Abstract The objectives of this study were to quantify the contribution of joint motion to dynamic knee valgus and to classify dynamic knee valgus alignment during single-leg jump landing motion in young female basketball players according to the dominant joint motion. Participants were 64 young female basketball players (age 16.1 ± 0.7 years, body mass 58.8 ± 7.8 kg, height 165.4 ± 9.3 cm, and body mass index 21.5 ± 1.8). We collected the motion data with 12 digital video cameras and calculated the knee-in angle and the toe-out angle in the frontal view to select the neutral and dynamic valgus (Knee-in & Toe-out: KI) groups. We also established three-dimensional data of hip, knee, and ankle joint motion. The results demonstrated that the ranges of hip adduction and knee valgus motion were significantly greater in the KI group than in the neutral group ($P < 0.0063$). In addition, the participants in the KI group were categorized into three different groups: hip dominant type (8 players), knee dominant type (6 players) and foot dominant type (6 players), depending on the dominant relative joint motion for dynamic knee valgus. Our current results suggest that, like other strength training programs, a lower extremity injury prevention program may need to be designed based on detailed kinematic assessment of an individual athlete.

Keywords: injury prevention, lower extremity biomechanics, anterior cruciate ligament
ior of one joint will affect that of the adjacent joint, and malalignment on either the proximal or distal joint may trigger dynamic knee valgus.

While the magnitude of the component motion of dynamic knee valgus has been investigated\(^\text{15}\), the contribution of each joint motion to dynamic knee valgus, which may alter the amount of stress imposed to knee structures\(^\text{16}\), has not been discussed enough. In addition, during our clinical observation, we frequently found individual differences in the relative position of each lower extremity in athletes who showed dynamic knee valgus; for example, one athlete seemed to show dynamic knee valgus with greater hip adduction and/or internal rotation, while in another athlete, knee valgus and foot abduction relative to the tibial segment were more apparent than hip adduction and/or internal rotation in the frontal view (Fig. 1). These previous findings and our clinical experience have made us speculate that each joint contribution to dynamic knee valgus may be different and individualized. Understanding of each contribution of joint motion in the alignment might help us identify the joint function, on which we need to focus in individual athletes for determining appropriate jump landing modifications.

Therefore, the purpose of our study was to quantify the contribution of each joint motion of the lower extremity to dynamic knee valgus alignment in athletes, and categorize the athletes depending on the most dominant joint motion in dynamic knee valgus.

Materials and Methods

Participants. Sixty-four high school female basketball players participated in this study. The mean (± standard deviation [SD]) age, body mass, height and Body Mass Index (BMI) of the participants were 16.1 ± 0.7 years, 58.8 ± 7.8 kg, 165.4 ± 9.3 cm, and 21.5 ± 1.8, respectively. The participants were free from lower extremity injuries and participated in regular practice sessions at the time of data collection. A signed informed consent form was obtained from each participant prior to participation in the study. The study protocol was approved by the Ethics Committee of the Institute of Sports Medicine and Science, Aichi, Japan.

Experimental setup and marker placement. We made all the data collection at the infield rehabilitation facility in our institution. Fig. 2 shows the experimental setup used in this study. We set 12 digital video cameras from different manufacturers (iVIS HV10, Canon Inc. Tokyo, Japan; HDR-HC3, Sony Corp. Tokyo, Japan) so that each marker would be caught with at least two cameras (60 frames/s). We had a set of 24 reflective markers (diameter 1.0 cm) and a set of 7 markers made of aluminum tape placed at bony landmarks of participants as follows: bilateral acromion, anterior superior iliac spine (ASIS), posterior superior iliac spine (PSIS), greater trochanter, medial and lateral epicondyle of femur, midpoint of patella, medial and lateral condyle of tibia, tibial tuberosity, medial and lateral malleolus, navicular, head and base of first and fifth metatarsal, and superior and inferior edges of talus (Fig. 3).

