ON THE ROLES OF BI-ARTICULAR MUSCLES DURING THE JUMPING MOVEMENTS WITH VARIOUS TAKE-OFF ANGLES

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INTRODUCTION

Many studies on maximal vertical jumps have been done in order to clarify the way human exerts ballistic movements (Bobbert and Ingen Schenau, 1988). However, humans often perform jumps with various take-off angles in various situations and the different muscular and segmental coordination may be involved in the jumps with the different take-off angles. For these reasons, it is necessary to investigate jumps in the directions other than vertical.

Eckert (1968) suggested that the motion of hip joint might play an important role in performances of standing long jumps (SLJ) and ankle and knee joints might play an important role in vertical countermovement jumps (CMJ). It was reported that the contribution of knee joint work to total joint work was smaller in SLJ than in CMJ (Robertson and Fleming, 1987). These studies led us to assume that the work of the knee joint might contribute more to the performance of the jumps with higher take-off angles and of the work of the hip joint might contribute more to those with lower take-off angles.

One needs to exert an external force to the ground in the direction opposite to the desired direction in which he/she intends to jump. In other words, it is necessary to control the direction of the ground reaction force in order to modulate the take-off angles. In many movements such as cycling (Ingen Schenau et al., 1992), contact control leg tasks (Jacobs and Ingen Schenau, 1992), backlift and leglift (Toussaing et al., 1992), it has been reported that rectus femoris (RF) and hamstrings (HAM), which are the bi-articular muscles crossing the knee and hip joints, tune the distribution of net torques about the joints and, as a consequence, control the direction of the external force exerted on the environment. Therefore, we hypothesized that the activities of RF and HAM might modulate the distribution of the torques at knee and hip joints, determine the direction of the ground reaction force and consequently control the take-off angles of the standing two-legged jumps.

The purpose of this study was to investigate, in the standing two-legged jumps, 1) the relationship between the take-off angles and the distribution of the positive works to lower limb joints and 2) the contribution of the activities of the bi-articular muscles crossing knee and hip joints to the control of the take-off angles.

METHODS

Subjects. Five male athletes of track and field (three jumpers and two sprinters; age: 19.4±1.5y, height: 1.77±0.04m, body mass: 70.2±5.8kg) participated in this study. They were informed about all procedures to be used and signed a statement of informed consent, in accordance with the ACSM policy statement regarding the use of human subjects and informed consent. The ethical committee of our institution (Graduate School of Human and Environmental Studies, Kyoto University) has approved the experimental procedures.

Procedures. First of all, the subjects performed three counter-movement jumps (CMJ) and standing long jumps (SLJ) with their maximal efforts. In CMJ they were instructed to jump as high as possible, and in SLJ as far as possible. In CMJ each jump height was calculated using the flight time measured by a force platform, and in SLJ each jump distance (from the tip toe at the starting position to the heel when landing) was manually measured. Maximal jump height and maximal jump distance for each subject were determined by averaging the three records.

We assumed that the take-off angle of SLJ was 45 degrees, which was an ideal angle to jump as far as possible. Similarly, the take-off angle of CMJ was assumed to be 90 degrees. The take-off angle was defined as the angle between the velocity vector of the center of the body mass (CBM) and the horizontal line when the toes lost contact with the force platform. In order to vary the take-off angles between 45 degrees (SLJ) and 90 degrees (CMJ), each subject was instructed to jump with maximal effort and land on the marks which located at 50.0% and 86.6% of the maximal jump distance (assuming that 1) the height of CBM at the take-off and that at the landing were identical, 2) the take-off velocity of all the jumps were identical). By landing on the instructed spots, the subjects were able to perform jumps with the take-off angle of approximately 60 degrees (86.6%) and 75 degrees (50.0%).

After some practice jumps, each subject performed three jumps maximally with take-off angles of approximately 60 and 75 degrees. In all jumps, they were instructed to start from upright standing on a force platform and keep their hands on their hips. They were also allowed to make counter-movements.

