EFFECT OF BIOMECHANICAL FACTORS ON ENERGY COST DURING RUNNING AT VARYING INCLINES

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This study aimed to investigate the characteristics of muscular activity of a support leg that affected energy cost at different inclinations of a treadmill while running. Eleven male Japanese distance runners ran on a treadmill at 13.5 km·h^{-1} for 3 min at five different inclinations: −6%, −3%, 0%, +3%, and +6%. Running kinematics, electromyography (EMG), expired gases, and blood lactate levels were measured. The following results were obtained: 1) the energy cost and integrated EMG (iEMG) of the vastus lateralis (VL) muscle increased with increasing inclination, and 2) iEMG of the VL and gluteus maximus (GM) muscles positively correlated with the vertical displacement of the body's center of mass and with a maximal angle of the thigh during the contact phase. Thus, the muscular activities of VL and GM might increase the energy cost while running at an inclination.

KEY WORDS: running economy, ground contact, electromyography

INTRODUCTION: Energy cost is a kind of running economy (RE) and is defined as the energy required to cover a unit distance. RE is related to distance running performance (Conley & Krahenbuhl, 1980). Williams and Cavanagh (1987) suggested that biomechanical factors could explain >54% of the observed variances in RE. Earlier studies (Arellano & Kram, 2014; Teunissen, Grabowski, & Kram, 2007) suggested that generating force to support the body weight is the primary determinant of energy cost during running. The force to support the body weight might be related to the vertical displacement to continuously raise the body's center of mass (CoM) during running. The kinematics of the lower limb with respect to the vertical raise of a body might affect energy cost. However, kinematic factors that affect energy expenditure during the support phase remain unclear. Changing the vertical displacement of the body's CoM may help in clarifying the kinematics characteristics that affect energy cost. The vertical displacement of the body's CoM can be altered by manipulating the inclination of a treadmill. In addition, measuring the muscular activity might help in clarifying its characteristics because earlier study has reported that muscular activity was related to energy expenditure (Bigland-Ritchie & Woods, 1976). Therefore, the present study aimed to clarify the characteristics of muscular activity of a support leg that affected energy cost while running at five different inclinations.

METHODS: The subjects were 11 male Japanese middle- and long-distance runners (height: 1.71 ± 0.05 m; body mass: 59.8 ± 4.29 kg). They were given their informed consent prior to participation in this study. This experiment was approved by the ethical committee in Faculty of Health and Sport Sciences, University of Tsukuba, Japan in accordance with the declaration of Helsinki. They were asked to run on a treadmill (Ohtake Root Kogyo, Japan) at 13.5 km·h^{-1} for 3 min at different inclinations: −6%, −3%, 0%, +3%, and +6%. Running kinematics were recorded using motion capture systems (Vicon MX, Vicon Motion systems) at 250 Hz. Thirty-nine reflective markers (hand, wrist, elbow, shoulder, toe, 5th metatarsal bone, heel, lateral malleolus, shank, lateral condyle, thigh, greater trochanter, anterior superior iliac spine, posterior superior iliac spine, head, ear, suprasternal notch, 7th cervical vertebrae, xipoid process, 10th thoracic vertebrae, and lower end of rib) were attached to body landmarks and reflective tape was attached to a belt of the treadmill to detect its speed. Coordinate data were smoothed using a Butterworth digital filter at 10 Hz. Kinematic variables on sagittal planes such as joint and segment angles and vertical displacement of the body's CoM were calculated. Electromyography (EMG) of the rectus femoris (RF), vastus lateralis (VL), gluteus maximus (GM), long head of biceps femoris (BF), tibialis anterior (TA), gastrocnemius (GA), and soleus (SO) muscles was recorded using active surface electrodes (SX-230, Biometrics) at 1000 Hz. 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 guideline of SENIAM. Isometric voluntary contractions (MVC) were measured prior to running trials to normalize EMG data. Running kinematics and EMG data were synchronized using the Vicon Nexus Software (Vicon Motion Systems). EMG data were high-pass filtered using a Butterworth digital filter at 10 Hz and subsequently rectified. Integrated EMG (iEMG) was calculated by rectifying and integrating EMG data during the contact phase. iEMG was normalized by a step length to obtain a value for covering a unit distance, similar to energy cost. These variables were averaged by analyzing 10 running cycles from the final 30 s of the 3-min period in each condition. Respiratory gases were continuously analyzed on a breath-by-breath basis using the computerized standard open circuit technique (AE-301s Minato Medical Science, Japan) (Iwayama et al., 2015). Blood samples were drawn from a fingertip for analyzing blood lactate (B-La) levels at rest. Energy expenditure was calculated using an energy equivalent of 20202 $J \cdot L^{-1}$ oxygen at a respiratory exchange ratio (R) of 0.82, in which a change of ±0.01 correlated with ±50 J changes in energy expenditure (Kyröläinen, Belli, & Komi, 2001). When B-La levels were >2.0 $mM \cdot L^{-1}$, energy expenditure was then calculated on the basis of an equivalent of 60 $J \cdot kg^{-1} \cdot mM^{-1}$ (3 mL $O_2 \cdot kg^{-1} \cdot mM^{-1}$) (Kyröläinen et al., 2001). This value was added to the overall energy expenditure. The energy cost was then calculated as the energy expenditure divided by the running speed. Differences between the test conditions were examined using ANOVA. If a significant F-value was detected, pairwise comparisons were made using the Tukey procedure. The associations between different variables were tested to calculate the Pearson product-moment correlation coefficient. The statistical significance level was set at 5%.

