EFFECT OF A BIOMECHANICAL FACTOR ON ENERGY EXPENDITURE BY DISTANCE RUNNERS DURING REPEATED VERTICAL JUMPS

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This study aimed to clarify a biomechanical factor that would affect energy expenditure during repeated vertical jumps. The subjects, nine male Japanese distance runners, jumped for 3-min periods on a force platform under four different conditions. Motion and electromyography (EMG) data were recorded with a high-speed camera and surface electrodes, respectively. The following results were obtained: 1) the integrated EMG of the rectus femoris and vastus lateralis was greater in the Low and Decline conditions than in the High and Incline conditions, and 2) mechanical work at the ankle was greater in the High and Incline conditions than in the Low and Decline conditions. Thus, increased knee extensor muscular activity may increase the energy expenditure, and the stretch-shortening contraction of the gastrocnemius muscle may be more efficient.

KEY WORDS: economy, ground contact, electromyography

INTRODUCTION: A proportion of distance running performance is influenced by the running economy (RE). Williams and Cavanagh (1987) suggested that biomechanical factors could explain more than 54% of the observed variance in RE. Many investigators have accordingly studied biomechanical factors that affect RE. Williams and Cavanagh (1987) further reported a significantly difference in the first peak of the vertical ground reaction force (GRF) between groups of runners with a high and low RE. Similarly, previous studies suggested that GRF and ground contact characteristics are related to RE (Heise & Martin, 2001). Arellano and Kram (2014) suggested that body weight support is the primary determinant of the net metabolic expenditure associated with running. However, the motions and muscular activities that affect energy expenditure during the support phase have remained unclear. McCaulley et al. (2007) reported that stretch-shortening cycle movement increased mechanical efficiency in a repeated drop jump exercise. However, the underlying mechanisms were not completely elucidated. Clarification of the relationships between biomechanical factors and energy expenditure during a continuous vertical jump would be significant. The purpose of this study was to clarify the relationship between biomechanical factors and energy expenditure during a repeated vertical jump exercise and to gain insight into the key factors needed to reduce energy expenditure in the supporting leg.

METHODS: The subjects were nine male Japanese middle- and long-distance runners (age: 21.1 ± 0.8 years; height: 1.73 ± 0.03 m; weight: 62.90 ± 4.33 kg). The subjects were asked to jump for 3 min on a force platform (1000 Hz; Kistler) at 120 bpm under the following different jumping conditions: (1) long flight time and short contact time, maintained by jumping frequency (High); (2) short flight time and long contact time (Low); (3) Incline; and (4) Decline. The latter used an 8° incline board fixed on the force platform while maintaining the jumping frequency. Jumping motion in the sagittal plane was recorded using a high-speed camera (EX-100PRO; Casio) at 120 Hz. A LED signal was used to synchronize the ground reaction force (GRF) data with the video image. Two-dimensional coordinates of nine body landmarks (toe, metatarsophalangeal joints, heel, lateral malleolus, lateral condyle, greater trochanter, anterior superior iliac spine, posterior superior iliac spine, and acromion) were obtained by digitizing the video images. Coordinate data was smoothed using a Butterworth digital filter at 4.8–10.8 Hz as a result of the residual analysis of each point. Joint torque at the hip, knee, and ankle was calculated using an inverse dynamic approach with a three rigid body model that represented the foot, shank, and thigh. Mechanical work at the hip, knee, and ankle was calculated by integrating the joint torque power, which was an inner product of the joint torque and joint angular velocity. Vertical displacement was calculated by subtracting the minimal height from the maximal height of the greater trochanter. Electromyography (EMG) of the rectus femoris (RF), vastus lateralis (VL), gluteus maximus (GM), biceps femoris long head (BF), tibialis anterior (TA), gastrocnemius (GA), and soleus (SO) was recorded using active surface electrodes (SX-230, Biometrics) at 1000 Hz. EMG data were filtered using a Butterworth digital high-pass filter at 10 Hz and subsequently rectified. iEMG was calculated by integrating the EMG data rectified during the contact phase and presented as a value relative to the High condition value. The muscle-tendon complex (MTC) length of the GA was estimated from the ankle and knee joint angles according to the method described by Grieve, Cavanagh, and Pheasant (1978). The MTC lengths of the RF, VL, BF, TA, and SO were estimated from the ankle, knee, and hip joint angles according to the method described by Hawkins and Hull (1990). The eccentric and concentric phases were divided based on changes in the MTC length. These variables were averaged for 10 jumps from the final 30 s of the 3-min period in each condition. VO_2 was analyzed using an expired gas analyzer (AE-301s, Minato Medical Science, Co., Ltd., Osaka, Japan). Differences between the conditions were tested using ANOVA. If a significant F-value was detected, pairwise comparisons were made using the Bonferroni procedure. The relationships between VO_2 and various variables were tested to calculate the Pearson product-moment correlation coefficient. The level of statistical significance was set at 5%.

