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Walking beyond preferred transition speed increases muscle activations with a shift from inverted pendulum to spring mass model in lower extremity

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ABSTRACT

Background: The triggers for the transition of gait from walking to running during increasing speed locomotion have been attributed to an energy conservation strategy or a relief of excessive muscle activation. Walking beyond the preferred transition speed (PTS) has been proposed as an exercise protocol for boosting energy consumption. However, the biomechanical factors involved while this protocol is used have not been investigated. Thus, this study investigated the difference between walking and running below, during, and beyond the PTS from a biomechanical perspective.
Methods: Sixteen healthy male participants were recruited. After determination of their PTS, five speeds of walking and running were defined. Kinematic data, including center-of-mass (COM) displacement, COM acceleration, and electromyography (EMG) data of rectus femoris (RF), biceps femoris, gastrocnemius (GAS), and tibialis anterior were collected at the five speeds for both walking and running.
Result: The vertical COM displacement and acceleration in running were significantly larger than those in walking at all five speeds ($p < 0.05$). EMG signals of the two antigravity muscles, RF and GAS, demonstrated a significant higher activation in walking than that in running at the speed beyond PTS ($p < 0.05$).
Conclusion: The larger energy consumption in walking than that in running beyond the PTS may be attributed to the high activation of lower-extremity muscles. The smaller vertical COM displacements and accelerations exhibited when participants walked beyond the PTS rather than ran did not indicate adverse effects of using walking beyond the PTS as an exercise prescription for boosting energy consumption.

1. Introduction

Walking and running are the two most common gait patterns in humans. The main difference between the two is the speed of locomotion; however, there are also distinctions in their physiological and biomechanical aspects. Walking and running are defined differently in center-of-mass (COM) moving patterns, which have been described as an invert pendulum model in walking and a spring–mass model in running [1,2]. In walking, the lower extremities work relatively stiff; the COM elevates to its highest point in the midstance phase by using the drive from kinetic energy and drops to the lowest point at the end of stance phase from the action of gravity [3]. In running, the lower extremities work as a spring; the COM drops to its lowest point in the midstance phase, while the kinetic and gravitational potential energies decrease to their lowest values with the compliance of the lower extremities [4]. The differences between walking and running in the moving patterns of the lower extremities also lead to a higher vertical ground reaction force (GRF) in running than in walking, and to a different usage of lower-extremity muscles [5,6].

Human typically choose between walking or running on the basis of the purpose and required speed and prefer walking at a slower speed and running at a higher speed. Studies have shown that human tend to switch gait patterns at a specific speed, called the preferred transition speed (PTS), in continuously increasing

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speed locomotion. The trigger for switching gait patterns from walking to running was proposed as an energy conservation strategy because walking above the PTS expends more energy than does running, and running below the PTS expends more energy than does walking [7]. However, the incongruity between the actual and the energetically optimal transition speed implies that other factors may influence gait transition [8–11]. Reducing the mechanical stress on musculoskeletal tissues to prevent injury was proposed as a trigger for the walk-to-run transition [12]. During incremental speed walking, the activation of the tibialis anterior (TA) muscle increases with speed; however, the walk-to-run transition reduces the muscular stress of the TA by reducing muscle activation from high to moderate levels [13]. Exaggerated TA, rectus femoris (RF), and hamstring (HAM) muscle activation during the swing phase of fast walking were also demonstrated to be triggers for the walk-to-run transition [14].

Walking near or above the PTS has been used as an effective exercise prescription for weight loss, in conjunction with diet control, because the metabolic cost of walking above the transition speed is higher than that of running at the same speed [15–17]. However, the biomechanical factors contributing to this energetic cost difference have not been examined. Moreover, the consequence that human insists on walking beyond the PTS regardless the triggers of transition gait from exaggerate muscle activation has not been well discussed. Thus, this study investigated the difference between walking and running below, during, and beyond the walk-to-run transition speed from a biomechanical perspective. The COM displacement, acceleration, and muscle activities of lower-extremity muscles were compared for walking and running. The information provided in this paper can aid in the prescription of exercise involving walking or running speeds below, during, and above PTS. The potential effects on musculoskeletal injuries are also discussed.

