Joint Torque and Power of the Takeoff Leg in the Long Jump

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The purposes of this study were to determine the joint torque (JT) and power (JP) of the takeoff leg and the relationship of the angular impulse and work done by the JTs to center of gravity (CG) velocity change during the long jump takeoff, and to identify the functions of the takeoff leg joints. The takeoff motion of eleven Japanese male long jumpers was videotaped (250 Hz) from the right side of the runway. Ground reaction forces were also recorded (1 kHz). The forward-backward component of the force platform was set parallel to the runway. The plantar-flexors and knee extensors exerted great negative JP during the first phase and positive JP during the second phase, and, thus, they functioned as great mechanical energy absorbers in the first phase and as mechanical energy generators in the second phase. The hip joint exerted extension torque immediately after touchdown and supported the body against the impact force and contributed to an increase in vertical CG velocity by pivoting the body over the takeoff foot during the first phase. There were no relationships of the magnitude of the peak joint torques of the takeoff leg and angular impulse and work of the takeoff leg joint torques to horizontal CG velocity at touchdown or jumping distance.

Keywords: joint torque, joint power, long jump, takeoff leg, takeoff technique

1. Introduction

The velocity of the center of gravity (CG) of a long jumper at takeoff is the most important determiner of jump distance. The horizontal velocity of the CG increases during the approach phase, and the vertical velocity of the CG is obtained during the takeoff phase of the jump. Although many investigations have suggested a significant relationship between approach velocity and jumping distance (Luhtanen and Komi, 1979; Hay, 1986; Hay, et al., 1986; Lees, et al., 1994), the initial vertical CG velocity was not significantly correlated with the jumping distance (Hay, et al., 1986) and was correlated less with the jumping distance than the initial horizontal velocity of the CG (Luhtanen and Komi, 1979). The strength of the relationship between approach velocity and jumping distance decreased with the increase in level of performance (qt.d. in Hay, 1986), which may imply that the takeoff technique becomes more important than the approach velocity at higher levels of performance.

A long jumper must transfer horizontal velocity obtained during the approach phase into vertical velocity during the takeoff phase to increase jumping distance (Rogers, 2004). There are three technical factors that increase the vertical velocity of the CG during the takeoff phase: a pivoting of the body over the takeoff foot, a swinging of the free limbs, and an extension of the body, particularly the takeoff leg joints (Ae, 1989). All forces generated by these factors must be effectively transmitted to the ground...
through the takeoff leg to obtain substantial vertical velocity of the CG. Therefore, the takeoff leg of the long jumper plays an important role in converting horizontal velocity into vertical velocity. It is essential to understand the function of the takeoff leg joints by investigating how the takeoff leg joints exert joint torque and power and how these are related to change in CG velocity during the takeoff phase.

Although a large volume of detailed studies on joint kinetics has been carried out on sprint running, and suggested proposals have been offered for sprint technique training methods, methods to increase specific strength and methods for the prevention of leg injury (Ae, et al., 1986; Chapman and Caldwell, 1983; Mann and Sprague, 1980; Simonsen, et al., 1985; Winter, 1983), there is only limited information on joint kinetics for the takeoff leg joints in the long jump. Very few studies have investigated the joint torque and joint power of the takeoff leg during the long jump takeoff (Ae, et al., 1989; Fuchimoto, et al., 1994; Stefanyshyn, et al., 1998). Ae, et al., (1989) investigated the joint torque and joint power of the takeoff leg for ordinary-level long jumpers (jumping distance, 6.75 ± 0.10 m). They reported that the knee extensors exerted the greatest negative joint power and contributed to supporting the body during the first half of the takeoff phase, and that the hip flexors exerted negative joint power to restrain hyperextension of the hip joint during the second half. Although the plantar-flexors did not exert as great a joint torque as the knee extensors, they generated considerable energy during the second half of the takeoff phase. Fuchimoto, et al., (1994) compared long jumps with the long and short approach distances and jumping distances of 6.65 ± 0.24 m and 6.06 ± 0.22 m. The horizontal velocity of the long approach run (9.07 ± 0.26 m/s) was significantly faster than that of the short approach run (8.03 ± 0.27 m/s), while no significant differences between the two approach runs were noted in the joint torque and joint power patterns of the takeoff leg. Stefanyshyn, et al., (1998) demonstrated that joint torque and joint power patterns of the takeoff leg for the running long jump were similar to the patterns of the running high jump. Hip extensor torque during the stance phase for the running long jumpers was greater than that of the high jumpers. Unfortunately, long-jump data were collected under laboratory conditions using a foam landing pit, and long jumps were performed at an approach velocity ranging from 6.1 to 6.6 m/s, which is slower than that of male high jumpers (7.52 ± 0.25 m/s, Liboshi, et al., 1994).

