ENERGY COST AND LOWER LIMB BIOMECHANICS OF REPEATED VERTICAL JUMPING AT DIFFERENT CONTACT TIMES

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The purpose of the present study was to examine the effects of the contact time on energy cost and lower limb biomechanics during repeated vertical jumping. Nine male Japanese distance runners jumped for three minutes on a force platform for a preferred and long contact time. Sagittal plane kinematics, ground reaction force, and electromyography (EMG) results were measured. The following results were obtained: 1) the energy cost was significantly smaller in the preferred than in long condition, 2) mechanical work of the ankle joint was significantly greater in the preferred than in long condition, 3) mechanical work of the knee joint was significantly greater in the long than in preferred condition. Therefore, a longer contact time alters the distribution of the mechanical work of the ankle and knee joints. This alteration may increase energy cost in the long condition.

KEYWORDS: running economy, stretch-shortening cycle, EMG.

INTRODUCTION: Many biomechanical factors that affect running economy have been reported. Arellano and Kram (2014) suggested that generating force to support the body weight is the primary determinant of energy cost during running, and this finding is consistent with many studies (e.g., Williams & Cavanagh, 1987). Contact time is also known as one of the factors explains running economy (e.g., Santos-Concejero et al., 2013), whereas its mechanisms have not yet been elucidated. Since running includes many tasks, such as supporting and propulsion of the body, it is difficult to elucidate these mechanisms. Seki et al. (2019) suggested that repeated vertical jumping is similar to the vertical movement during running, and jumping exercise may serve to elucidate how biomechanical factors affect the energy cost of running. Therefore, the purpose of the present study was to examine the effects of the contact time on energy cost and lower limb biomechanics during repeated vertical jumping. We hypothesized that a longer contact time might increase energy cost, since the contact time would affect the stretch-shortening cycle (SSC) action of the leg extensors.

METHODS: The subjects were nine male Japanese distance runners (age: 21.1 ± 0.8 yrs.; height: 1.73 ± 0.03 m; body mass: 62.9 ± 4.3 kg). The subjects were asked to jump vertically at a frequency of 2 Hz, guided by a metronome, for three minutes at two different contact times: preferred and long conditions. Sagittal plane kinematics were recorded using a high-speed camera (Ex-100Pro, Casio Computer, Japan) at 120 fps. An LED signal was used to synchronize the ground reaction force and electromyography (EMG) results with the kinematics. Coordinate data of the body landmarks were smoothed using a Butterworth digital low-pass filter at 10 Hz. The ground reaction force was measured using a force platform (9287B, Kistler, Switzerland) at a sampling frequency of 1kHz and smoothed using a Butterworth digital low-pass filter at 10 Hz. Joint torque of the ankle, knee, and hip joints was calculated using an inverse dynamic approach with a three rigid body model that represented the foot, shank, and thigh. Angular impulse was calculated by integrating the joint torques. Mechanical work was calculated by integrating the joint torque power, which was an inner product of the joint torque and joint angular velocity. EMG of the rectus femoris (RF), vastus lateralis (VL), gluteus maximus (GM), biceps femoris long head (BF), tibialis anterior (TA), gastrocnemius medial head (GA), and soleus (SO) muscles were recorded with active surface electrodes (SX-230, Biometrics, UK) at a sampling frequency of 1 kHz. The electrodes were placed longitudinally over the muscle bellies between the center of the innervation zone and the distal tendon of each muscle in accordance with the guideline of SENIAM. EMG data were high-pass filtered using a Butterworth digital filter at 10 Hz. Rectified EMG data were low-pass filtered using a Butterworth digital filter at 15 Hz. Integrated EMG (iEMG) was calculated by integrating rectified EMG data. Respiratory gases were continuously analyzed on a breath-by-breath basis using the computerized standard open circuit techniques (AE-301s, Minato Medical Science, Japan) (Iwayama et al., 2015). The vertical displacement of the center of mass (CoM) was defined as the difference between the highest and lowest points of the greater trochanter. Energy cost was calculated using the method of Seki et al. (2019). Kinematics, kinetics, and EMG results were averaged during the contact phase of 10 jumps from each condition which were selected stating from 2.5 min after the beginning of the 3-min jumping period. Mechanical work, angular impulse, and iEMG results were normalized by the vertical distance of the CoM. Time histories of joint kinematics and kinetics, such as joint angular velocity, were normalized based on the contact time in the preferred condition. Difference between the conditions were examined using paired t-test. The level of statistical significance was set at 5%.