Experimental procedure. We had the participants perform a single-leg drop jump task described by Hewett et al.\(^\text{5}\) (Fig. 4). After being accustomed to the task with sufficient practice, the participants stepped off from a box (30cm in height) with their dominant leg and jumped up straight as soon as they landed on the floor. In this study, the dominant leg was defined as the leg of the jump off side when they perform a layup shoot from the preferred side. All participants chose their left leg as the dominant side. Each participant conducted five drop jumps and was allowed to take a rest between trials as needed. The participants wore black T-shirts and a pair of tight span-

![Fig. 1 Examples of dynamic knee valgus observed in clinical situation: (a) greater hip adduction and internal rotation, (b) greater knee valgus alignment and (c) greater tibial external rotation.](image-url)
Data reduction and analysis. The video images of the single-leg drop jump task were transferred to a personal computer and the video images were superimposed on the computer display for kinematic analysis. We normalized all the kinematic data from the point of foot contact with the floor to that of the foot off the floor into a 100% scale.

To differentiate the athletes with high risk biomechanics, we first calculated knee-in angle (KIA) and toe-out angle (TOA) of each participant from a frontal view using two-dimensional motion analysis software (Dartfish ver. 4.0, Tokyo, Japan). KIA was defined as an angle formed with the line between ASIS and the midpoint of the patella marker, and the midline of the patella marker and the midline of ankle joint in the frontal plane; while TOA was defined as an angle between the two lines formed with the midline of the patella marker and midline of the ankle joint, and the midline of the ankle joint and the third toe in the frontal plane. Both the angles were calculated when the knee flexion angle reached its peak in landing. We divided the participants into two groups based on the summed value of KIA and TOA: the knee-in (KI) group and the neutral group. Concerning the score with KIA added to TOA, 20 higher-ranking participants were in the KI group, and 20 lower-ranking participants were in the neutral group (Fig. 5).

We also obtained three-dimensional coordinates of each marker in the working space. The markers placed on a landmark were automatically tracked with the use of a
two- to three-dimensional motion analyzer (Frame-DIAS II, DKH Inc, Tokyo, Japan). We calculated the joint angle of hip adduction, hip rotation, knee flexion/extension, knee valgus/varus, tibial rotation, ankle dorsiflexion/plantarflexion, and foot abduction/adduction within a time frame from foot contact with the floor to toe off the floor in the drop jump motion. The joint angles were defined as relative angles between two adjacent segments adopted from Miyashita (Appendix 1). We then normalized the obtained joint angle curve into a 100% scale.

Fig. 4  Single-leg drop jump task: (a) starting position, (b) single-leg landing and (c) single leg jump motion.

Fig. 5  Definition of knee-in (KI) and toe-out (TO) angles: KI angle is an angle formed with the line between ASIS and the midpoint of the patella marker, and the line between the midpoint of the patella marker and the middle point of ankle joint in frontal plane. TO angle is an angle between the two lines formed with the midpoint of patella marker and middle point of ankle joint, and the middle point of ankle joint and the third toe in frontal plane. The white arrow shows the KI angle, and black arrow shows the TO angle.
to facilitate comparisons among the participants. The cardinal angles of each joint motion were set as 0º when the participants stood in an upright position, and hip adduction, hip internal rotation, knee valgus, tibial external rotation, and foot abduction angles were represented as positive values in this study.

We first summed the hip adduction, knee valgus, and foot abduction angles at peak knee flexion in each participant of the KI group and assumed the summed value as the range of motion of dynamic knee valgus collapse. We then categorized the KI group into three subgroups according to the most dominant joint motion in the range of motion: hip dominant type, knee dominant type, and foot dominant type. For instance, a participant who demonstrated a higher ratio of hip adduction, in the range of motion of dynamic knee valgus, than each ratio of knee valgus and foot abduction in the same range of motion was categorized as hip dominant type (Fig. 6).

Statistical means and SDs for all measured variables were calculated for each group. Mann-Whitney U tests were used to compare differences in each joint angle at peak knee flexion during jump landing between the groups. In addition, a Bonferroni correction method was used for performing multiple comparisons18). Therefore, the alpha level was considered significant at 0.0063 in this study.

Results
Table 1 shows each joint angle motion for the KI and neutral groups in the single-leg drop jump task. The hip adduction, hip internal rotation, and knee valgus angles were significantly greater in the KI group than the neutral group.

Eight participants were categorized as hip dominant type, six participants in the KI group were categorized as knee dominant type, and six participants were categorized as foot dominant type (Fig. 7).

