EFFECTS OF WALKING SPEED ON THE VARIABILITY OF BODY’S CENTER OF MASS MOTION RELATIVE TO THE CENTER OF PRESSURE

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SUMMARY
Fall is a common accident in daily life which would cause serious injuries, especially in the elderly. Loss of balance is a main cause of falls. Clinically, patients and the elderly are often asked to walk slowly to avoid imbalance. Significant decrease in gait speed has also been found during obstacle-crossing in the elderly. It remains unclear whether walking with reduced speed would really help improve the dynamic balance of the body. The current study addressed this issue by investigating the effects of gait speed on the variability of the body’s COM motion relative to the COP while walking on an instrumented treadmill. The current results suggest that the control of the locomotor system during different phases of gait is closely involved in the control of the body’s COM motion and stability, and that greater COM motion was related to walking at speeds slower than the preferred speed. Reducing walking speed may not be a good choice in improving dynamic stability.

INTRODUCTION
Fall is a common accident in daily life which would cause serious injuries, especially in the elderly. Loss of balance is a main cause of falls. Although biomechanical variables of the lower limb joints during gait are useful for understanding the mechanical demands of the locomotor system, dynamic stability of the body is better represented by the motion of the body’s center of mass (COM) with respect to the base of support represented by the center of pressure (COP) of the ground reaction force (GRF). Among the variables available in the literature to describe the body’s COM motion were proposed in order to remove the influence of anthropometric differences among subjects [1]. Previous studies also indicated that the medial-lateral COM-COP inclination angle might be a sensitive measure to quantify gait instability in the elderly [2].

Clinically, patients and the elderly are often asked to walk slowly to avoid imbalance. Significant decrease in gait speed has also been found during obstacle-crossing in the elderly [3]. It remains unclear whether walking with reduced speed would really help improve the dynamic balance of the body. What would be the optimum walking speed for maintaining balance during walking? The current study addressed this issue by investigating the effects of gait speed on the variability of the body’s COM motion relative to the COP while walking on an instrumented treadmill.

METHODS
Ten young male adults (age: 23±3 years; body height: 170.0±6.2 cm; body weight: 68.8±7.8 kg; leg length: 89.7±4.4 cm), without any neuromusculoskeletal disease, participated in the current study with informed written consent. Each subject walked at 8 different speeds (1, 2, 2.5, 3, 3.5, 4, 4.5 and 5 km/hr) on an instrumented treadmill that allowed the measurement of the 6-component GRF. Three-dimensional (3D) trajectories of forty-five infrared retro-reflective markers placed on specific bony landmarks of all the segments of the body were also measured using a 5-camera motion capture system (VICON570, VICON Motion Systems Ltd., UK). Kinematic and kinetic data were measured for more than 5 gait cycles for each of 5 trials at a given speed. Subjects were allowed a 5-min rest between speed conditions to avoid muscle fatigue.

With the measured marker data, the position of the body’s COM was calculated using a thirteen-segment model of the whole body with subject-specific anthropometry defined by Dempster’s coefficients. Center of pressure (COP) was measured by the well-calibrated instrumented treadmill that was equipped with four 3-axis load cells positioned on each corner. The anterio-posterior (A/P) and medial-lateral (M/L) inclination angles of the COM relative to the COP (Figure 1) were then calculated at five key events during the gait cycle, namely leading limb heel-contact (T1), trailing limb toe-off (T2), trailing limb heel-contact (T3), leading limb toe-off (T4), leading limb toe-off (T5). For all calculated variables, one-way ANOVA followed by trend analysis were performed to detect the effects of walking speed. A significance level set at α=0.05 was used for all statistical tests. All statistical analyses were performed with SPSS (SPSS Inc., Chicago, USA).
Figure 1: Typical three-dimensional trajectories of the COM and COP motion during level walking. The COM-COP line and its A/P inclination angle (α) and M/L inclination angle (β) are also shown.

RESULTS AND DISCUSSION
The mean values and standard deviations of the A/P and M/L inclination angles at the five events of the gait cycle for all speeds are shown in Fig. 2 and 3, respectively. Significant speed effects were found in A/P and M/L inclination angles at each event. Linear relationships with walking speed were found in A/P inclination angles at T1~T5 and in M/L inclination angles at T2 and T4. Quadratic relationships with speed were found in M/L inclination angles at T1, T3 and T5.

Figure 2: Anterior-Posterior inclination angle at different speeds at T1~T5. Linear relationship was shown at each event. The bar with the color of deepest black was the average preferred gait speed of all the subjects.

Figure 3: Medio-lateral inclination angle at different speeds at T1~T5. Quadratic relationship was shown at T1, T3, T5 and Linear relationship was shown at T2 and T4. The bar with the color of deepest black was the average preferred gait speed of all the subjects.

†: Significant difference with quadratic relationship.
*: Significant difference with quadratic relationship.

With increasing gait speed, the A/P inclination angles were increased at the five events. This is expected as increased velocity of the COM in the A/P direction would require increased angular momentum relative to the COP in the sagittal plane, leading to increased inclination angles.

Therefore, the significance difference between inclination angles across different speeds might result from the gait speed itself not from the balance control of the body. Compared to the A/P inclination angles, the significant speed effect on the M/L inclination angles did not appear to result from the gait speed related mechanical effect of angular momentum in the sagittal plane. The forward speed did not contribute to the angular momentum in the frontal plane directly. Instead, it led to a nonlinear (quadratic) effect on the certainly key event.

For the heel-on events (T1, T3, T5) in M/L direction, beginning of double limb support with temporarily reduced speed in a gait cycle, the greater inclination angles appeared at the preferred speed indicated that, using the inverted pendulum concept, the most unstable state occurred at the preferred gait speed. The young subjects had no problem in keeping balance at the self-selected speed with an inclination angle higher than other speeds. This indicates that the neuromusculoskeletal system may have to pay more attention to controlling the mechanical balance state at the other unfamiliar gait speeds. For the toe-off events (T2, T4) in M/L direction, beginning of the single limb support phase with temporarily increased speed in the gait cycle, the inclination angles decreased with increasing gait speed, indicating that greater stability was needed at higher speeds. However, these results may also indicate that, at the beginning of single limb support, the inverted pendulum may be disturbed on M/L direction more easily while walking with a lower forward momentum.

CONCLUSIONS
Increased M/L stability was necessary at the beginning of single limb support (toe-off) while walking at high speed. Minimum M/L stability was needed at the beginning of double limb support (heel-on) while walking at preferred gait speed. The neuromusculoskeletal system appears to require less control effort while the COM starts to get a bigger support area at heel-on especially at a preferred speed. In contrast, it may need more control effort and forward momentum to keep balance while the COM starts to move with reducing support area especially at higher speeds. The current results suggest that the control of the locomotor system during different phases of gait is closely involved in the control of the body's COM motion and stability, and that greater COM motion was related to walking at speeds slower than the preferred speed. Reducing walking speed may not be a good choice in improving dynamic stability.

REFERENCES