RESULTS: The mean ± SD step lengths at −6%, −3%, 0%, +3%, and +6% were 1.28 ± 0.06, 1.27 ± 0.06, 1.26 ± 0.06, 1.25 ± 0.05, and 1.24 ± 0.05 m, respectively. The respective step frequencies were 2.90 ± 0.14, 2.93 ± 0.14, 2.96 ± 0.14, 2.99 ± 0.14, and 3.03 ± 0.13 Hz. The oxygen uptake at −6%, −3%, 0%, +3%, and +6% were 33.7 ± 4.1, 38.4 ± 4.5, 43.3 ± 3.6, 51.5 ± 4.1, and 58.2 ± 4.0 $ml \cdot kg^{-1} \cdot min^{-1}$, respectively. Figure 1 demonstrates the significant differences in the energy costs at different inclinations. There were significant differences in the energy cost among all inclination conditions. Figure 2 demonstrates the vertical displacement to raise CoM for covering a running distance of 1 km at each condition. There were significant differences in the vertical displacement among all inclination conditions. Furthermore, the vertical displacement positively correlated with the energy cost ($r = 0.90$; $p < 0.001$).

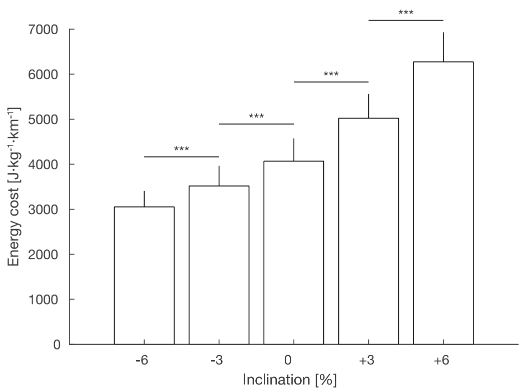

Figure 1: Mean (±SD) energy costs in each condition.

