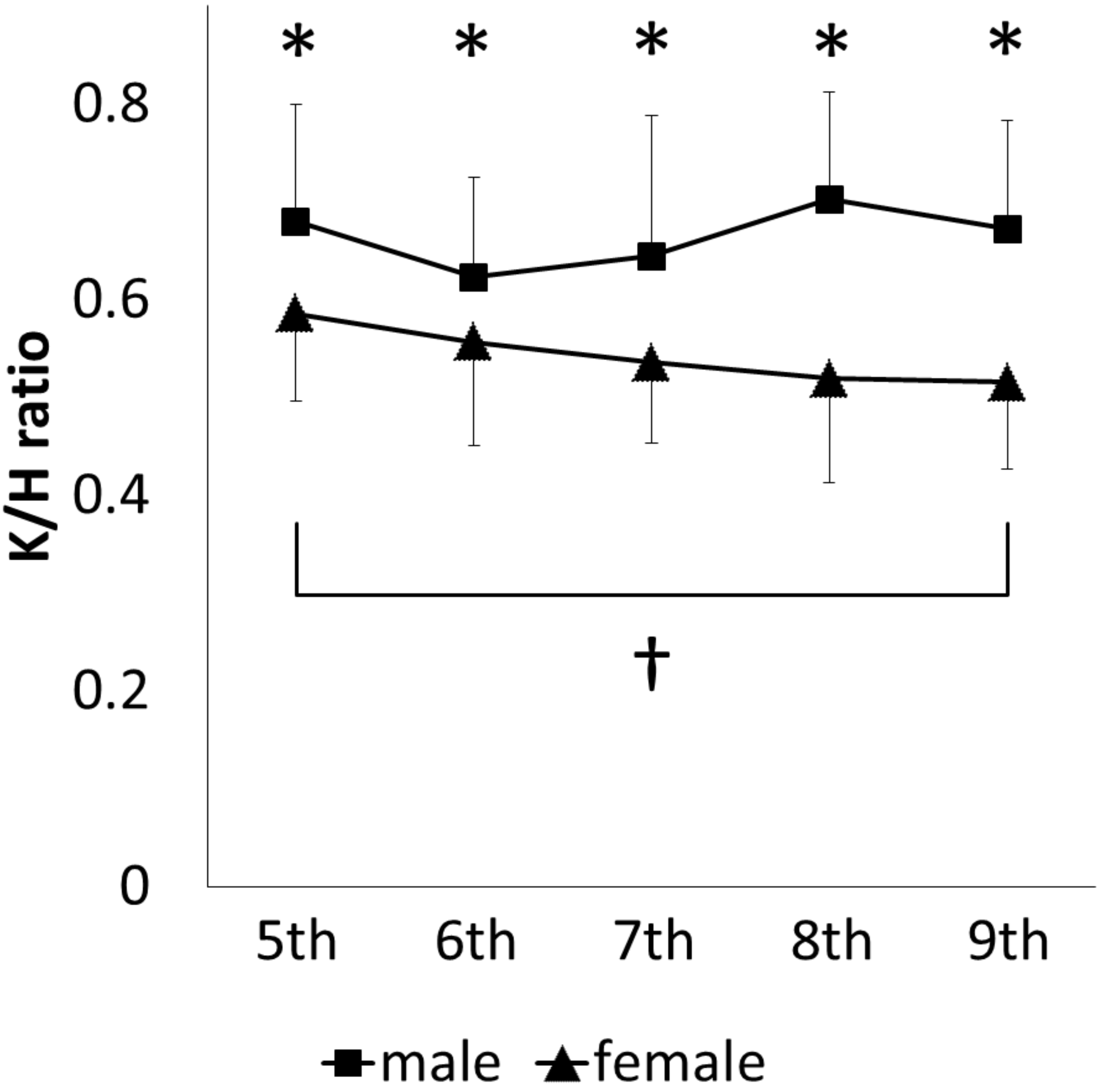
Figure 3



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