The purpose of this study was to elucidate the effects of the lower limb joint moments on the horizontal and vertical velocities of the body mass center during jumping in different directions. Ten male university students performed forward, vertical, and backward jumps, during which their jumping motion (150 Hz) and ground reaction force (600 Hz) were collected. Induced acceleration analysis was performed to quantify the body mass center velocity produced by each joint moment. In all jump conditions, the hip, knee, and ankle joints exerted extension and plantarflexion moments, and most of vertical velocity of the body mass center was produced by the ankle moment. Additionally, the knee moment produced backward velocity and the ankle moment produced forward velocity, while the hip moment produced neither horizontal nor vertical velocities. These results indicate that the knee moment accelerates the body mass center backward and the ankle moment accelerates it upward and forward, regardless of jumping direction. Although there was no significant difference in the peak joint moments, significant differences were observed in the horizontal velocities produced by the knee and ankle moments. Moreover, significant differences were observed in the forward lean angle of the trunk at the beginning of the jump motion and lower limb segments at take-off. These results indicate that the velocity of body mass center was affected by not only the joint moments but also body configuration.

Keywords: induced acceleration analysis, motion analysis, squat jump, equation of motion

1. Introduction

Jump motions are one of the most fundamental motion skills for humans, and these motions have been examined in numerous biomechanical studies. Because vertical jumps are frequently performed in sports, almost all of these previous studies have investigated vertical jump motions (Pandy and Zajac, 1991; Bobbert and Casius, 2005). However, in many sports, athletes usually also have to generate some amount of forward or backward momentum to achieve good performance rather than simply jumping vertically. Therefore, it is also important and valuable to investigate the mechanism of the motions in horizontal jumps.

To jump higher or farther, athletes need to obtain greater velocity of the body mass center (BMC) at take-off. Most previous studies have investigated the roles of lower limb joints using kinematic, kinetic, and electromyographic (EMG) measurements because the velocity of BMC is mainly produced by the lower limb joint moments. Robertson and Fleming (1987) compared moments and mechanical work of the lower limb joints during forward and vertical jumps and reported that mechanical work done by the knee joint is smaller in forward jumps. Fukashiro et al. (2005) compared joint kinetics and muscle activations of the lower limb between
forward and vertical jumps, and reported that hamstring activity was greater and rectus femoris activity was lower in forward jumps than in vertical jumps. These studies identified the changes in the joint kinetics and muscle activities of the lower limb with jumping direction, and inferred that work output and muscle activity, especially around the knee joint, might play an important role in controlling jumping direction. Furthermore, these and several other previous studies have addressed joint kinetics and EMG measurements during jumping; however, these methods are not able to determine how differences in these jump conditions affect the production of BMC velocity and control of the jumping direction.

Some studies estimated the contributions of muscle forces (Hamner and Delp, 2013) and joint moments of the lower limbs (Koike et al., 2010) to changes in the velocity of BMC during running using an induced acceleration analysis. Because this method is able to quantify the acceleration of BMC produced by each joint moment based on the equations of motion, it is useful in clarifying how the lower limb joint moments accelerate BMC during jumping in different directions and in understanding the mechanisms of jumping motion and the roles of the lower limb joints during jump.

Therefore, the purpose of this study was to elucidate the effects of the lower limb joint moments on the horizontal and vertical velocities of BMC during jumping in different directions by using an induced acceleration analysis.

2. Methods

2.1. Participants

Participants in this study were 10 male university students (age: 20.7 ± 1.0 years; height: 1.73 ± 0.05 m; body mass: 61.1 ± 7.9 kg). The purpose and experimental protocol of this study were explained to the participants and written informed consent was obtained before the experiment. This study was approved by the ethics committee of Ibaraki Prefectural University of Health Sciences.

2.2. Data collection

Three-dimensional coordinates of 35 retro-reflective markers fixed on the body of a participant according to the Plug-in-Gait marker placement and ground reaction forces of the right foot were collected using a VICON T10 system (Vicon Motion Systems, Ltd., Oxford, UK) with eight cameras operating at 150 Hz and a Kistler force platform (9287A, Kistler Instrumente AG, Winterthur, Switzerland) operating at 600 Hz. During jumping, the markers were monitored in three dimensions; however, only sagittal plane projections were used in this study. The coordinate data and ground reaction force data were synchronized for subsequent analysis.