RESULTS: The contact times in the High, Low, Incline, and Decline conditions were 227 ± 28, 320 ± 38, 241 ± 38, and 253 ± 39 ms, respectively. The contact time in the Low condition differed significantly from those in the High ($p < 0.001$), Incline ($p < 0.01$), and Decline conditions ($p < 0.01$). The vertical displacements in the High, Low, Incline, and Decline conditions were 0.242 ± 0.012, 0.207 ± 0.021, 0.236 ± 0.024, and 0.229 ± 0.017 m, respectively. Similarly, the vertical displacement in the Low condition differed significantly from those in the other conditions (High, $p < 0.01$, Incline, $p < 0.05$, Decline, $p < 0.05$). The $\dot{V}O_2$ values in the High, Low, Incline, and Decline conditions were 31.9 ± 1.5, 32.0 ± 2.5, 30.1 ± 3.4, and 33.8 ± 3.9 $ml \cdot kg^{-1} \cdot min^{-1}$, respectively. The $\dot{V}O_2$ was significantly higher in the Decline condition than in the Incline condition. Figure 1 presents the $\dot{V}O_2$ in each condition. The $\dot{V}O_2$ in the Decline condition was significantly higher than that in the Incline condition ($p < 0.001$). Figure 2 demonstrates the mechanical work at the ankle, knee, and hip in each condition. In the ankle, significant differences in mechanical work were observed between the Incline and the Low ($p < 0.001$) and Decline conditions ($p < 0.01$) and between the High and Low conditions ($p < 0.01$). Furthermore, significant differences in mechanical work at the knee were observed between the Incline and the other three conditions (High: $p < 0.001$, Low: $p < 0.01$, Decline: $p < 0.05$). The total mechanical work values of the three joints in the High, Low, Incline, and Decline conditions were 1.82 ± 0.04, 1.48 ± 0.06, 1.73 ± 0.06, and 1.64 ± 0.06 $J \cdot kg^{-1}$, respectively. The total mechanical work in the Low condition differed significantly from the corresponding values in the High ($p < 0.01$), Incline ($p < 0.01$), and Decline conditions ($p < 0.05$).

Figure 3 shows the average joint angle and joint torque patterns at the ankle, knee, and hip in each condition. In all conditions, the joint angles at these locations exhibited flexion during the first half, followed by extension in the second half. The ankle torque exhibits plantar flexion throughout the contact phase in each condition. The knee joint exhibited extension torque throughout the contact phase in all conditions. Figure 4 shows the iEMG values for the RF, VL, GM, BF, TA, GA, and SO. Significant differences in the iEMG of the RF were observed from the Incline to Low ($p < 0.05$) and Decline conditions ($p < 0.05$). The iEMG of the VL in the Low condition was significantly greater than that in the Incline condition ($p < 0.05$). The iEMG of the BF in the Decline condition was significantly greater than that in the Low condition ($p < 0.01$). Regarding the difference between the High and Low conditions, the $\dot{V}O_2$ correlated positively with the iEMG of the RF ($r = 0.76$, $p < 0.05$) and mechanical work at the hip ($r = 0.67$, $p < 0.05$).

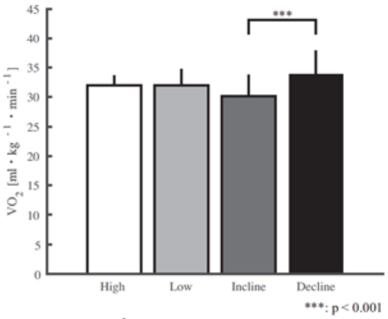

Figure 1: $\dot{V}O_2$ in each condition.

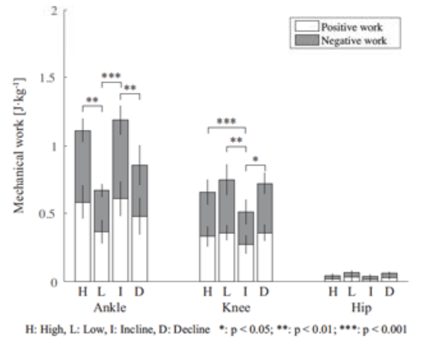

Figure 2: Mechanical work at the ankle, knee, and hip.