Kinematics and Kinetics. Five reflective markers were placed on fifth metatarsophalangeal joint, lateral malleolus, lateral femoral epicondyle of the knee, greater trochanter and acromion on the right side of the subjects’ body. The jumping movements were filmed from the right side of the subjects (60 frames/s) using a two-dimensional kinematic optoelectric system (Quick MAG OKK Inc, Japan). The coordinates of the marker points were smoothed using the Butterworth low-pass filter (2nd order, zero lag). The cut-off frequency of this filter was determined in every marker (Winter, 1990). These filtered body markers defined the position of the four body segments: foot, shank, thigh, and head-arms-trunk (HAT) segments. Angles of the hip, knee, and ankle joints were calculated. Linear and angular velocities and accelerations of the segments were calculated by numerical differentiation.

Vertical and fore-aft components of the ground reaction force and its point of application were measured using a force platform (Kistler, model 9281B, Kistler Instruments, Switzerland) and sampled at 1200Hz. The angle of the ground reaction force vector, which was defined as the angle between the vector and the horizontal line, was calculated. After synchronization of the film and force platform data, resultant joint reaction forces and resultant joint torques were
calculated for the hip, knee and ankle joints using four link-segment models. The segmental masses, the mass center location of each segment, and their moment of inertia were estimated using the data from Dempster (1955) and the individual subjects’ anthropometric data. Extension torque was considered positive at all joints. Joint powers of ankle, knee, and hip joints were also calculated by multiplication of the net joint torques and the joint angular velocities. Positive work for each joint was calculated by integrating the joint power curve while it was positive. The contribution of each joint work to the total joint work (the sum of the work of ankle, knee, and hip) was calculated.

The movement duration was defined as the phase between the instant that the vertical component of the ground reaction force started to decrease and the instant that the toes lost contact with the force platform. The distance between the point where the ground reaction force applied and the center of body mass was calculated. The push-off phase was determined from the instant that this distance was the shortest to the end of the movement duration. The performances of the four kinds of jumps were evaluated from their take-off velocities. The take-off velocity was defined as the magnitude of the velocity vector of the center of body mass at the end of the movement time.

Electromyography. Pairs of disposable bipolar surface electrodes (Ag/AgCl, with leadoff area 3.0 cm²) were applied to the right lower limb after standard skin preparation techniques. They were placed in longitudinal direction, with center-to-center distance of 3.0cm, on the skin covering gluteus maximus (GM), rectus femoris (RF), long head of biceps femoris (BF), vastus lateralis (VL), and lateral head of gastrocnemius (GAS). The electromyographic (EMG) signals were amplified (band-pass filtered between 5 and 500Hz) and sampled at 1200Hz.

After the digitized EMG signals were high-pass filtered (2nd order Butterworth high-pass filter with cutoff frequency of 7Hz) to eliminate movement artifacts they were full-wave rectified. Subsequently EMG signals were normalized by expressing them as a fraction of the maximum value attained of all the trials. Then, integrated normalized EMG signals (IEMG) were calculated for each muscle by integrating EMG signals during the push-off phase.

MTC Length. The length changes of the muscle-tendon complex (MTC) during the jumping movements were estimated for GM, RF, BF, VL, and GAS using the joint angle changes and the coefficients derived from the previous studies (GM: Nemeth and Ohlsen, 1985, RF, BR, VL: Visser et al., 1990, GAS: Grieve et al., 1978). The MTC length at the upright standing was set as a reference length. The length changes from the reference length were expressed as a percentage of segment lengths (GM, RF, BF, VL: thigh segment, GAS: shank segment). The length change data of four kinds of jumps were averaged at each percentage of the movement duration across three trials and five subjects.

