INTRODUCTION

In the long jump, jumper runs toward the takeoff board and jumps for the distance with one leg. The velocity of the center of gravity (CG) of the jumper at the instant of the takeoff is the most contributing factor to the jumping distance. Horizontal velocity of CG is developed in the run-up and the vertical velocity is acquired by the jumper with the minimum loss of the horizontal velocity during the takeoff phase. Since the takeoff leg exerts large force to the ground and supports the jumper’s body during the takeoff, the flexion and extension of the takeoff leg joints play an important role to convert the horizontal velocity into the vertical during the takeoff phase. It is useful to investigate the contribution of the joint angular velocity of the takeoff leg to the velocity of CG during the takeoff phase for understanding the mechanism of the long jump takeoff and improving the performance. The purpose of this study was to determine kinematic contribution of the takeoff leg joints to the velocity of CG during the takeoff of the long jump.

METHODS

Data collection

Eleven Japanese male long jumpers participated in this study as subjects (four elite jumpers with the best performance of 7.83 to 8.15 m and seven college level jumpers of 6.45 to 7.41 m). The takeoff motion of the subjects with full run-up was videotaped with a high speed VTR camera (250 Hz). The trial analysed was the best jump of each jumper. Two dimensional coordinates of the endpoints of the body segments were obtained by digitizing VTR images. The segmental inertia parameters used were after Ae et al. (1991) for the Japanese athlete. The coordinates data were smoothed using a Butterworth digital filter (5-10Hz). The data were normalized by the time of the takeoff phase for the subjects and averaged. The takeoff phase was divided into two phases at the instant of the maximum knee flexion (MKF), which was 47 % of the takeoff phase.

Kinematic model of CG velocity

It can be assumed that the velocity of CG during the takeoff phase is the sum of the tangential and radial velocities of the segments of the takeoff leg and the torso (CG-hip). First of all, the CG velocity can be considered as the sum of the relative velocities as follows:

\[ \mathbf{v}_{CG} = \mathbf{v}_{CG/hip} + \mathbf{v}_{hip/knee} + \mathbf{v}_{knee/ankle} + \mathbf{v}_{ankle/toe} + \mathbf{v}_{toe}, \]

where \( \mathbf{v}_{ij} \) is the linear velocity of the endpoint i relative to the endpoint j of the body segment, \( \mathbf{v}_{i} \) is linear velocity of the endpoint i of the body segment. In equation (1), the relative linear velocity \( \mathbf{v}_{ij} \) can be expressed as follows:

\[ \mathbf{v}_{ij} = \mathbf{v}_{r}(k) + \mathbf{e}_{k} \times \mathbf{r}_{ij}, \]

where \( \mathbf{e}_{k} \) represents cross product, \( \mathbf{v}_{r}(k) \) is the radial velocity of segment k, \( \mathbf{e}_{k} \) is angular velocity of segment k, \( \mathbf{r}_{ij} \) is position vector between the endpoint i and j. Segment angular velocity \( \mathbf{e}_{k} \) can be expressed as the sum of the relative angular velocities, which is similar to equation (1), and position vector \( \mathbf{r}_{ij} \) can be represented by the sum of two vectors (\( \mathbf{r}_{ij} = \mathbf{r}_{CG} - \mathbf{r}_{CG(i)} \)). Finally, substituting equation (2) for equation (1) and rearranging equation (1) gives the following equation of the velocity of CG:

\[ \mathbf{v}_{CG} = (\mathbf{e}_{CG/hip} \times \mathbf{r}_{CG/hip}) + (\mathbf{e}_{hip/knee} \times \mathbf{r}_{CG/knee}) + (\mathbf{e}_{knee/ankle} \times \mathbf{r}_{CG/ankle}) + (\mathbf{e}_{ankle/toe} \times \mathbf{r}_{CG/toe}) + \mathbf{v}_{toe} + \mathbf{v}_{r}(CG-hip) + \mathbf{v}_{r}(knee) + \mathbf{v}_{r}(ankle) + \mathbf{v}_{r}(foot). \]