These three studies are limited in that they used only ordinary-level jumpers as subjects and experimental conditions used by Stefanyshyn, et al., (1998) were very different from those of an actual long jump. In addition, the studies did not refer to the relationship of the joint torques of the takeoff leg to the change in CG velocity during the takeoff. Investigating the kinetics of the takeoff leg and the relationship to the jumping distance and CG velocity change in the long jump takeoff from a fast approach velocity helps to compensate for the lack of the previous studies. Therefore, the purposes of this study were to determine the joint torque and power of the takeoff leg and the relationship of the angular impulse and work done by the joint torques to the CG velocity change during long jump performed by elite and ordinary-level Japanese male jumpers.

2. Methods

2.1. Subjects

Eleven Japanese male long jumpers (height, 1.76 ± 0.04 m; body mass, 68.0 ± 4.3kg; personal best record, 7.31 ± 0.55 m from 6.56 to 7.99 m) participated in this study and were asked to perform a long jump on a force platform with their own full approach run. The jumping distance in the experiment was 6.96 ± 0.49 m, ranging from 6.25 to 7.60 m. The purpose and significance of the study, details of the data collection process, and the safety of the experimental set-up were explained to the subjects prior to the experiment and informed consent was obtained from all subjects.

2.2. Data collection

Subjects prepared for the experiment as they would for competition and performed from three to five jumps on a force platform (0.6 m × 0.4 m, Kistler AG, Switzerland) covered with an artificial surface, landing in a sand pit. The jumping distance was measured by tape measure and reported to the subject immediately after the trial. The takeoff motions of the subjects were videotaped with a high-speed video camera operating at 250 Hz (HSV-500 C1, NAC Co., Japan) for two-dimensional motion analysis.
The camera was located 35 m from the right side of the runway. The ground reaction forces during the takeoff phase were sampled with a force platform at 1000 Hz. The forward-backward component of the force platform (Fy) was set parallel to the runway. An LED synchronizer was used to synchronize the video tape data with the ground reaction force data.

2.3. Data reduction

We analyzed a jump for which the subject placed the takeoff foot completely on the force platform and recorded the maximum distance. Two-dimensional coordinates of 23 body landmarks of the hands, wrists, elbows, shoulders, toes, first metatarsal bones, heels, ankles, knees, greater trochanters, head, ears, and suprasternale were obtained by digitizing each video tape frame from 10 frames before touchdown to 10 frames after the toe-off with a Frame-DIAS system (DKH Co., Japan). Digitized coordinates were converted to real coordinates using reference markers placed on both sides of the approach lane and the takeoff area and were smoothed with a fourth-order Butterworth low-pass digital filter. The optimal cut-off frequencies, ranging from 5 to 10 Hz, were determined by the residual error method proposed by Wells and Winter (1980). A 14-segment link model, comprised of hands, forearms, upper arms, feet, shanks, thighs, head, and trunk, was used to calculate the linear and angular kinematics of joints and segments, and was also used with the ground reaction force data to estimate the joint torque and joint power for the takeoff leg joints. An increase (decrease) in the joint angle in this study indicated that the joint was extended (flexed) or plantar-flexed (dorsi-flexed). The mass, location of the center of mass, and the moment of inertia for body segments were estimated from the body segment parameters for Japanese athletes developed by Ae (1996).