2. Methods

2.1. Participants

Sixteen healthy male participants (age: 23 ± 2.39 y, height: 171.69 ± 3.03 cm, weight: 67.44 ± 4.86 kg) with regular exercise habits were included in this study. To minimize individual differences, the recruited participants were limited to those with a body height of 165–175 cm and a leg length of 81–89 cm. The study was approved by the Institutional Review Board of Taipei Medical University. The experimental procedures were explained to all participants, who provided written informed consent.

2.2. Experimental design

The walk-to-run transition speed of each participant was first defined. A 5 min warm-up section with self-selected speed (3–5 km/h) was applied before the testing procedures. We used a continuous protocol which was modified from previous study [18]. Each participant first walked at the speed of 5 km/h; the test administrator then increased the speed in 0.1 km/h increments each second without informing the participant. The participant changed his gait to running when he felt the speed was suitable for doing so. After the participant had changed the gait to running and last for 5 s, the test administrator recorded the speed and stopped the treadmill. The running gait was identified when flight phase was observed from the signals of four load cells underneath the treadmill. The PTS testing protocol was applied 5 times repeatedly for each participant.

Average PTS across 5 trials of all the participants was calculated and was set as a speed for walking and running in the following experiment. In order to investigate the conditions that participants walking or running in their non-preferred speed, the largest (smallest) PTS among the 5 trials of every participant was selected as two other speeds. The largest PTS plus 1 km/h and smallest PTS subtract 1 km/h were also selected as the two extreme speeds. The 5 speeds used in the following experiment were smallest PTS subtract 1 km/h, smallest PTS, average PTS, largest PTS, and largest PTS plus 1 km/h.

Before the main experiment, electromyography, accelerometer, and reflective markers for motion analysis were affixed to each participant. Participants walked and ran under the five experimental speeds. Data were collected for 10 s under each condition and 3 gait cycles were used for data analysis.

2.3. Modalities

A motion analysis system (Motion, USA) equipped with ten cameras was used to calculate the body COM in this study. The 29 reflective markers were affixed to the bony landmarks of each participant according to the Helen Hayes marker placement. The sampling rate was set to 100 Hz. The COM displacements in mediolateral and vertical directions were analyzed from 3 continuous gait cycles. The absolute value of the difference between 2 frames was calculated and the summation of these values across the whole gait cycle was calculated. An accelerometer (CXL50LP3, Crossbow, USA) with 1000 Hz sampling rate was affixed at the second segment of the lumbar spine (L2) to assess mediolateral and vertical COM acceleration. The calculation of COM accelerations were the same as COM displacement except that only 1 gait cycle was used in COM acceleration. Four load cells (Delta Transducer, India) underneath the treadmill with 1000 Hz sampling rate were used to detect the flight phase for determining the walking and running gait patterns.

The muscle activities of the RF, TA, biceps femoris (BF), and gastrocnemius (GAS) were recorded according to standard electromyography procedures by using a data acquisition system (Biopac, USA) with the AcqKnowledge 3.9.1 software. Electromyography (EMG) signals were band-pass filtered (10–500 Hz), full-wave rectified, and low-pass filtered (6 Hz) to obtain a linear envelope signal. The average value of the EMG signals of 3 gait cycles were calculated and divided by the maximal isometric voluntary contraction (MVIC) for normalization. The MVIC of RF, TA, GAS were tested in sitting position and BF was tested in prone position. Manual resistances were provided and 5 s of contractions were performed for every muscle.

2.4. Statistics

The two-way analysis of variance (ANOVA) was used to examine the effect of different gait patterns and speeds on acceleration, EMG, and COM displacement. Shapiro–Wilk test was used to determine the normality of data distribution and Tukey post hoc analysis was used when ANOVA indicated a significant main effect. The significance level was set at $\alpha = 0.05$.

3. Results

3.1. Preferred transition speed

The average PTS of the 16 participants was 7.33 ± 0.41 km/h. The slowest (fastest) transition speed among the 16 participants was 6.2 km/h (8.2 km/h). Therefore, the five experimental speeds for walking and running were defined as 5.2, 6.2, 7.3, 8.2, and 9.2 km/h.

3.2. COM displacement

The vertical COM displacements in running were consistently larger than those in walking ($p < 0.05$). In walking, the vertical COM