RESULTS: The preferred contact time was significantly ($p < 0.001$) shorter (0.23 ± 0.03 s) than the long contact time (0.32 ± 0.04 s). The vertical displacement of the CoM was significantly ($p < 0.01$) greater in the preferred (0.24 ± 0.01 m) than in the long condition (0.21 ± 0.02 m). Energy cost was significantly ($p < 0.05$) greater in the long (26.2 ± 3.9 $J \cdot kg^{-1} \cdot m^{-1}$) than in preferred (23.0 ± 1.85 $J \cdot kg^{-1} \cdot m^{-1}$) condition.
Figure 1 shows the average joint angular velocities of the ankle, knee, and hip joints during the contact phase in each condition. The ankle joint plantarflexed immediately after dorsiflexed in the preferred condition. However, in the long condition the angular velocity of the ankle joint was slowdown after dorsiflexion during the first one-third of the contact phase. Subsequently, the ankle joint plantarflexed gradually. Maximal dorsiflexion angular velocity was significantly greater in the preferred than in long condition ($p < 0.001$). Maximal plantarflexion angular velocity and maximal extension angular velocity of the knee joint was significantly greater in the preferred than in long condition ($p < 0.001$).
Figure 2 demonstrates differences in the mechanical works of the ankle, knee, and hip joints during each contact phase. Positive mechanical work of the ankle joint was significantly greater in preferred than in the long condition ($p < 0.05$). Negative mechanical work of the ankle joint was significantly smaller in the preferred than in long condition. On the other hand, positive and negative mechanical work of the knee joint showed opposite tendencies to the ankle joint. No significant difference in the positive and negative mechanical work of the hip joint and total of the lower limb joints were found.
Figure 3 demonstrates differences in extension (plantarflexion) angular impulses of the ankle, knee, and hip joints during the contact phase. The plantarflexion angular impulse and extension angular impulse of the hip joint did not differ between the conditions. The extension angular impulse of the hip joint was significantly greater in the long than in preferred condition.

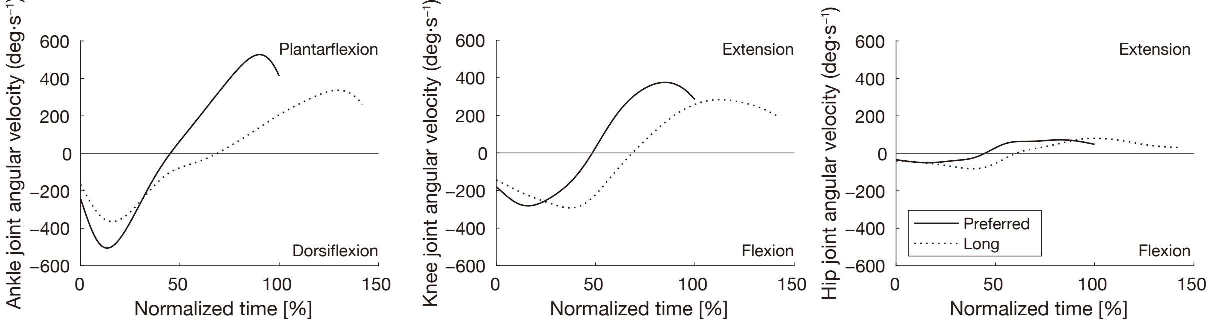

Figure 1: Average angular velocities of the ankle, knee, and hip joints during the contact phase in the preferred and long contact time conditions.

Figure 4 demonstrates the differences in iEMG of the lower limb muscles. The iEMG of the RF, VL, GM muscles during contact phase were significantly greater in long than in preferred conditions ($p < 0.05$–0.001). However, no significant differences in iEMG of the plantarflexors were observed.

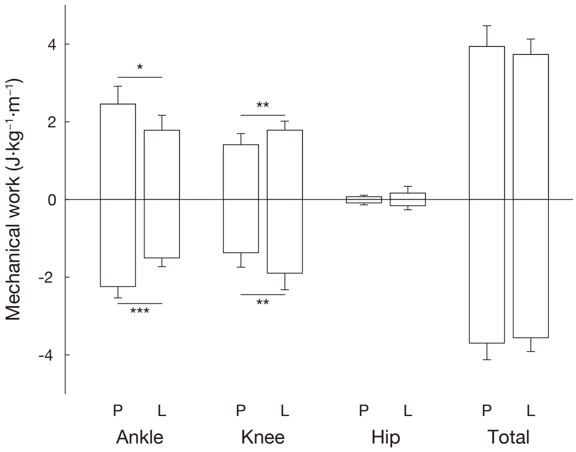

Figure 2: Mechanical works of the lower limb joints during the contact phase in the preferred (P) and long (L) conditions.
***: p < 0.05; **: p < 0.01; ***: p < 0.001.**