RESULTS

Jump Performance. The averaged movement durations, push-off durations, take-off angles, take-off velocities, positive joint work, and joint work contribution of the four kinds of jumps (SLJ, SLJ60, SLJ75, CMJ) are presented in Table 1. The averaged take-off angle

<table>
<thead>
<tr>
<th>Table 1: kinematic and kinetic variables of the four kinds of jumps</th>
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<tr>
<td><strong>SLJ</strong></td>
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<tr>
<td>movement duration (s)</td>
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<tr>
<td>push-off duration (s)</td>
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<tr>
<td>take-off angle (deg)</td>
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<td>take-off velocity (m·s⁻¹)</td>
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<td>positive joint work (joule)</td>
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<td>joint work contribution (%)</td>
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The averaged movement durations, push-off durations, take-off angles, take-off velocities, positive joint work, and joint work contribution of the four kinds of jumps (SLJ, SLJ60, SLJ75, CMJ) are presented in Table 1. The averaged take-off angle in each jump corresponded well to given instructions.

Figure 1 shows the stick diagrams of the jumping movements during a) SLJ, b) SLJ60, c) SLJ75, and d) CMJ (one subject). The mean curves of joint torque at the a) ankle, b) knee, and c) hip joints are depicted in Figure 2. They are expressed as a fraction of each subject’s body mass.
Correlation Analysis. Figure 3 shows the relationships between the take-off angles and the positive work (expressed as a fraction of each subject's body mass) at hip joint. There is a significant negative correlation between them (r = -0.687, p < 0.001). There was a significant but weak positive correlation at the knee joint (r = 0.471, p < 0.001). At the ankle joint, the correlation coefficient between the joint work and the take-off angles was very low (r = 0.059, n.s.).

![Figure 1: Stick diagrams of the jumping movements during a) SLJ, b) SLJ60, c) SLJ75, d) CMJ (one subject). Time elapsed from left to right panel. Dotted line: ground reaction force vector, star: center of body mass, angle: take-off angle (deg), velocity: take-off velocity (m/s).](image)

The coefficients of correlation between IEMG of the lower limb muscles and the take-off angles were —0.200 (n.s.) at GAS, —0.047 (n.s.) at VL, 0.292 (p < 0.01) at RF, —0.618 (p < 0.001) at BF, and 0.022 (n.s.) at GM. There was a significant but weak positive correlation at RF, and a significant negative correlation at BF. Figure 2: Mean curves (n=5) of joint torque at a) ankle, b) knee, c) hip joints during SLJ, SLJ60, SLJ75, CMJ as a function of standardized movement time (100-0% from start of the downward movement to take-off). Joint torque was expressed as a fraction of each subject's body mass (kg). Extension torque was considered positive at all joints.
4 shows the IEMG of hip extensors (BF and GM) as a function of the take-off angles.

![Graph showing IEMG of hip extensors](image)

**Figure 3.** Relationship between the take-off angle and the positive joint work at the hip joint. All individual data are shown.

Figure 5 shows the changes of the angle of the ground reaction force vector during the four kinds of jumps (SLJ, SLJ60, SLJ75, CMJ). The angles were averaged at each percentage of the movement duration across three trials and five subjects.

**MTC Length.** The length of the muscle tendon complex changed similarly among the four kinds of jumps at GAS, VL, and GM. Take-off angles modulated the length changes in RF and BF (Figure 6). The patterns of BF length changes didn’t vary among the jumps with different take-off angles. But, as the take-off angle was increased, the peak values of BF lengthening were decreased. By contrast in RF, the take-off angles changed the pattern of the length change. When the take-off angle was small, RF was lengthened almost through the movement duration and shortened a little just prior to the take-off. When the take-off angle was large, RF was shortened largely during the latter half of the push-off phase. And at the beginning of the push-off phase, RF length was little changed.

**DISCUSSION**

In the present study, the subjects were instructed to control the take-off angles by means of landing on the corresponding marks. Jensen and Phillips (1991) used overhead targets to make their subjects control take-off angles. In their study, the differences between the average take-off angles and the overhead target angles were increased at lower take-off angles, and the standard deviations of the take-off angles were larger than those in our study. Therefore, the way used in the present study to control jump distance might be better than the way using the overhead targets.

Some studies have showed the kinematic and kinetic features of CMJ and SLJ (see introduction). They suggested that the motion of the hip joint would play an important role in the performance of SLJ and the motion of the knee joint might in CMJ. Our results that the positive work at the knee joint was increased and at the hip decreased as the take-off angle was increased (Table 1 and Figure 3) supported their suggestion. These results indicated that the ratio of the positive joint work between hip and knee was the important factor that determines the take-off angle in standing two-legged jumps.