Joint forces and joint torques acting on the takeoff leg joints were calculated by an inverse dynamics procedure (Winter, 1990). Equations of motion for the body segments were solved from the distal to the proximal segments of the takeoff leg. Positive (negative) joint torque indicated that the extensors (flexors) and plantar-flexors (dorsi-flexors) were dominant. Note that joint torque is the net effect of muscle activity at a joint and comprises the effect of passive structures, such as ligaments, and any friction at a joint or within muscles. Joint power was determined as an inner product of joint torque and the angular velocity of the joint. Positive (negative) joint power was interpreted to indicate that mechanical power was generated by concentric (eccentric) contraction of the agonist muscles at a joint. The angular impulse and mechanical work done by the joint torques were calculated by numerically integrating joint torque and joint power during a given period of time, respectively. The absolute mechanical work of the joint was calculated as the sum of the positive work and the absolute value of the negative work for the joint.

The joint torque, joint power and mechanical work of all subjects were normalized by the body mass and by the time of the takeoff phase of each subject, and were then averaged. The normalized times of the touchdown and toe-off were defined as the 0% and 100% points of the takeoff phase, respectively. The jumper supported the body with his takeoff leg joints flexed in the first half of the takeoff phase and then extended in the latter half of the takeoff phase. Therefore, the takeoff phase was divided into two phases. The first phase began at the instant of the takeoff foot touchdown and ended at the instant of the maximum knee flexion of the takeoff leg, and the second phase was from the end of the first phase to the instant of the toe-off. The averaged time of the maximum knee flexion of the takeoff leg appeared at 47.0 ± 4.6% point of the takeoff phase.

Pearson's product moment correlation coefficients were calculated to examine the relationships of the magnitude and normalized time of the peaks of joint torque to the horizontal CG velocity at touchdown, and the relationships of the CG velocity change to the angular impulse and mechanical work of the takeoff leg joint torques during the first and second phases. An analysis of variance for repeated measures (ANOVA) was used to compare the mechanical work done at the takeoff leg joints in the phases of the takeoff. The Tukey HSD test was used to test the differences among joints and between phases. The level of statistical significance was set at $p < 0.05$.

3. Results

3.1. Velocity of the center of gravity of the body

Figure 1 illustrates averaged patterns of the horizontal and vertical velocities of the CG during the takeoff phase. The horizontal velocity at touchdown
was 9.22 ± 0.46 m/s, and the horizontal and vertical velocities at the toe-off were 8.08 ± 0.48 and 3.22 ± 0.30 m/s. The vertical CG velocity increased until the 94% point of the takeoff phase, and the horizontal CG velocity decreased until the 72% point of the takeoff phase. The net changes in the horizontal and vertical velocities of the CG were greater in the first phase (horizontal, - 1.12 ± 0.32 m/s; vertical, 2.03 ± 0.29 m/s) than in the second phase (horizontal, - 0.03 ± 0.31 m/s; vertical, 1.22 ± 0.36 m/s). Although the horizontal CG velocities at touchdown and toe-off correlated significantly with jumping distance (touchdown, \( r = 0.86, p = 0.001 \); toe-off, \( r = 0.83, p = 0.002 \)), there was no significant correlation between the vertical CG velocity at the toe-off and jumping distance (\( r = 0.15, p = 0.66 \)). The change in the vertical CG velocity did not significantly correlate with the horizontal CG velocity change during the first (\( r = -0.45, p = 0.16 \)) and second (\( r = -0.05, p = 0.89 \)) phases.

