MUSCLE CONTRIBUTIONS TO BODY MASS CENTER VELOCITY DURING VERTICAL AND FORWARD JUMPING

Yuta Suzuki[1], Yasuto Kobayashi[2], Munenori Murata[3], and Megumi Takizawa[2]

Osaka City University, Osaka, Japan[1]
Ibaraki Prefectural University of Health Sciences, Ami, Japan[2]
Japan Institute of Sports Sciences, Tokyo, Japan[3]

The purpose of this study was to quantify the horizontal and vertical velocities of the body mass center produced by the lower limb muscles during vertical and forward jumps. Vertical and forward jumps were simulated using a model of the musculoskeletal system consisting of four rigid segments actuated by six leg muscles. It was found that most of the vertical velocity of the body mass center was produced by the soleus and gastrocnemius in both jump conditions. The horizontal velocity at take-off was larger for the forward jump, caused by a larger forward velocity produced by the hamstrings, soleus, and gastrocnemius and a smaller backward velocity produced by the vasti and rectus femoris. The force development patterns were different only in the hamstrings and rectus femoris, indicating that these bi-articular muscles may play an important role in the control of jumping direction.

KEY WORDS: squat jump, equation of motion, forward dynamic simulation, muscle function

INTRODUCTION: Jump motion is one of the most fundamental motion techniques for humans. To jump higher or further, we need to produce a greater velocity of the mass center of the body until take-off. Because the lower limb joint moments caused by muscle forces produce most of the velocity of the body mass center, some studies have investigated the roles of lower limb joints using kinematic, kinetic, and electromyographic measurements (Fukashiro et al., 2005; Robertson and Fleming, 1987). In addition, Ridderikhoff et al. (1999) and Nagano et al. (2007) investigated the differences in joint kinetics and muscle activities between vertical and forward jumps using a computer simulation technique. These studies have identified the changes in the joint kinetics and muscle activities of the lower limb with jumping direction but have not demonstrated how these differences affected the production of the body mass center velocity and the control of jumping direction. The purpose of this study was to quantify the horizontal and vertical velocity of the body mass center produced by the lower limb muscles during vertical and forward jumps.

METHODS: Vertical (VJ) and forward squat jumps (FJ) were simulated using a forward dynamic model of the musculoskeletal system (Fig. 1). The musculoskeletal system consisted of four rigid segments (head-arms-trunk, thighs, shanks, and feet) connected with hinge joints. In this model, six muscle-tendon complexes (gluteus maximus (GLU), hamstrings (HAM), vasti (VAS), rectus femoris (REC), soleus (SOL), and gastrocnemius (GAS)) were implemented. A Hill-type muscle model consisting of a contractile element, a series elastic element, and a parallel elastic element was used to represent each of these six muscle-tendon complexes. Activation dynamics of muscles were modeled according to Hatze (1981) and Bobbert & van Zandwijk (1999). The stimulation of each muscle was increased toward its maximum of 1.0 and subsequently decreased toward its minimum of 0.

For simulation of the VJ, the initial body configuration was set as follows: (1) the hip and knee joints were flexed 90 degrees and the ankle joint was dorsiflexed 20 degrees from the upstanding position; and (2) all segments were rotated to make the vector from the center of pressure to the mass

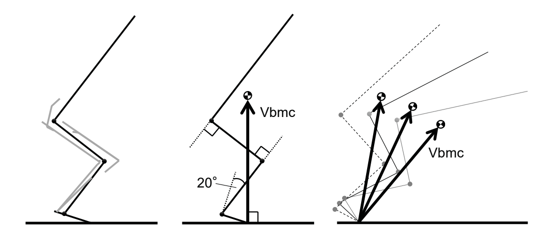

Fig.1 Model of the musculoskeletal system used in this study and the body configurations at the start of vertical and forward jumps.

center of body (Vmcb) vertical (Fig. 1). The initial activation level of each muscle was determined to keep the initial body configuration. The stimulation onset and offset times of each muscle were optimized to obtain the maximum jump height.
For the FJ, the initial joint angles and muscle activities were the same as in the VJ. However, the angle of Vmcb relative to the vertical axis at the start of simulation was changed from 5 to 40 degrees, and simulations were performed every 5 degrees (i.e., 8 jumps were simulated in total). As with VJ, the stimulation onset and offset times of each muscle were optimized to maximize the jump distance. Because the maximum horizontal distance was observed at 25 degrees, this value was chosen for FJ.
For the obtained VJ and FJ, the horizontal and vertical velocities of the body mass center produced by the six muscles were calculated according to Koike et al. (2007).