The direction of the ground reaction force vector determines the direction of acceleration of the center of body mass as well as the angular momentum of the body with respect to its center of mass during jumping (van Ingen Schenau, 1989). In our results, during the jumping movements with lower take-off angles the subjects exerted backward force on the force platform (Figure 1 and 5). When exerting a backward force to environment, the moment arm length of the ground reaction force vector is larger around the hip joint and smaller at the knee joint than when exerting a force in the vertical direction (Figure 1). These differences in moment arm lengths of ground reaction force explain partially the results that larger hip joint work and smaller knee joint work were required in the jumps with lower take-off angles.

Both gluteus maximus and long head of biceps femoris functioned as hip extensors during the push-off phase of the jumping movements in the present study. However, IEMG of BF was correlated with the take-off angle while that of GM was not (Figure 4). This indicates the different roles between mono- (GM) and bi-articular muscles. Although there’s no linear relationship between EMG signal and muscle force in dynamic movement because of the muscle intrinsic properties (e.g. force-length-velocity relation), it is natural to attribute the increased hip joint work and the
decreased knee joint work during the jumps with the lower take-off angles mainly to the increased activity of BF. From this result, we speculated that in order to increase the hip joint work and decrease the knee joint work the central nervous system (CNS) would apply the simpler strategy of increasing the activity of bi-articular muscle of BF, rather than that of increasing the activity of mono-articular hip extensor (GM) and decreasing the activity of mono-articular knee extensor (VL). Additionally based on the present results, one could speculate that in backward jumps CNS might increase the activity of RF and consequently increase the knee joint work and decrease the hip joint work.

It has been reported in various movements that the activities of the bi-articular muscles crossing knee and hip joints distributed net torques between these joints. Ingen Schenau et al. (1995) suggested that mono-articular muscles were activated in such a way that they contributed to positive work and irrespective of the required distribution of the net torques about the joints that were crossed. Based on these studies, the researchers have suggested the hypothesis that mono-articular muscles might be used as work generators (active when shortening), while bi-articular muscles might be used to manipulate joint torques such that the resulting force direction meets the specific task demands. This hypothesis was based on the experimental results obtained during static or quasi-static tasks. In such a ballistic and dynamic motion like a maximal jump where the coordination of movement is more complicated, we could not show clear relationship between the activity of bi-articular muscles and joint torque or exerted force. Though it is undoubtedly that long head of biceps femoris is a bi-articular muscle crossing the hip and knee joint plays an important role in controlling the directions of jumping movements.

The length changes of the muscle tendon complex at RF and BF were modulated by the take-off angles (Figure 6). The MTC shortening of BF was increased with the decreased take-off angles. This increased shortening of BF increased the potential to exert muscle work, which was favorable to increase the hip joint work. The patterns of the length change curve at RF were adjusted by the take-off angles. In the jumps with the lower take-off angles, RF would hardly contributed to the positive work at knee joint because RF was lengthened almost through the push-off phase. On the other hand, in the jumps with the higher take-off angles RF would contributed greatly to the positive work at knee joint because of its large MT shortening.

It has been suggested that bi-articular muscles transfer mechanical energy from proximal joints to distal joints in vertical jumps, which were called "tendon action" (Prilutsky, 1994). The different pattern of MTC length change between jumping movements with various take-off angles would regulate this energy transfer. To clarify the details of how muscle and tendon behave respectively during the jumping movement with various take-off angles, the study using musculoskeletal model are needed in future.

SUMMARY

Five male athletes exerted two-legged countermovement jumps with the take-off angles of approximately 45, 60, 75, and 90 degrees with maximal effort. We found the increased activities of long head of biceps femoris during the push-off phase of the jumping movements with the lower take-off angles. The activities of BF would predominantly determine the proportion of the positive joint work between hip and knee joints, consequently controlled the take-off angle.

REFERENCES