The participants performed three kinds of jumps starting with their right foot on the center of the force platform: forward jump (FJ), vertical jump (VJ), and backward jump (BJ). Participants were instructed to keep their hands on their hips and make no counter movements. For VJ, participants jumped as high as possible without forward or backward motions, and in FJ and BJ, they aimed to land on lines set 1 m forward or backward from the center of the force platform, while also jumping as high as possible. All trials were performed in random order with sufficient resting time between trials to minimize the effects of fatigue. After three successful trials of each jump, the trials with the highest jumps were selected for detailed analysis.

2.3. Data analysis

The coordinates and ground reaction forces were smoothed using a quantic spline function (Woltring, 1986) with a cut-off frequency of 10 Hz. The location of the center of mass and the inertial parameters of the body segments were estimated using body segment parameters for Japanese athletes (Ae, 1996). Jump motions were analyzed from the instant of BMC was at its lowest to the instant of take-off. The segment angles of the trunk and thigh, shank, and foot of the right leg were calculated as the angle between a vector from the distal to the proximal ends of each segment and the vertical axis. Joint forces and joint moments at the hip, knee, and ankle joints of the right leg were calculated by an inverse dynamics approach (Winter, 2009). The equations of motion were solved from the distal to proximal segments by using the ground reaction forces and the center of pressure locations. The joint moments throughout the jump motion were integrated to obtain joint angular impulses. The
joint moments and angular impulses were normalized by the participant's body mass.

Induced acceleration analysis was performed to quantify the acceleration of BMC produced by right leg joint moments (Koike et al., 2007). The translational and rotational equations of motion for each segment were summed in matrix form as

\[ MV = PF + QN + H + G \]  

where \( M \) is the inertia matrix and \( V \) is the generalized velocity vector, which includes the translational and rotational velocities of each segment, \( P \) is the coefficient matrix of vector \( F \), which contains joint force vectors, \( Q \) is the coefficient matrix of vector \( N \), which contains joint moment vectors, \( H \) is the gyro moment vector of all segments, and \( G \) is the vector of the gravitational component. However, in this study, we analyzed jump motions in only two dimensions and \( H \) was always zero, so it was ignored.

The equation for the constraint condition in which adjacent segments are connected by a joint is expressed as follows (Fujii and Hubbard, 2002):

\[ \dot{v}_{i+1} = \dot{v}_i + \omega_i \times r_{i-1} + \omega_i \times (\omega_i \times r_{i-1}) - \omega_{i+1} \times r_{i+1-1} - \omega_{i+1} \times (\omega_{i+1} \times r_{i+1-1}) \]  

(2)

where \( v_i \) and \( \omega_i \) are the translational and rotational velocity vectors of the \( i_{th} \) segment, and \( r_{i-1} \) is the relative position vector from the mass center of the \( i_{th} \) segment to the \( j_{th} \) joint. This geometric constraint equations for all segments are summed in matrix form as

\[ \dot{C}V + CV = \eta \]  

(3)

where \( C \) is the geometric constraint coefficient matrix of the generalized velocity vector, \( \eta \) is the position vector of constraint points. In this study, because the right and left balls of the feet were fixed to the ground, vector \( \eta \) contains their positions.

From Equation 1, \( \dot{V} \) is obtained as

\[ \dot{V} = M^{-1}PF + M^{-1}QN + M^{-1}G \]  

(1').