3.2. Ground reaction forces

Figure 2 depicts averaged patterns of the horizontal and vertical ground reaction forces during the takeoff phase. There were peaks at the 9% and 42% points of the takeoff phase in the vertical component. The first peak (103.07 ± 16.48 N/kg) was much greater than the second peak (46.47 ± 5.30 N/kg). The horizontal ground reaction force reached its negative peak at the 9% point of the takeoff phase (- 57.92 ± 8.19 N/kg) and continued to be negative (deceleration, - 1.38 ± 0.16 N·s/kg) during four-fifths of the takeoff phase.

3.3. Joint angular velocities

Figure 3 illustrates averaged patterns of the joint angular velocities of the ankle, knee and hip of the takeoff leg during the takeoff phase. The ankle joint dorsiflexed from touchdown to the 55% point of the takeoff phase and then plantar-flexed until the toe-off. The peak dorsiflexion and plantar-flexion velocity appeared at the 27% and 90% points of the takeoff phase. The knee joint flexed during the first phase and extended during the second phase. The peak flexion velocity appeared at the 16% point and the peak extension velocity appeared at the 81% point of the takeoff phase for the knee joint earlier than for the ankle joint. The hip angular velocity was positive throughout the takeoff phase but was greater in the second phase than in the first phase. The peak of the hip angular velocity appeared at the 82% point of the takeoff phase.
3.4. Joint torques

Figure 4 presents averaged patterns of the joint torques of the ankle, knee, and hip of the takeoff leg during the takeoff phase. The ankle joint torque was positive throughout the takeoff phase and reached its peak at the 58% point of the takeoff phase. The knee joint torque was positive in the majority of the takeoff phase; however, it became negative immediately after touchdown and before the toe-off, indicating that the knee extensors were dominant. Positive peaks of the knee joint torque appeared at the 9% and 27% points of the takeoff phase. The hip joint torque quickly increased in the initial part of the takeoff phase, followed by a second peak at the 14% point of the takeoff phase. The hip joint exerted small flexor and extensor torques at approximately the 23 to 49% points of the takeoff phase. The hip joint torque fluctuated at approximately zero in the second phase. The standard deviation of the hip joint torque was substantial in the initial part of the takeoff phase. There were no significant correlations between the horizontal CG velocity at touchdown and the magnitude and normalized time of the peak joint torques of the takeoff leg.

3.5. Joint powers

Figure 5 depicts averaged patterns of the joint powers of the ankle, knee, and hip of the takeoff leg during the takeoff phase. The ankle joint power was negative from the 0 to 55% points of the takeoff phase. The knee joint power was negative in the majority of the takeoff phase; however, it became positive immediately after touchdown and before the toe-off, indicating that the knee extensors were dominant. Positive peaks of the knee joint power appeared at the 9% and 27% points of the takeoff phase. The hip joint power quickly increased in the initial part of the takeoff phase, followed by a second peak at the 14% point of the takeoff phase. The hip joint exerted small flexor and extensor powers at approximately the 23 to 49% points of the takeoff phase. The hip joint power fluctuated at approximately zero in the second phase. The standard deviation of the hip joint power was substantial in the initial part of the takeoff phase. There were no significant correlations between the horizontal CG velocity at touchdown and the magnitude and normalized time of the peak joint powers of the takeoff leg.
phase and reached negative peak at the 37% point of the takeoff phase. The ankle joint power was positive in the second phase and reached its peak at the 77% point of the takeoff phase, which was greater than that of the knee and hip joint powers. There was short positive power immediately after the touchdown, after which knee joint power became negative in the first phase, in which negative peaks appeared at the 9% and 26% points of the takeoff phase. Knee joint power returned to positive in the second phase, reached positive peak at the 69% point of the takeoff phase and became negative again before the toe-off. Hip joint power was positive in most of the first phase and negative at approximately the 49% to 89% points of the takeoff phase. Although the magnitude of the hip joint torque was greater than that of the other takeoff leg joints in the first phase (Figure 4), the hip joint power was surprisingly small in the corresponding phase.