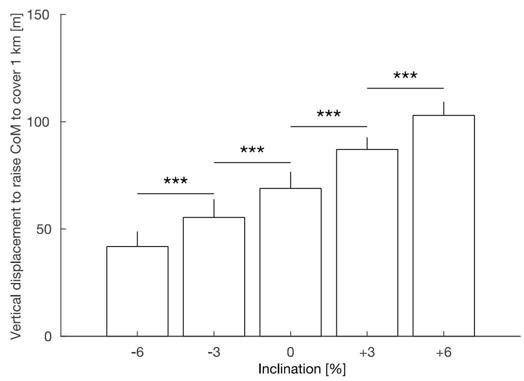

Figure 2: Mean (±SD) vertical displacement to raise the body's CoM to cover 1 km in each condition.

Figure 3 shows iEMG of the RF, VL, GM, BF, TA, GA, and SO muscles during the contact phase over a distance of 1 km. There were significant differences in the iEMG of the VL muscles between −6% and 0%, −3% and 0%, −3% and +3%, and 0% and +6%. There were significant differences in iEMG of SO muscles between −6% and −3%, −3% and 0%, −6% and 0%, −3% and +3%, −3% and +6%, and 0% and +6%. The iEMG of GA muscles positively correlated with the energy cost ($r = 0.38$; $p < 0.01$). The iEMG of the VL ($r = 0.27$; $p < 0.05$) and GM ($r = 0.38$; $p < 0.01$) muscles positively correlated with the vertical displacement. Figure 4 demonstrates the averaged patterns of the foot, shank, and thigh segment angles during the contact phase at each inclination. The maximal angles of the thigh during the contact phase at −6%, −3%, 0%, +3%, and +6% were 26 ± 3, 27 ± 2, 28 ± 2, 30 ± 2, and 32 ± 3 degrees, respectively. There were significant differences in the maximal angles of the thigh during the contact phase among all inclinations, except between −6% and −3%. The maximal angle of the thigh during the contact phase positively correlated with the energy cost ($r = 0.48$; $p < 0.001$); the vertical displacement ($r = 0.64$; $p < 0.001$); and iEMG of the RF ($r = 0.27$, $p < 0.05$), VL ($r = 0.46$, $p < 0.001$), and GM ($r = 0.29$, $p < 0.05$) muscles. The angular displacements of the thigh during the contact phase at −6%, −3%, 0%, +3%, and +6% were 46 ± 3, 46 ± 3, 48 ± 3, 49 ± 3, and 52 ± 4 degrees, respectively. There were significant differences in the angular displacement of the thigh during the contact phase among all conditions, except between 0% and +3%. The angular displacement of the thigh during the contact phase positively correlated with the energy cost ($r = 0.43$; $p < 0.01$), the vertical displacement ($r = 0.45$; $p < 0.01$) and iEMG of the RF muscles ($r = 0.46$; $p < 0.001$) and negatively correlated with iEMG of the VL muscles ($r = −0.37$; $p < 0.01$).