Substituting Equation 1' into Equation 2 and solving for \( F \), we obtain

\[ F = -(CM^{-1}P)^{-1}[M^{-1}QN + \dot{C}V + M^{-1}G - \eta] \]  

(4)

In addition, by substituting Equation 3 into Equation 1', the equations of motion for the system can be obtained as follows:

\[ \dot{V} = A_N N + A_V + A_G G \]  

(5)

\[ A_N = -M^{-1}P(CM^{-1}P)^{-1}CM^{-1}Q + M^{-1}Q \]

\[ A_V = -M^{-1}P(CM^{-1}P)^{-1}(CV - \eta) \]

\[ A_G = -M^{-1}P(CM^{-1}P)^{-1}CM^{-1} + M^{-1} \]

where, \( A_N \) and \( A_G \) are the coefficient matrices of the joint moment vector \( N \) and the gravitational component vector \( G \), and \( A_V \) is the motion dependent acceleration vector. The accelerations of BMC produced by each joint moment \( (\dot{V}_{BMC}) \) were calculated using Equation 6:

\[ \dot{V}_{BMC} = S A_N N \]  

(6)

where \( S \) is a transformation vector from the segments’ mass center accelerations to the acceleration of BMC. Furthermore, angles between the acceleration vectors of BMC produced by knee and ankle moments and the vertical axis were calculated and averaged throughout the jump motion.

2.4. Statistical analysis

One-way ANOVA was used to test the effect of the jumping direction with the level of significance set at 5%. Bonferroni correction was used for multiple comparisons.

3. Results

Stick diagrams and the ground reaction force vectors of FJ, VJ, and BJ are presented in Figure 1. The horizontal velocities of BMC at the instant of take-off of FJ were positive (forward), while those of VJ and BJ were negative (backward), and there were significant differences in the horizontal velocity among the three jump conditions (Table 1). The vertical velocities of BMC at the instant of take-off...
Table 1  Horizontal and vertical velocities of the body mass center at the take-off and motion times.

<table>
<thead>
<tr>
<th></th>
<th>FJ</th>
<th>VJ</th>
<th>BJ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal velocity (m/s)</td>
<td>0.62 (0.14)</td>
<td>-0.38 (0.09)</td>
<td>-1.32 (0.11)</td>
</tr>
<tr>
<td>Vertical velocity (m/s)</td>
<td>2.46 (0.23)</td>
<td>2.58 (0.18)</td>
<td>2.25 (0.13)</td>
</tr>
<tr>
<td>Motion time (sec)</td>
<td>0.30 (0.05)</td>
<td>0.27 (0.04)</td>
<td>0.26 (0.03)</td>
</tr>
</tbody>
</table>

Note: Mean value (SD).

Figure 2  Time histories of trunk, thigh, shank, and foot angles.

were significantly larger in VJ than in BJ (Table 1). No significant differences were observed in the motion times among the three jump conditions (Table 1).

At the beginning of jump motion, the trunk angle was significantly larger in FJ (53.9 ± 6.0 deg) than in VJ (40.1 ± 6.3 deg) and BJ (35.6 ± 6.8 deg) (Figure 2). At the instant of take-off, the thigh, shank, and foot angles were significantly larger in FJ (21.7 ± 3.2 deg, 18.3 ± 2.7 deg, −37.7 ± 5.8 deg) than in VJ (7.2 ± 2.5 deg, 0.9 ± 1.5 deg, −54.0 ± 4.1 deg) and BJ (−14.4 ± 3.4 deg, −14.7 ± 2.9 deg, −67.7 ± 3.7 deg), and larger in VJ than in BJ.

In all jump conditions, the hip, knee, and ankle joints exerted extension and plantarflexion moments (Figure 3), and no significant differences were noted in the peak extension and plantarflexion moments of the hip, knee, and ankle joints. The plantarflexion moment at the beginning of the jump motion was significantly larger in BJ (−0.89 ± 0.18 Nm/kg) than in FJ (−0.11 ± 0.15 Nm/kg) and VJ (−0.17 ± 0.19 Nm/kg). The angular impulse of ankle joint was significantly larger in BJ (−0.34 ± 0.08 Nms/kg) than in FJ (−0.27 ± 0.04 Nms/kg) and VJ (−0.26 ± 0.07 Nms/kg), but no significant differences were observed in the angular impulse of the hip and knee joints.

In all jump conditions, the knee moment produced backward acceleration, but the ankle moment produced forward acceleration (Figure 4). At the
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Figure 3 Time histories of hip, knee, and ankle joint moments.