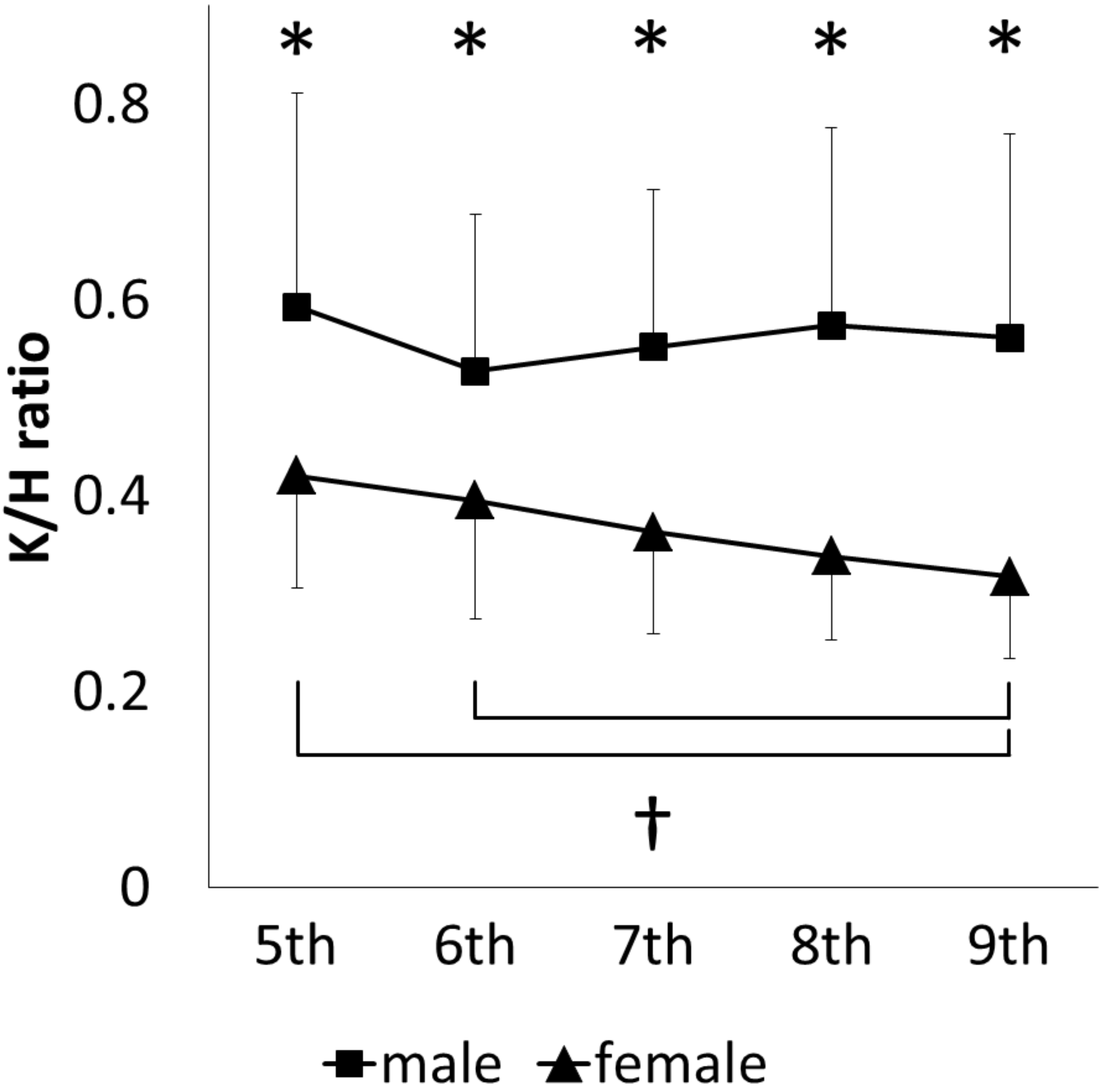
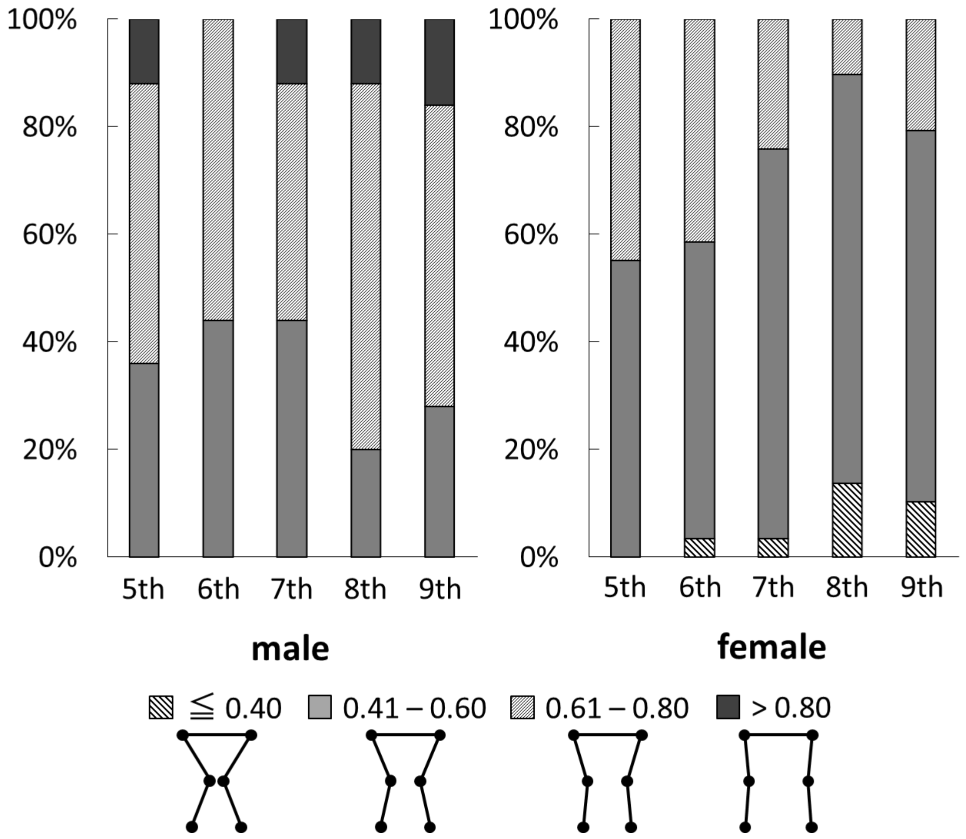