### Table 1

<table>
<thead>
<tr>
<th>Joint motion</th>
<th>Joint angle</th>
<th>Ratio to the range of motion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hip adduction</td>
<td>10.9º</td>
<td>50.8%</td>
</tr>
<tr>
<td>Knee valgus</td>
<td>5.8º</td>
<td>26.2%</td>
</tr>
<tr>
<td>Foot abduction</td>
<td>4.9º</td>
<td>23.0%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>21.4º</strong></td>
<td><strong>100.0%</strong></td>
</tr>
</tbody>
</table>

**Three-dimensional analysis**

**Categorization**

**Hip dominant type**

Fig. 6 A typical kinematic presentation of a hip-dominant type basketball player in a single-leg drop jump task at peak knee flexion and the flow of the categorization: Because the ratio of hip adduction angle to the range of motion of the dynamic knee valgus is the greatest, we categorized the particular participant as the “hip dominant” type.

Table 1. Mean values (± standard deviation) of the range of joint motion of lower extremity in the drop jump for the Knee-in & Toe-out and the neutral groups.

<table>
<thead>
<tr>
<th></th>
<th>KI group (N=20)</th>
<th>Neutral group (N=20)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hip adduction</td>
<td>10.3 ± 5.0º</td>
<td>4.6 ± 5.8º</td>
</tr>
<tr>
<td>Hip internal rotation</td>
<td>0.4 ± 5.0º</td>
<td>-3.0 ± 5.7º</td>
</tr>
<tr>
<td>Knee valgus</td>
<td>8.3 ± 4.9º</td>
<td>0.0 ± 3.6º</td>
</tr>
<tr>
<td>Tibial external rotation</td>
<td>-0.9 ± 4.9º</td>
<td>-1.9 ± 5.3º</td>
</tr>
<tr>
<td>Foot abduction</td>
<td>6.7 ± 7.3º</td>
<td>5.0 ± 4.8º</td>
</tr>
<tr>
<td>Hip flexion</td>
<td>50.2 ± 11.5º</td>
<td>47.8 ± 12.0º</td>
</tr>
<tr>
<td>Knee flexion</td>
<td>63.5 ± 7.6º</td>
<td>60.2 ± 9.3º</td>
</tr>
<tr>
<td>Ankle dorsiflexion</td>
<td>29.3 ± 6.5º</td>
<td>27.1 ± 5.1º</td>
</tr>
</tbody>
</table>

*P < 0.0063
Discussion

In order to improve knee joint biomechanics during athletic maneuvers, we need to understand in detail each joint movement of the dynamic alignment so that we can provide a more effective prevention program to athletes. Knee kinematics in the frontal plane is greatly affected by hip, knee and foot joint movements, yet there is little information provided about which joint movements are the most dominant in this specific dynamic alignment. Therefore, we designed the study to quantify the contribution of each joint of the lower extremity to the dynamic knee valgus and to analyze the kinematic linkage in jump landing.

In our study, the ranges of hip adduction, hip internal rotation and knee valgus were significantly different between the KI group and neutral knee group. These results suggest that we need to pay closer attention to the function of the hip joint in athletes who exhibit dynamic knee valgus. Previous studies have also stated the importance of the hip position, stiffness, and hip joint abduction strength in dynamic alignment during athletic maneuvers\(^\text{19,20}\). However, more recent research demonstrated no relationship between hip strength and the knee valgus angle\(^\text{21}\). Moreover, Geiser et al.\(^\text{22}\) reported that neuromuscular fatigue of the hip abductor muscle increased the knee valgus angle, but that the change may not be clinically significant. Although we might all agree that the hip joint needs to be well controlled to maintain low-risk knee alignment during jump landing, the effect of hip strengthening on ACL injury prevention still requires further investigation.

A notable finding in this study was that the joint motion, which occurred dominantly in the dynamic knee valgus, may vary from individual to individual among athletes in the high-risk group. In addition, results showed that one-third of the athletes with dynamic knee valgus showed that hip motion was the most dominant joint motion in dynamic knee valgus; while the other two-thirds showed that the most dominant joint motion was either knee valgus or foot abduction. It seems obvious that there is individuality in the contribution of each joint motion to dynamic knee valgus.