3.6. Mechanical work done by the joint torques

Figure 6 illustrates the absolute, positive, and negative mechanical work done by the ankle, knee, and hip joint torques of the takeoff leg during the takeoff phase. The sum of the positive and negative work done by the takeoff leg joint torques was negative during the takeoff phase (-0.87 ± 0.69 J/kg). There were no significant relationships between the horizontal CG velocity at touchdown and the absolute, positive, and negative work during the overall, first, and second phases.

The absolute work performed by the ankle and knee joint torques throughout the entire phase was greater than that of the hip joint torque ($p < 0.01$).
The greatest absolute work was performed by the knee joint torque during the first phase ($p < 0.01$) and by the ankle joint torque during the second phase ($p < 0.01$). The greatest positive work was performed by the ankle joint torque throughout the entire phase ($p < 0.01$), and most of this was performed during the second phase ($p < 0.01$). Although it was minimal, the greatest positive work during the first phase was performed by the hip joint torque ($p < 0.05$). The greatest negative work was performed by the knee joint torque throughout the entire phase ($p < 0.01$), and most of that was performed during the first phase ($p < 0.01$). The negative work performed by the ankle and knee joint torques in the first phase was greater than that of the hip joint torque ($p < 0.01$). However, the hip joint torque performed the greatest negative work of the three joints during the second phase ($p < 0.05$).

### 3.7. Relationships of angular impulse and mechanical work to the CG velocity change

Figures 7 and 8 depict the relationship of the angular impulse of the takeoff leg joint torques to the CG velocity change during the first and second phases, respectively. In the first phase, the positive knee and negative hip angular impulses significantly correlated with horizontal CG velocity change (knee, $r = -0.69, p = 0.02$; hip, $r = 0.68, p = 0.02$), and the positive ankle angular impulse significantly correlated with vertical CG velocity change ($r = 0.64, p = 0.03$). In the second phase, there were significant relationships of the vertical CG velocity change to the positive ankle and hip angular impulses and the negative knee angular impulse (ankle, $r = -0.67, p = 0.001$; knee, $r = 0.77, p = 0.004$). The positive knee angular impulse significantly correlated with the horizontal CG velocity change during the second phase ($r = 0.67, p = 0.02$).

Figure 9 presents the relationship of the mechanical work done by the takeoff leg joints to the CG velocity change during the second phase. No significant correlations were found between the mechanical work at the takeoff leg joints and CG velocity changes during the first phase. However, in the second phase, the positive work of the ankle and knee joints significantly correlated with horizontal CG velocity change (ankle, $r = 0.77, p = 0.006$; knee, $r = 0.68, p = 0.02$), and for vertical CG velocity change there were significant relationships to the negative work at the ankle and knee joints and the positive work at the hip joint (ankle, $r = -0.64, p = 0.02$; knee, $r = -0.81, p = 0.002$; hip, $r = 0.83, p = 0.002$).
4. Discussion

4.1. Characteristics of joint torque patterns in the takeoff from long approach run

We investigated the joint kinetics of the takeoff leg for elite and ordinary-level Japanese jumpers. There were no relationships of the magnitude and normalized time of the peak joint torques and joint powers of the takeoff leg to the jumping distance.