RESULTS: Stick diagrams and the vector of the body mass center velocity for the simulated VJ and FJ are presented in Fig. 2. The horizontal and vertical velocities of the body mass center at take-off were 0.0 m/s and 2.4 m/s for VJ and 2.3 m/s and 1.9 m/s for FJ, respectively. The vertical velocity was larger for VJ, and the forward velocity was larger for FJ.
Fig. 3 presents the changes in the muscle force development for the VJ and FJ. There were marked differences in the force development of the HAM and REC between the VJ and FJ, whereas no marked differences were observed in the other muscles. The muscle force of the HAM was larger for VJ at the beginning of the jump motion, but it then became larger for FJ. The REC produced more force in the VJ than in the FJ.
Fig. 4 presents the horizontal and vertical velocities of the body mass center produced by the six muscles. The forward velocities produced by the HAM (VJ, 0.43 m/s; FJ, 0.87 m/s), SOL (VJ, 0.70 m/s; FJ, 1.68 m/s), and GAS (VJ, 0.43 m/s; FJ, 1.02 m/s) were smaller and the backward velocities produced by the VAS (VJ, -1.31 m/s; FJ, -1.10 m/s) and REC (VJ, -0.43 m/s; FJ, -0.17 m/s) were larger for the VJ than for the FJ.

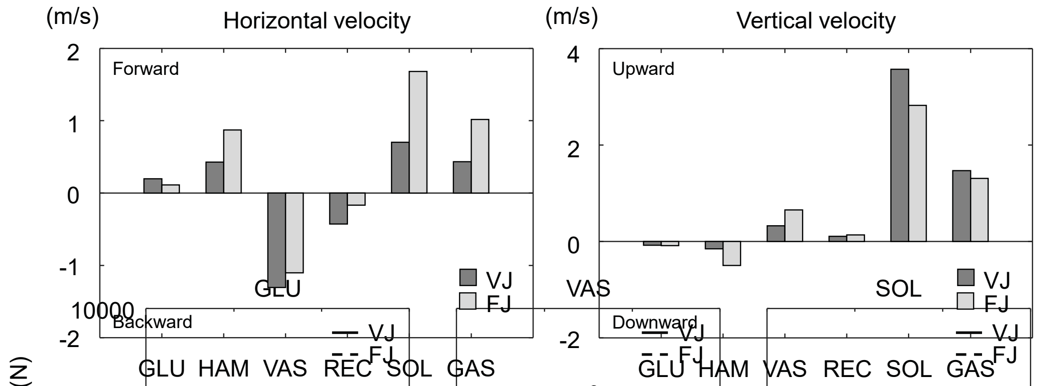

Fig. 4 Horizontal and vertical velocities of the body mass center produced by each muscle.