RESULTS AND DISCUSSION

The averaged takeoff time of the elite jumpers (EJ) and college level jumpers (CLJ) were 0.108±0.012 s and 0.123±0.009 s, respectively. Although the time in the first half of the takeoff phase (0.055 s) was same in EJ and CLJ, EJ took shorter time in the second half than CLJ (EJ: 0.053±0.006 s, CLJ: 0.068±0.005 s). The average horizontal velocity of CG in the takeoff phase was 8.29±0.28 m/s (EJ: 8.81±0.28 m/s, CLJ: 7.99±0.33 m/s). The horizontal velocity of CG rapidly decreased immediately after the touchdown (EJ: -1.14±0.21 m/s, CLJ: -1.16±0.32 m/s), while the vertical velocity of CG began to increase from the touchdown (EJ: 3.01±0.18 m/s, CLJ: 3.32±0.35 m/s).

Figure 1 shows changes in angular velocities and horizontal and vertical components of position vectors, which were included in the equation (3), in the takeoff phase. Positive (negative) angular velocity of the hip and ankle indicate extension (flexion) and the knee was flexed (extended) and the foot was rotated forward (backward). The hip, knee and ankle joints of the takeoff leg flexed in the first half of the takeoff phase and extended until the toeoff. The foot rotated forward about the heel in the initial phase and about the toe in the rest of the takeoff phase.

Negative horizontal component of \( \mathbf{r}_{CG(i)} \) indicates that the jumper placed the endpoint i of the body segment forward relative to CG. Although the horizontal component of all position vectors changed from the negative to the positive during the takeoff phase, the most remarkable changes were
The vertical components of $\mathbf{r}_{\text{CG} \text{hip}}$ and $\mathbf{r}_{\text{CG} \text{ankle}}$ were constant in the first half of the takeoff phase, and then slightly increased until the toeoff. Although the vertical components of $\mathbf{r}_{\text{CG} \text{ankle}}$ and $\mathbf{r}_{\text{CG} \text{toe}}$ increased during the takeoff phase, $\mathbf{r}_{\text{CG} \text{toe}}$ increased more than the others.

Figure 2 shows the horizontal and vertical velocity produced by the angular velocity of the hip, knee, ankle joint and foot, which were represented by the first, second, third and fourth terms of equation (3). In the first half of the takeoff phase, the hip increased no horizontal velocity of CG, while the ankle and foot largely increased the positive horizontal and vertical velocity of CG. To the contrary, the knee decreased the horizontal and vertical velocity of CG in the first half. Since there were no big differences in the maximum angular velocities of three joints of the takeoff leg, the difference in velocity components among the joints will be caused by the position vectors between CG and the joint of the takeoff leg.

In the second half of the takeoff phase, the hip extension and ankle plantar flexion decreased the horizontal velocity of CG and increased the vertical velocity of CG. Although the extension of the knee and the forward rotation of the foot increased the horizontal velocity of CG, they decreased the vertical velocity of CG in the second half of the takeoff phase.

It will be summarized that the knee flexion of the takeoff leg decreases the horizontal and vertical velocity of CG while the ankle dorsiflexion increases the horizontal and vertical velocity of CG in the first half of the takeoff phase. In the second half, the faster the jumper extends the hip and ankle, the more the vertical velocity of CG increases, but the horizontal velocity of CG decreases. To the contrary, the faster extension of the knee decreases the vertical velocity of CG and increases the horizontal velocity of CG. These results suggest that the jumper should flex the ankle and rotate the foot forward as fast as possible and keep the knee more extended in the first half of the takeoff phase. It is worth to note that the jumper should use the appropriate takeoff motion in the second half of the takeoff phase because the effects of angular velocity of the hip, knee, ankle and foot on the horizontal and vertical velocity of CG inconsistent.