As previous studies have indicated (Luhtanen and Komi, 1979; Hay, 1986; Hay, et al., 1986; Lees, et al., 1994; Ueya, et al., 1984), the present study showed a significant relationship between horizontal CG velocity at touchdown and jumping distance. There were no relationships of the magnitude and normalized time of the peak joint torques of the takeoff leg to the horizontal CG velocity at touchdown. The approach velocity of the subjects in this study was greater than that in the previous studies (Ae, et al., 1989, 9.14 ± 0.34 m/s; Fuchimoto, et al., 1994, 9.07 ± 0.26 m/s; Stefanyshyn, et al., 1998, 6.1 to 6.6 m/s). The patterns of the ankle, knee, and hip joint torques were similar to those of Fuchimoto, et al., (1994) and Ae, et al., (1998), even though the standard deviations of the hip and knee joint torques of the subjects were substantial in the initial part of the takeoff phase. These results indicated that the characteristics of the joint torque patterns of the takeoff leg in the takeoff phase did not change with the increase of horizontal CG velocity at the touchdown. While the two sizeable positive peaks of the hip joint torque immediately after touchdown did not appear in the study by Stefanyshyn, et al., (1998), and the first positive peak of the knee joint torque was much smaller than that in this study. This would be due to the fact that smoothed ground reaction force data were used in Stefanyshyn’s study. Thus, the joint torque patterns of the knee and hip joints do not reflect the influence of the impact ground reaction force in their study.

The hip joint exerted flexion torque and the knee joint exerted extension torque in the final part of the takeoff phase in a long jump following a short approach run (Fuchimoto, et al., 1994). However, that the hip joint exerted small extension torque and the knee joint exerted flexion torque before the toe-off in the long jump after a long approach run in the present study and previous studies (Fuchimoto, et al., 1994; Ae, et al., 1993). Bobbert, et al., (1988) indicated that the existence of bi-articular muscles enabled mono-articular muscles to remain active until the toe-off in a vertical jump without the risk of joint damage. The horizontal CG velocity was much faster in the long jump from a long approach run than that of a short approach run, and, thus, the jumper would have to extend the takeoff leg much faster to maintain CG velocity during the takeoff phase following the knee flexion torque and the small hip extension torque. Reaction to the knee flexion torque results in a flexion moment on the thigh, which contributes to hip flexion. The small hip extension torque for a long approach run may serve as a counterpart to the hip flexion moment caused by the reaction to the knee flexion torque. The existence of the bi-articular hip extensors would also play a role in preventing hyperextension of the knee joint after the toe-off from a long approach run. These inter-joint relationships would be one of the characteristics of a long jump takeoff from a long approach and help to prevent injury from the hyperextension of the knee joint after the toe-off.
4.2. Functions of takeoff leg joints

4.2.1. The ankle joint

The ankle joint torque and joint power were not substantial in the initial part of the takeoff phase, even though a great impact force appeared immediately after touchdown. Since the ankle plantar-flexors were contracted eccentrically during the first phase, the ankle plantar-flexors absorbed the mechanical energy of the body together with the knee extensors, particularly in the latter part of the first phase. The plantar-flexors were the greatest energy generators in the second phase (Figure 6). Although the changes in CG velocity were much smaller in the second phase than in the first phase, the plantar-flexors contributed to an increase in mechanical energy and, subsequently, CG velocity during the second phase.

The angular impulse of the plantar-flexion torque would help to increase vertical CG velocity during the first phase (Figure 7) and contribute to the increase in vertical CG velocity, and the positive work would decrease the reduction of horizontal CG velocity during the second phase (Figure 8 and 9). Therefore, the ankle plantar-flexors act as an energy absorber in the first phase and as an energy generator in the second phase, and would help in the increase of CG velocity throughout the takeoff phase. The plantar-flexors would play an important role in transmitting the force generated by the takeoff leg joints and the other body parts to the ground through the takeoff foot. The negative work done by the plantar-flexors related to the increase in vertical CG velocity during the second phase (Figure 9). This suggests that the jumper should exert plantar-flexion torque in early timing so that the negative work done by the plantar-flexors during the second phase is minimized.