Figure 5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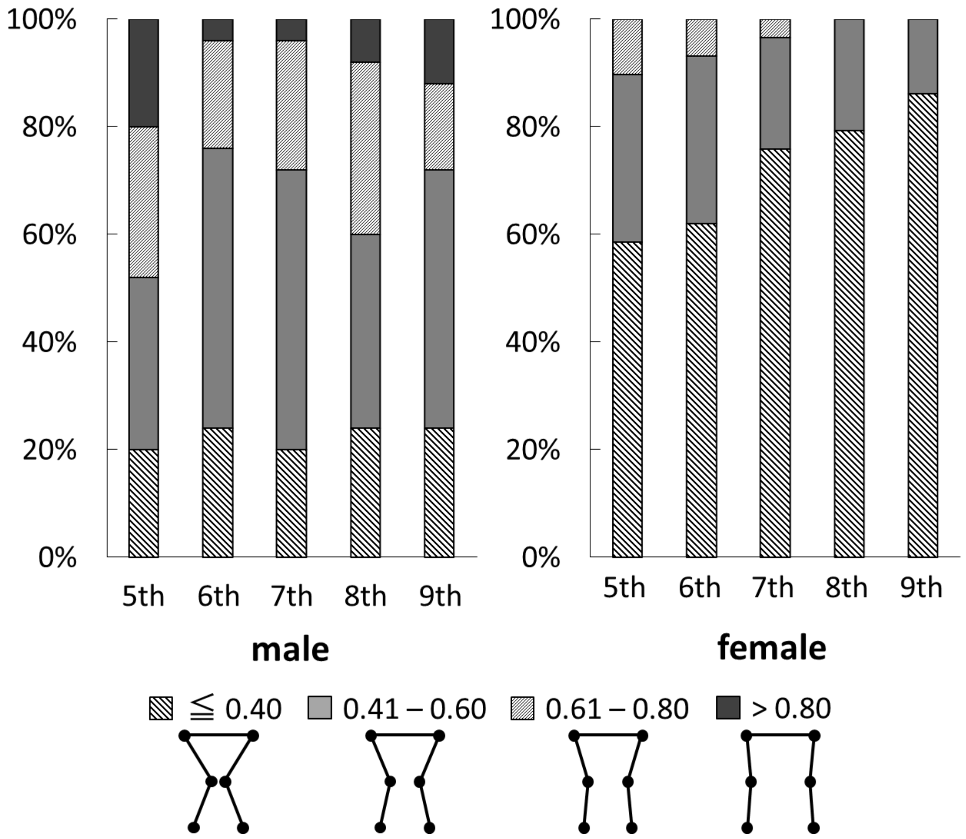
374 Figure 6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8th
9th
male
female
≦ 0.40
0.41 – 0.60
0.61 – 0.80
> 0.80