In the horizontal direction, the effect of the joint angular velocity of the hip and knee was smaller than that of the ankle and foot. Although the magnitude of the joint angular velocity of the hip, knee and ankle were almost equal, the vertical component of the position vector was large in descending order of the $\mathbf{r}_{\text{CG} \text{toe}}$, $\mathbf{r}_{\text{CG} \text{ankle}}$, $\mathbf{r}_{\text{CG} \text{knee}}$ and $\mathbf{r}_{\text{CG} \text{hip}}$. Therefore the effect of the angular velocities on the horizontal velocity of CG was largely dependent on the vertical component of the position vector. Since the vertical component of the position vector was positive during the takeoff phase, the effect of the angular velocities on the horizontal velocity of CG was influenced by both the angular velocity of joint and the vertical component of position vector.

In the vertical direction, the effect of the angular velocity of the hip was almost equal to zero because the horizontal component of the position vector $\mathbf{r}_{\text{CG} \text{hip}}$ was almost equal to zero during the takeoff phase. Since the jumper placed the takeoff leg forward relative to CG at the instant of the touchdown and pivoted over the takeoff foot, the horizontal
component of all position vectors changed from the negative to the positive during the takeoff phase. Therefore the effect of the angular velocity on the vertical velocity of CG was opposite to that of the horizontal velocity of CG in the second half of the takeoff phase.

The effect of the position vector on the velocity components, which described above, implies that the position of the body segments relative to CG will partially determine the effect of the angular velocity of the joints on the velocity of CG.

Figure 2 shows the effect of the angular velocity of the hip, knee, ankle joint and foot on the horizontal and vertical velocity of CG for EJ and CLJ. In the first half, EJ increased the horizontal and vertical velocity of CG by the ankle dorsiflexion and decreased the horizontal velocity of CG by the knee flexion. These velocities were larger than CLJ. In the second half, the effect of the angular velocity of the ankle and foot on the horizontal and vertical velocity of CG in EJ changed more rapidly than that of CLJ.

In the first half, jumper pivots over the takeoff foot by the horizontal velocity of CG developed in the run-up. Since the shank rotated forward faster than the thigh and foot, the ankle was dorsiflexed and the knee was flexed in this phase. The effect of the joint angular velocity of the ankle on the horizontal and vertical velocities of CG in EJ was larger than CLJ in the first half. The effect of the joint angular velocity of the ankle indicated that the jumper should rotate the shank as fast as possible in the first half of the takeoff phase.

The knee flexion decreased the horizontal and vertical velocities of CG in the first half of the takeoff phase. However, since the knee flexion plays an important role to absorb the impact force immediately after the touchdown, the jumper have to change his knee motion from flexion to extension quickly. In the first half of the takeoff phase, the amount of the knee flexion of EJ and CLJ was almost equal. The knee angle of the takeoff leg of EJ was larger than that of CLJ through the takeoff phase, because EJ extended the knee joint more than CLJ at the instant of the takeoff foot touchdown. The relationship between the knee angle and the leg extension force exerted by isometric condition in standing position indicates that the larger knee angle of the leg, the larger the force exerted. These results about the knee joint may explain that the jumper should place the takeoff leg with the extended knee to avoid too much knee flexion after the touchdown.

The comparisons of EJ and CLJ, which described above, suggest that the jumper should place the takeoff leg in extended joint at the touchdown to avoid too much knee flexion after the touchdown and then rotate the takeoff leg (thigh and shank) forward over the takeoff foot to increase the joint angular velocity of the ankle (dorsiflexion) and to control the knee flexion in the first half of the takeoff phase.

REFERENCES

Figure 3: The effect of the angular velocity of the hip, knee, ankle joint and foot on the horizontal and vertical velocities of CG for EJ and CLJ. The data were normalized by the takeoff time for EJ (0.108±0.012 s) and CLJ (0.123±0.009 s) and averaged.