4.2.2. The knee joint

The knee extensors generated large torque and did the most significant negative work of the takeoff leg joints in the first phase (Figure 5 and 6). These results indicated that the knee joint resisted the impact force and absorbed the mechanical energy of the body during the first phase. While vertical CG velocity was increased by pivoting the jumper's body over the takeoff foot during the first phase (Lees, 1994). Therefore, the knee extensors had to exert sufficient great torque to support the body and would contribute to increasing vertical CG velocity by the forward rotation of the body around the takeoff foot. The knee extensors would act to compensate for the drop of the hip extension torque around the 9% point of the takeoff phase, and the knee and hip extensors would play important roles in supporting the body in the impact phase.

The knee extension torque decreased gradually during the second phase. The positive correlations of the positive angular impulse and mechanical work of the knee joint to horizontal CG velocity indicate that the concentric contraction of the knee extensors would contribute to reduce the decrease in horizontal CG velocity during the second phase (Figure 8 and 9).

In summary, the knee joint supported the body to maximize the effect of the pivoting of the body over the takeoff foot during the first phase and extended during the second phase to increase CG velocity throughout the takeoff phase.

4.2.3. The hip joint

The hip joint exerted considerable extension torque around the 0 to 23% points of the takeoff phase (Figure 4). However, hip angular velocity and hip joint power were less than expected. An extremely large force acted upward and backward on the takeoff foot when the jumper settled his takeoff foot on the ground, as illustrated in Figure 2. The horizontal momentum of the upper body caused the upper body to rotate forward around the hip joint. The takeoff foot hit the ground in front of the body, and the vertical force resulted in a backward moment on the thigh of the takeoff leg, which acted to flex the hip joint. Therefore, the hip extensors exerted torque to prevent the upper body from rotating forward and hip flexion immediately after touchdown, and to support the body together with the knee joint immediately after touchdown. The hip joint exerted small flexion torque and extension torque around the 23 to 49% points of the takeoff phase (Figure 4); however, the hip joint power fluctuated around zero due to the small extension velocity. In the second phase, the takeoff leg thigh was rotated backward explosively, which would have rotated the torso backward by the reaction if the hip flexors had not been exerted in this phase. Therefore, the hip flexors would restrain excess backward rotation of the torso and maintain it in an upright position during the second phase.

In summary, the hip joint exerted joint torque to
keep the torso in a nearly upright position throughout the takeoff phase and resisted the substantial impact force for an increase in vertical CG velocity by pivoting the body over the takeoff foot.

### 4.3. Compensatory function of the hip and knee joints

Very large hip and knee extension torques were exerted immediately after touchdown, which acted in cooperation to resist the impact force. When the hip extensors exerted considerable torque immediately after touchdown, the knee joint torque was minimal in the corresponding phase, and vice versa in the initial part. This compensatory function of the hip and knee joint torques was observed in all subjects. We can understand this function of the hip and knee joints by examining the positional relationship between the impact force vector and the hip and knee joints since the direction and moment arm of the ground reaction force vector affect the pattern and magnitude of joint torque.

**Figure 10** provides an example of the joint torque of the takeoff leg and the ground reaction force vector when the peak hip and knee joint torques appeared. Greater extension torque by the hip extensors appeared to prevent the hip joint from collapsing against the hip flexion moment of the ground reaction force vector when the impact force vector passed in front of the hip joint with a long moment arm around the hip joint (Figure 10, left). The hip joint torque decreased when the impact force vector passed close to the hip joint (Figure 10, right); however, the knee joint torque increased because the moment arm of the knee joint was longer. This shift from the hip to knee joint torque may indicate that the two joints cooperate in response to the substantial impact force. However, these peaks appeared within 24 ms, and it is not possible that both joints alternately switched the exertion of the extension torque in such a brief time. It is reasonable to consider the possibility that the jumper would extend or fix both joints in anticipation of the substantial impact force and could use this compensatory function as the result.

### 4.4. Effects of the joint torque on the CG velocity change

No significant correlations were found between the jumping distance and the angular impulse and mechanical work during the first and second phases.