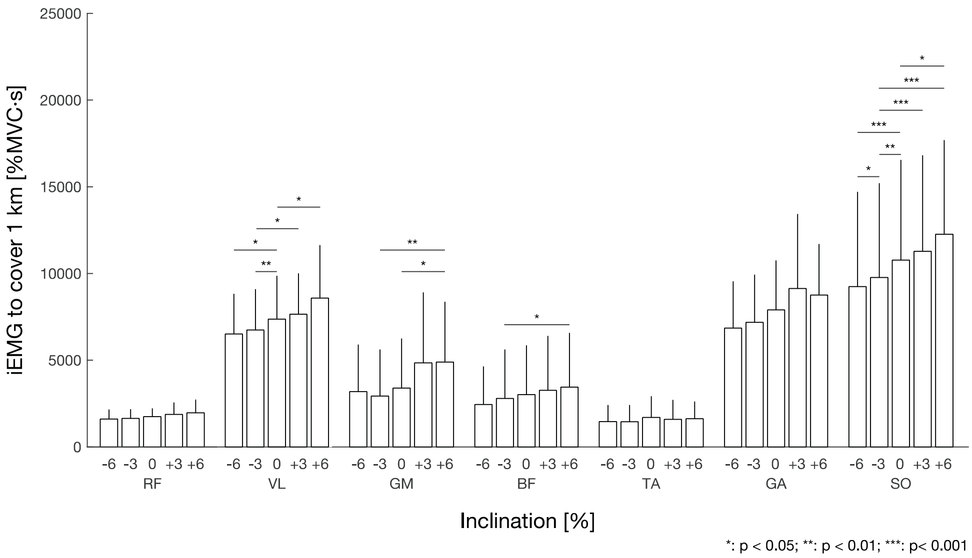

Figure 3: Mean (±SD) integrated EMG (iEMG) of the rectus femoris (RF), vastus lateralis (VL), gluteus maximus (GM), biceps femoris (BF), tibialis anterior (TA), gastrocnemius (GA), and soleus (SO) muscles during the contact phase at each inclination to cover a distance of 1 km.

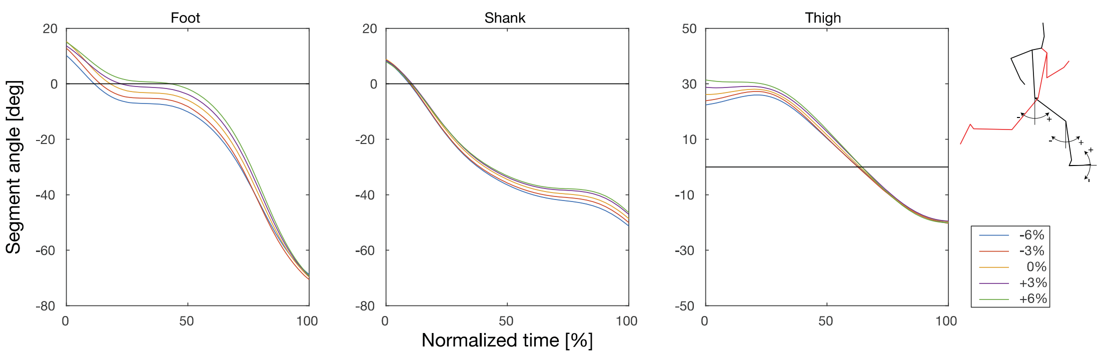

Figure 4: Angle of the foot, shank, and thigh segments during the contact phase at each inclination.

DISCUSSION: The energy cost and the vertical displacement increased with increasing inclination of the treadmill while running. The strongest correlation observed between the energy cost and the vertical displacement, emphasizing that the vertical displacement related to the energy cost (Moore, 2016). In addition, the maximal angle of the thigh during the contact phase increased with an increasing inclination and its angle positively correlated with both the energy cost and the vertical displacement. The backward swing of the thigh during the first half of the contact phase might be a motion to raise the body's CoM. iEMG of the VL muscles increased with an inclination, and their iEMG positively correlated with the vertical displacement and maximal angle of the thigh during the contact phase. Furthermore, iEMG of the GM muscles positively correlated with the vertical displacement and the maximal angle of the thigh during the contact phase. The greater the maximal thigh angle during the contact phase, the greater the knee extension and hip extension torque required to enable the thigh segment to swing backward against gravity. The moment of the knee joint force acting on the thigh to move from an opposite direction to a backward swing direction would be greater if the thigh angle during the contact phase was greater. The maximal angle of the thigh increased the VL and GM muscular activities during the contact phase at inclinations of +3% and +6% to swing the thigh in a backward direction. These results suggest that the VL and GM muscular activities increase the energy cost through thigh swing to raise the body's CoM.

CONCLUSION: The energy cost increased with increasing inclination while running. iEMG of the VL and GM muscles increased with the vertical displacement of the body's CoM and the maximal angle of the thigh during the contact phase. Thus, the muscular activities of VL and GM to raise the body's CoM through thigh swing during the contact phase might increase the energy cost while running at an inclination.

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