Our results may give us some insights into the design of an appropriate ACL injury prevention program. It may require a specific approach to correct the lower extremity biomechanics in the drop jump according to the dominant joint motion. For example, in order to modify dynamic malalignment, athletes whose hip joint motion occurs dominantly might respond better to a hip strengthening program. On the other hand, the athlete with foot dominant pattern might need to pay more attention to the foot function rather than hip. In addition, in the augmented feedback approach, the priority during instruction might be a great factor for the successful modification of the assigned movement. Identifying the most dominant joint motion in dynamic knee valgus may allow us to give more effective feedback to athletes. Therefore, accurate analysis of joint motion in the athletic movement is required to develop an effective ACL injury prevention program.

The limitation of the study was that we did not collect kinetic data. Therefore, we are not able to discuss whether the stress applied to the knee joint varies from one type of joint dominance pattern to another. In addition, the interpretation may be applicable only to young female athletes. Also, it has been reported that there is a gender difference in knee joint biomechanics and responses to the ACL prevention program. To deepen our understanding of ACL injury prevention, we need to further investigate the dynamic alignment related to injury occurrence in jump landing task.

Conclusion

The hip adduction and knee valgus angles may be different between the athletes who show the dynamic knee

<table>
<thead>
<tr>
<th>Joint Type</th>
<th>Hip Adduction</th>
<th>Knee Valgus</th>
<th>Foot Abduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hip adduction type</td>
<td>56.2±12.4%</td>
<td>29.3±10.3%</td>
<td>32.6±6.7%</td>
</tr>
<tr>
<td>Knee valgus type</td>
<td>25.3±9.2%</td>
<td>48.4±6.4%</td>
<td>28.3±6.7%</td>
</tr>
<tr>
<td>Foot abduction type</td>
<td>18.5±12.2%</td>
<td>22.3±11.8%</td>
<td>28.3±8.7%</td>
</tr>
</tbody>
</table>

Fig. 7 Types of relative contribution of each joint angle consisting of dynamic knee valgus at peak knee flexion.
valgus and neutral alignment during the single-leg drop jump; but the hip, internal rotation, and foot abduction angle don’t differ. In addition, the contribution of the hip, knee, and foot kinematics to dynamic knee valgus alignment varies according to the female basketball players.

References


Appendix

Hip adduction

Points (x1, y1, z1), (x2, y2, z2) and (x3, y3, z3) represent marker positions of right anterior superior iliac spine, left anterior superior iliac spine and midpoint of patella, respectively, in the 3D coordinate system. Inner product A (X1, Y1, Z1) was projected perpendicularly from an established triangle between right anterior iliac spine and left anterior superior iliac spine. Vector A (X1, Y1, Z1) was calculated by the equations below:

\[ X_1 = x_2 - x_1 \]
\[ Y_1 = y_2 - y_1 \]
\[ Z_1 = z_2 - z_1 \]

Inner product B (X2, Y2, Z2) was calculated with left anterior superior iliac spine and midpoint of patella markers by the equations below:

\[ X_2 = x_3 - x_2 \]
\[ Y_2 = y_3 - y_2 \]
\[ Z_2 = z_3 - z_2 \]

Hip adduction was defined as the inner product between the two vectors:

\[ \cos \theta = \frac{(X1 \cdot X2 + Y1 \cdot Y2 + Z1 \cdot Z2)}{\sqrt{(X1 \cdot X1 + Y1 \cdot Y1 + Z1 \cdot Z1)} \cdot \sqrt{(X2 \cdot X2 + Y2 \cdot Y2 + Z2 \cdot Z2)}} \]

The angle between two vectors (A, B) was obtained by calculating \( \cos \theta \), which was defined as hip adduction angle in this study.
Knee flexion
The angle between two vectors (A, B) was obtained by calculating \(\cos \theta\), which was defined as knee flexion angle in this study. Inner product A (X1, Y1, Z1) was projected perpendicularly from an established triangle between greater trochanter and lateral epicondyle of femur. Inner product B (X2, Y2, Z2) was calculated with lateral epicondyle of femur and lateral condyle of fibula.