The changes in horizontal and vertical CG velocities were greater in the first phase than in the second phase. Horizontal CG velocity necessarily decreases in order to increase vertical CG velocity during the first phase. However, the increase in vertical CG velocity did not significantly correlate with the decrease in horizontal CG velocity during the first phase. Therefore, it is important to minimize the loss of horizontal CG velocity during the first phase. The hip and knee extensors of the takeoff leg exerted torques to support the body and maximize the effect of the pivoting movement of the takeoff leg during the first phase. However, since the backward leaning body was positioned behind the takeoff foot at the touchdown, the angular impulse by the knee extension torque would cause a decrease in horizontal CG velocity during the first phase (Figure 7). Therefore, to minimize the loss of horizontal CG velocity during the first phase, a jumper should place the takeoff foot closer to the body at the touchdown.
And a more extended knee joint at touchdown may be effective in enhancing leg stiffness and provide support for the body without increasing the angular impulse of the knee extensor torque during the first phase. The negative angular impulse of the hip joint caused the decrease in the reduction of horizontal CG velocity during the first phase (Figure 7). Although the hip flexors played a role in preventing excess backward rotation of the torso, the hip flexion torque would restrain the backward rotation of the takeoff leg thigh during the latter part of the first phase. The angular impulse of the plantar-flexors contributed to the increase in vertical CG velocity during the first phase (Figure 7). As mentioned above, the ankle joint would play an important role of transmitting the forces generated to the ground and help to support the body during the first phase.

In the second phase, the positive angular impulse and mechanical work of the plantar-flexors and knee extensors significantly related to CG velocity change (Figure 8 and 9). Therefore, a jumper should exert large ankle plantar-flexion and knee extension torques and extend the knee and ankle joint quickly to increase CG velocity during the second phase. Although small knee flexion and hip extension torques were exerted only before the toe-off (Figure 4) and vertical CG velocity reached its peak at the 94% point of the takeoff phase (Figure 1), the angular impulse and mechanical work of the knee flexors and hip extensors significantly correlated to the increase in vertical CG velocity during the second phase (Figure 8 and 9). These results imply that a long jumper should not ignore even final and small hip extension torque before the toe-off to increase in vertical CG velocity and passively-exerted knee flexion torque to prevent the hyperextension of the knee joint, as described above.

5. Conclusions

The plantar-flexors and knee extensors functioned as great energy absorbers in the first phase of a long jump takeoff and as energy generators in the second phase. The plantar-flexors acted to transmit the force generated by the body segments to the ground and to increase CG velocity during the takeoff phase. Compensatory exertion of the extension torques at the hip and knee joints was observed immediately after the touchdown, which implied that both hip and knee joints cooperated in response to the abrupt change in the ground reaction forces and contributed to increase vertical CG velocity by pivoting the body over the takeoff foot during the first phase. The hip joint exerted flexion torque and restrained excess backward rotation of the torso during the second phase and contributed to maintaining the torso in a stable position throughout the takeoff phase.

CG velocity changed from horizontal to the vertical during the first phase, and, thus, a jumper had to exert the extension torques of the hip and knee joints to support the body. The great knee extension torque helps to minimize the decrease in horizontal CG velocity and convert horizontal velocity to vertical velocity. This suggests the importance of the first phase in the long jump takeoff from the viewpoint of the joint kinetics. In the second phase, the jumpers increased CG velocity largely by the extension and plantar-flexion of the knee and ankle of the takeoff leg. Therefore, a jumper should train the hip extensors to support the body against the impact force immediately after the touchdown and the stretching-shortening ability of the knee extensors and plantar-flexors to effectively increase vertical CG velocity during the takeoff phase.

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Main Works:

Membership in Learned Societies:
• Japan Society of Physical Education, Health and Sport Sciences
• Japanese Society of Biomechanics
• Japanese Society of Sport Methodology
• Japan Journal of Studies in Athletics
• International Society of Biomechanics
• International Society of Biomechanics in Sports