Figure 4 Time histories of horizontal and vertical accelerations of the body mass center produced by the hip, knee, and ankle joint moments.

instant of take-off, the backward velocity of BMC produced by the knee moment was significantly smaller in FJ \((-0.30 \pm 0.12 \text{ m/s})\) than in VJ \((-0.48 \pm 0.13 \text{ m/s})\) and BJ \((-0.62 \pm 0.09 \text{ m/s})\), and smaller in VJ than in BJ (Figure 5). However, the forward velocity produced by the ankle moment was significantly larger in FJ \((0.69 \pm 0.09 \text{ m/s})\) than in VJ \((0.43 \pm 0.14 \text{ m/s})\) and BJ \((0.03 \pm 0.16 \text{ m/s})\), and larger in VJ than in BJ. A significant difference in the vertical velocity produced by knee moment was observed between VJ \((0.57 \pm 0.18 \text{ m/s})\) and BJ \((0.34 \pm 0.07 \text{ m/s})\). The hip joint barely produced horizontal and vertical velocity in all three jump conditions.

In the knee joint, the angle of the acceleration vector of BMC for BJ was negative and large in magnitude throughout the jump motions (Figure 6), while the angles for FJ and VJ were almost equal to
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Figure 5  Time histories of horizontal and vertical velocities of the body mass center produced by the hip, knee, and ankle joint moments.

Figure 6  Time histories of the angle of acceleration vector of the body mass center produced by the knee and ankle moments to the vertical axis.

Zero at the beginning of jump motion, after which they decreased. The mean angle of the acceleration vector of BMC produced by the knee moment was significantly larger in FJ (-36.1 ± 7.9 deg) and VJ (-42.8 ± 6.8 deg) than in BJ (-60.8 ± 3.2 deg). In the ankle joint, the angles of the acceleration vector of BMC were positive in the initial part of the jump motion, and then became negative before take-off. The mean angle of the acceleration vector of BMC produced by the ankle moment was significantly larger in FJ (25.3 ± 6.2 deg) than in VJ (16.1 ± 4.9 deg), which was in turn larger than that in BJ (-1.5 ± 4.2 deg).

4. Discussion

The purpose of the present study was to elucidate the effects of the hip, knee, and ankle moments on
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The velocity of BMC during jumping in different directions. Fukashiro et al. (2005) reported that there were significant differences in the peak moments of the hip and knee joints between VJ and FJ. Ridderikhoff et al. (1999) compared the joint kinetics between VJ and FJ, and reported that lower limb joint moments are adapted to the direction of the jump. In this study, however, no significant difference was observed in the peak joint moments (Figure 3), and the time histories of joint moments were similar among the three jump conditions. In the previous studies, subjects tried to jump as far as possible in FJ, while in the present study, the subjects were asked to jump as high as possible and land on a line placed 1 m away. Therefore, these differences in the experimental tasks are likely account for the discrepancy in the findings. Significant differences were observed in the horizontal velocity of BMC at take-off (Table 1). Therefore, the results of this study may be able to provide useful information for understanding of the control mechanisms of jumping direction and the role of the lower limb joints during jumping.

The ankle moment is a major contributor to the vertical velocity of BMC. The vertical velocity of BMC at take-off was slightly smaller in BJ than in VJ (Table 1) due to the smaller velocity of BMC produced by the knee moment (Figure 5). In BJ, the ankle exerted a large plantarflexion moment in the early part of jump motion (Figure 3). During the same period in BJ, the angle of acceleration vector of BMC produced by the knee and ankle moments and vertical velocity of BMC produced by the knee moment were smaller (Figure 6 & 5). These results indicate that the ankle exerted a large moment to compensate for the smaller vertical acceleration produced by the knee moment. For all jump conditions, the ankle exerted a plantarflexion moment during jumping, and this moment produced most of the vertical velocity. These results suggest that the ankle moment plays an important role in obtaining vertical velocity regardless of the jumping direction.