Hip internal rotation
Points (x1, y1, z1), (x2, y2, z2), (x3, y3, z3), and (x4, y4, z4) represent marker positions of left anterior superior iliac spine, greater trochanter, lateral epicondyle of femur and medial epicondyle of femur, respectively, in the 3D coordinate system. Inner product A (X1, Y1, Z1) was projected perpendicularly from an established triangle between left anterior superior iliac spine, greater trochanter and lateral epicondyle of femur. Vector A (X1, Y1, Z1) was calculated by the equations below:

\[
X1 = (y2-y1)*(z3-z1)-(y3-y1)*(z2-z1) \\
Y1 = (z2-z1)*(x3-x1)-(z3-z1)*(x2-x1) \\
Z1 = (x2-x1)*(y3-y1)-(x3-x1)*(y2-y1)
\]

Inner product B (X2, Y2, Z2) was calculated with lateral epicondyle of femur and medial epicondyle of fibula by the equations below:

\[
X2 = (y2-y1)*(z4-z1)-(y4-y1)*(z2-z1) \\
Y2 = (z2-z1)*(x4-x1)-(z4-z1)*(x2-x1) \\
Z2 = (x2-x1)*(y4-y1)-(x4-x1)*(y2-y1)
\]

Hip internal rotation was defined as the inner product between the two vectors:

\[
\cos \theta = \frac{X1*Y2+Y1*Z2+Z1*X2}{\sqrt{(X1^2+Y1^2+Z1^2)(X2^2+Y2^2+Z2^2)}}
\]

The angle between two vectors (A, B) was obtained by calculating \(\cos \theta\), which was defined as hip internal rotation angle in this study.

Knee valgus
The angle between two vectors (A, B) was obtained by calculating \(\cos \theta\), which was defined as knee valgus angle in this study. Inner product A (X1, Y1, Z1) was projected perpendicularly from an established triangle between left anterior superior iliac spine, midpoint of patella and midpoint between medial epicondyle of femur and lateral epicondyle of femur. Inner product B (X2, Y2, Z2) was calculated with midpoint of patella, midpoint between medial epicondyle of femur and lateral epicondyle of fibula and midpoint between medial condyle of tibia and lateral condyle of fibula.

Tibial external rotation
The angle between two vectors (A, B) was obtained by calculating \(\cos \theta\), which was defined as tibial external rotation angle in this study. Inner product A (X1, Y1, Z1) was projected perpendicularly from an established triangle between medial epicondyle of femur, lateral epicondyle of femur and lateral condyle of fibula. Inner product B (X2, Y2, Z2) was calculated with midpoint of patella, midpoint between medial epicondyle of femur and lateral epicondyle of femur and midpoint between medial condyle of tibia and lateral condyle of fibula.

Foot Abduction
The angle between two vectors (A, B) was obtained by calculating \(\cos \theta\), which was defined as foot abduction angle in this study. Inner product A (X1, Y1, Z1) was projected perpendicularly from an established triangle between inferior edge of talus, midpoint between medial condyle of tibia and lateral condyle of fibula and midpoint between toe and inferior edge of talus. Inner product B (X2, Y2, Z2) was calculated with midpoint of patella, midpoint between medial condyle of tibia and lateral condyle of fibula, midpoint between toe and inferior edge of talus and third finger.

Hip flexion
The angle between two vectors (A, B) was obtained by calculating \(\cos \theta\), which was defined as hip flexion angle in this study. Inner product A (X1, Y1, Z1) was projected perpendicularly from an established triangle between left anterior superior iliac spine, right anterior superior iliac spine and greater trochanter. Inner product B (X2, Y2, Z2) was calculated with midpoint of patella, midpoint of right anterior superior iliac spine, greater trochanter and lateral epicondyle of femur.

Ankle dorsiflexion
The angle between two vectors (A, B) was obtained by calculating \(\cos \theta\), which was defined as ankle dorsiflexion angle in this study. Inner product A (X1, Y1, Z1) was projected perpendicularly from an established triangle between tibial tuberosity, medial condyle of tibia and lateral condyle of fibula. Inner product B (X2, Y2, Z2) was calculated with midpoint of patella, midpoint between medial epicondyle of tibia, lateral condyle of fibula and third finger.