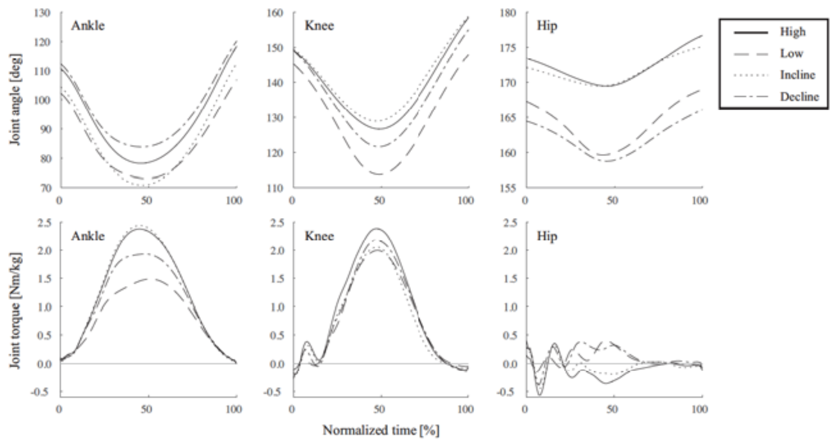

Figure 3: Average joint angle and joint torque patterns in the ankle, knee, and hip in each condition.

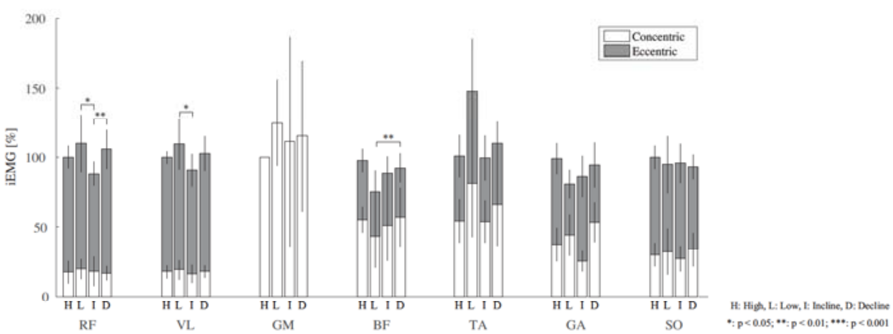

Figure 4: iEMG values of each muscle during contact in each condition.

DISCUSSION: Among all of the conditions, the $\dot{V}O_2$ was lowest in the Incline condition. The vertical displacement was significantly lower in the Low condition than in the other conditions. The total mechanical work was greater in the High and Incline conditions than in the Low and Decline conditions. Although the total mechanical work was significantly lower in the Low condition than in the other conditions, no significant difference in $\dot{V}O_2$ was observed between the Low condition and the other three conditions. Efficiency was determined by dividing the total mechanical work by the energy expenditure. The findings suggest that the efficiency tended to be greater in the High and Incline conditions than in the Low and Decline conditions.

Mechanical work at the knee was greater in the Low and Decline conditions than in the High and Incline conditions. The iEMGs of the RF and VL were greater in the Low and Decline conditions than in the High and Incline conditions. In addition, a significant positive correlation was observed between the change in $\dot{V}O_2$ and change in iEMG of the RF from the High to Low condition. This finding suggests that energy expenditure might be related to knee extensor muscular activity.

The mechanical work at the ankle was greater in the High and Incline conditions than in the Low and Decline conditions. In addition, the ratios of negative to positive work were greater in the High and Incline conditions than in the Low and Decline conditions. The ratio of eccentric to concentric iEMG phases at the GA was greater in the High and Incline conditions than in the Low and Decline conditions. A previous study reported that the energy expenditure for negative work was dramatically less than that for positive work (Cavanagh & Kram, 1985). Greater muscular activity in the GA during the concentric phase in the High and Low conditions might contribute to reduced efficiency. Bosco et al. (1982) reported that a greater ratio of eccentric to concentric iEMG phases was associated with high efficiency, and suggested the utilization of stored elastic energy. In addition, Holt, Roberts, and Askew (2014) reported that the energy expenditure for a stretch-shortening cycle was significantly lower than that of a shortening movement alone. These findings suggest that jumping efficiency might be a major factor in energy expenditure, and the stretch-shortening contraction in the GA is one of the greatest features of jump efficiency; although the GA work increases, the energy expenditure decreases.

CONCLUSION: iEMGs of RF and VL were greater in the Low and Decline conditions than in the High and Incline conditions. The mechanical work at the ankle was greater in the High and Incline conditions than in the Low and Decline conditions. In addition, the ratio of negative to positive work was greater in the High and Incline conditions than in the High and Incline conditions. Therefore, increased knee extensor muscular activity may affect the energy expenditure, and stretch-shortening contraction of the GA may affect efficiency.

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