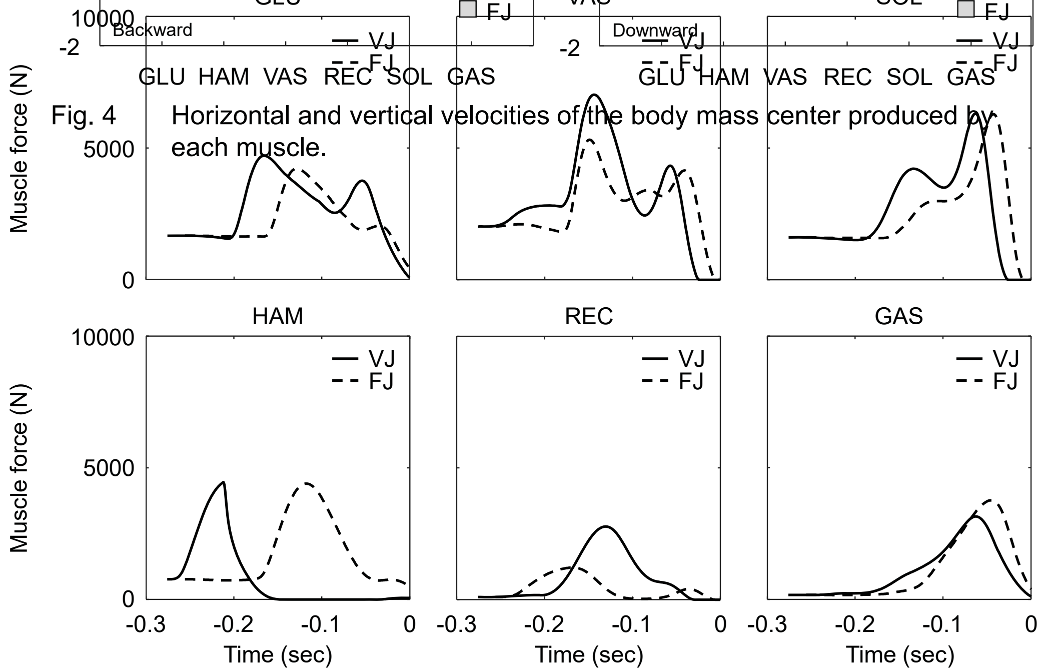

Fig. 3 Changes in the muscle force development for vertical and forward jumps.

DISCUSSION: For both the FJ and VJ, most of the vertical velocity was produced by the SOL and GAS. Because the produced vertical velocities were larger for VJ than for FJ, the vertical velocity of the body mass center at take-off was also larger for VJ. The SOL and GAS also produced forward velocities, as well as the HAM, and all of them were larger for FJ. In addition, the backward velocities produced by the VAS and REC were smaller for FJ than for VJ, so that the horizontal velocity of the body mass center at take-off was larger for FJ. While the produced velocities of the lower limb muscles were different between VJ and FJ, the patterns of force developments of these muscles were similar to each other, except for the HAM and REC. These results indicate that the differences in the produced velocity could be caused by the body configuration. The body configuration at the start of the simulation leaned more forward for FJ, so that the muscle forces were effectively converted to the forward velocity.

In this study, the force development of the bi-articular HAM and REC were different between VJ and FJ. These results are consistent with the findings of a previous study (Fukashiro et al., 2005) that compared the electromyography findings of VJ and FJ and reported that HAM activity was lower and REC activity was higher for VJ. For both VJ and FJ, the HAM produced forward velocity and the REC produced backward velocity, and both of these muscles slightly accelerated the body mass center in the vertical direction. The results of this study and a previous study thus indicate that the HAM and REC could play an important role in the control of jumping direction.

CONCLUSION: In this study, we estimated the contributions of lower limb muscles to the horizontal and vertical velocity of body mass center. While the force developments of most muscles were similar between the two jump conditions, the produced velocities were different because of the body configuration. In addition, only the HAM and REC showed different force development patterns between VJ and FJ, indicating that the HAM and REC could play an important role in the control of jumping direction.

REFERENCES:

Bobbert, M.F., and van Zandwijk, J.P. (1999). Sensitivity of vertical jumping performance to changes in muscle stimulation onset times: a simulation study. Biol. Cybern., 81, 101-108.

Fukashiro, S., Besier, T.F., Barrett, R., Cochrane, J., Nagano, A., and Lloyd, D.G. (2005). Direction control in maximal horizontal and vertical jumps. International Journal of Sports and Health Science, 3: 272-279.

Hatze H (1981) Myocybernetic control models of skeletal muscle. University of South Africa, Pretoria, pp 31-42.

Koike, S., Mori, H., and Ae, M. (2007). Three-dimensional analysis of jump motion based on multibody dynamics -The contribution of joint torques of the lower limbs to the velocity of the whole body center of gravity-. The Impact of Technology of Sport 2, Taylor & Francis: 649-654.

Nagano, A., Komura, T., and Fukashiro, S. (2007) Optimal coordination of maximal-effort horizontal and vertical jump motions- a computer simulation study. BioMedical Engineering OnLine, 6: 20

Ridderikhoff, A., Batelaan, J.H., and Bobbert, M.F. (1999). Jumping for distance: control of the external force in squat jumps. Med. Sci. Sports Exerc., 31, 1196-1204.

Acknowledgement

This work was supported by JSPS KAKENHI (15K16444).