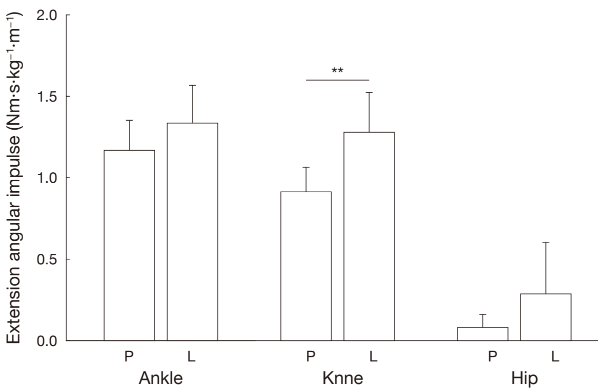

Figure 3: Extension (plantarflexion) angular impulse of the ankle, knee, and hip joints during the contact phase in the preferred (P) and long (L) contact time conditions.
****: p < 0.01.**

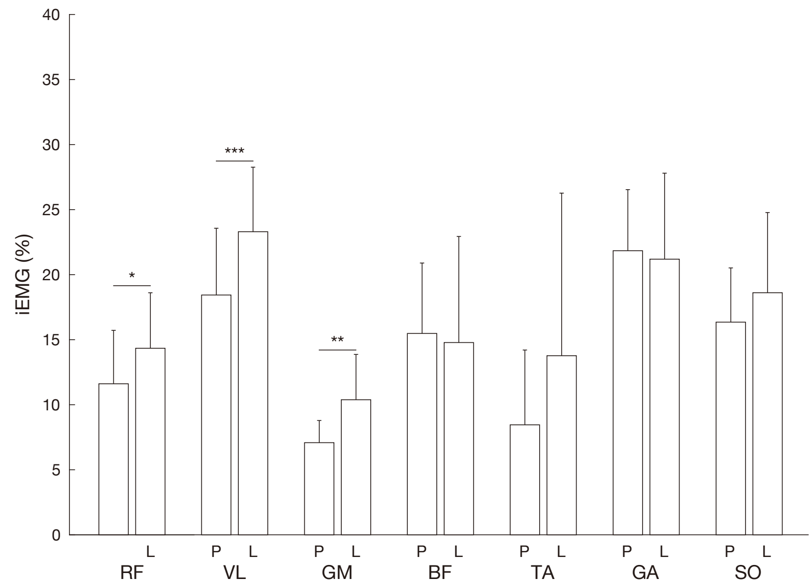

Figure 4: iEMG of the RF, VL, GM, BF, TA, GA, and SO muscles during the contact phase in the preferred (P) and long (L) conditions. *: p < 0.05; **: p < 0.01; ***: p < 0.001.

DISCUSSION: The preferred condition showed a shorter contact time and small energy cost. These results are well in line with our hypothesis. Although total mechanical work of the lower limb joints did not differ between conditions, distribution of the mechanical work did differ between the conditions. Seki et al. (2019) reported that distribution of the mechanical work could explain the difference of energy cost during repeated vertical jumping utilizing different surface slopes. Consequently, the present study suggests that longer contact time may alter joint distribution and thus increase energy cost.
Greater mechanical work of the ankle joint was found in the preferred condition. However, the plantarflexion angular impulse and iEMG of the plantarflexors did not differ between conditions. Greater dorsiflexion velocity was found in the preferred condition, which is one of characteristics of SSC action. Angular velocity of the ankle joint showed quite different patterns

at middle of the contact phase. The ankle joint showed small angular velocity at that time in the long condition. A longer contact time may prolong the time of switching from eccentric to concentric actions, and therefore increase coupling time between eccentric and concentric actions. Subsequently, performance and mechanical efficiency decreases in the present SSC action. The plantarflexors would have done SSC action in preferred condition, although its muscles might have done isolated eccentric and concentric action in the long condition. Accordingly, the ankle joint did insufficient mechanical work in the long condition.
Mechanical work of the knee joint was significantly smaller in the preferred condition as compared to the long condition. The distribution of mechanical work of the ankle and knee joints in the preferred condition may be a strategy of reducing energy cost. Sawicki et al. (2009) and Seki et al. (2019) indicated that the ankle joint has higher mechanical efficiency as compared to the knee and hip joints. Decreasing mechanical work of the knee joint would improve energy cost of the exercise. On the other hand, distribution of these mechanical works in the long condition might be a factor of greater energy cost. The knee joint generated greater extension angular impulse and mechanical work in long condition. The iEMG of the knee extensors are also greater in the long condition. The ankle and knee joints are in a trade-off relationship (Seki et al., 2019). The knee joint would compensate mechanical work in long condition, since the ankle joint did insufficient mechanical work caused by longer contact time. This compensation might increase energy cost in the long condition.

CONCLUSION: The longer contact time increased the energy cost. SSC action of the plantarflexors might have been prohibited by a longer contact time and then the ankle joint did insufficient mechanical work. The knee extensors did greater mechanical work despite their lower mechanical efficiency. These distributions of mechanical work would increase energy cost in the longer contact time.

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