The horizontal velocity of BMC was determined by the backward velocity produced by the knee moment and the forward velocity produced by the ankle joint. In all jump conditions, the knee moment accelerated BMC backward (Figure 4), while the ankle accelerated it forward, and significant differences were observed in the horizontal velocities of BMC at take-off (Table 1). These results indicate that the magnitude of the horizontal velocity of BMC at take-off was determined by the relative magnitudes of velocities of BMC produced by the knee and ankle moments. Previous studies, including both an experimental study (Fukashiro et al., 2005) and a musculoskeletal simulation study (Nagano et al., 2007), have reported that vasti activity was reduced during push off in FJ. The results of the present study suggest that the reason for this reduction in vasti activity in FJ is to reduce the production of backward velocity of BMC by a knee extension moment.

Body configuration affected the conversion of the joint moments to acceleration of BMC. Although the angular impulse of ankle joint was significantly larger in BJ than in FJ and VJ, the forward velocity of BMC produced by the ankle moment was significantly smaller in BJ (Figure 3 & 5). In addition, although no significant difference was found in the angular impulse of the knee joint, significant differences were observed in the backward velocity of BMC produced by the knee moment (Figure 3 & 5). As the angles of the acceleration vector of BMC produced by the knee and ankle moments differed among the three jump conditions (Figure 6), the differences in the produced velocities of BMC were likely caused by the differences in the angle of the acceleration vector of BMC. Fukashiro et al. (2005) suggested that the forward lean of the trunk at the beginning of the push-off plays an important role in increasing forward velocity in the counter movement jump. As shown in Equation 5, the coefficient matrix of the joint moments that converts joint moments to translational and rotational accelerations of each segment contains matrices consisting of the inertial parameters, moment arms for joint forces, and joint constraints. Because the coefficient matrix for the joint force vector P and the geometric joint constraint C change with body configuration and the inertial parameters are constant throughout jump motions, the coefficient matrix of joint moments could be changed only through body configuration. The results of this study and the previous study indicate that the velocity of BMC was affected not only by the joint moments but also by the body configuration, and that body configuration plays an important role in the effective conversion of the joint moments to acceleration of BMC and control of the jumping direction.

In contrast with the ankle and knee moment, the
hip moment slightly accelerated BMC in all jump conditions (Figure 4). Previous studies have reported that the hip joint produces a large positive power during jumping (Ae et al., 1994; Fukashiro et al., 2005). The present results also show that the hip joint exerted a large extension moment (Figure 3), especially in the early part of the jump motion. The trunk was leaned forward at the beginning of the jump motion and recovered toward take-off (Figure 2). At the beginning of the jump motion, the hip moment produced a small vertical acceleration of BMC, and this vertical acceleration was possibly caused by the backward angular acceleration of trunk. These results indicate that the positive power of the hip joint caused this trunk rotation and that the hip moment may play a role in controlling the body configuration, especially the trunk motion during jumping, rather than accelerating BMC.

The results of this study indicate that the ankle moment produces most of the vertical velocity of BMC in all jump conditions (Figure 5). Previous musculoskeletal simulation studies have shown that biarticular muscles (rectus femoris and gastrocnemius) transfer mechanical energy from the proximal joints to the distal joints during jumping (Bobbert et al., 1986; Fujii and Moriwaki, 1992; Prilutsky and Zatsiorsky, 1994). These results of this and previous studies suggest that the velocity of BMC produced by the ankle moment was created by not only the ankle plantarflexors, but also the hip and knee extensors. The present study has quantified the horizontal and vertical velocity of BMC produced by the joint moments during jumping, and demonstrated that the velocity of BMC at takeoff was affected not only by the joint moments but also by the body configuration. However, it remains unclear to what extent body configuration affects the conversion of the joint moments to acceleration of BMC. This issue should be addressed in future studies.

5. Conclusions

In all the jump conditions investigated here, the vertical velocity of BMC was mostly produced by the ankle moment. Although no marked difference was observed in the time histories of joint moments, there were significant differences in the backward velocity produced by the knee moment and the forward velocity produced by the ankle moment among the three jump conditions. In addition, significant differences were observed in the trunk angle at the beginning of the jump motion and in the lower limb segment angles at the take-off. These results indicate that the velocity of BMC was affected not only by the joint moments, but also by the body configuration.

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References


Effects of Joint Moments on Mass Center Velocity in Jumping


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