375 Figure 7

Figure 8

Table 1. Data of anthropometric measurements and percentage of subjects who had regular sports habits in each of the five grades.

Grade	age		Height (cm)		Weight (kg)		BMI (kg/m2)		Lower limb muscle mass (kg/weight)		Trunk muscle mass (kg/weight)		Sports habit (+)	
	male	female	male	female	male	female	male	female	male	female	male	female	male	female
5^{th}	10.5±0.5	10.6±0.5	145.9±6.5	144.4±7.2	41.7±12.0	37.9±7.3	19.3±4.4	18.1±2.6	0.140±0.017	0.136±0.015	0.396±0.090	0.421±0.033	80%	59%
6^{th}	11.5±0.5	11.6±0.5	152.1±7.6	150.5±6.3	46.5±12.9	43.15±7.7	19.9±4.3	19.0±2.8	0.146±0.018*	0.134±0.014	0.395±0.069	0.405±0.035	76%	62%
7^{th}	12.5±0.5	12.6±0.5	160.7±7.2*	155.0±5.2	53.5±13.7	47.9±7.6	20.5±4.2	19.9±3.1	0.142±0.017*	0.121±0.012	0.403±0.054	0.400±0.041	92%*	45%
8^{th}	13.5±0.5	13.6±0.5	165.3±6.5*	156.5±5.2	57.3±12.5*	49.0±7.1	20.8±3.7	20.0±3.0	0.144±0.016*	0.120±0.011	0.400±0.055	0.394±0.038	84%	40%
9^{th}	14.6±0.5	14.7±0.5	169.1±5.2*	157.3±5.0	62.1±13.1*	50.4±7.0	21.6±4.1	20.4±2.9	0.144±0.014*	0.123±0.011	0.387±0.056	0.377±0.036	72%*	45%

* indicates a significant difference between males and females at a level of less than 0.05.

Table 2. Investigation of factors which had influence on K/H ratio in female subjects by using multiple linear regression analysis.

	IC		MKF	
	β	*P*-value	β	*P*-value
Height	-0.014	0.962	-0.576	0.040
Weight	0.333	0.509	0.434	0.338
Lower leg muscle mass	0.249	0.384	0.431	0.098
Trunk muscle mass	-0.029	0.942	-0.158	0.660

The dependent variable was K/H ratio in the 9th grader and independent variable was the amount of change of height, body weight, lower leg muscle mass and trunk muscle mass between the first year and the last year of this study, which was adjusted by either he or she had regular sports habit. K/H ratio at MKF in the 9th grader female subjects was significantly affected by the amount of change of height during five years significantly (β = -0.576, P = 0.040).