Analysis of walking variability through simultaneous evaluation of the head, lumbar, and lower-extremity acceleration in healthy youth

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Abstract. [Purpose] The purpose of this study was to clarify whether walking speed affects acceleration variability of the head, lumbar, and lower extremity by simultaneously evaluating of acceleration. [Subjects and Methods] Twenty young individuals recruited from among the staff at Kurashiki Heisei Hospital participated in this study. Eight accelerometers were used to measure the head, lumbar and lower extremity accelerations. The participants were instructed to walk at five walking speeds prescribed by a metronome. Acceleration variability was assessed by a cross-correlation analysis normalized using z-transform in order to evaluate stride-to-stride variability. [Results] Vertical acceleration variability was the smallest in all body parts, and walking speed effect had laterality. Antero-posterior acceleration variability was significantly associated with walking speed at sites other than the head. Medio-lateral acceleration variability of the bilateral hip alone was smaller than the antero-posterior variability. [Conclusion] The findings of this study suggest that the effect of walking speed changes on the stride-to-stride acceleration variability was individual for each body parts, and differs among directions.

Key words: Cross-correlation, Accelerometer, Gait

INTRODUCTION

Although walking is a periodic motion, the related kinematic and kinetic profiles vary. Walking variability should be properly maintained since excessive movement variability implies dynamic instability. Studies on walking variability have assessed the spatiotemporal characteristics2, 3), ground reaction forces1), and acceleration patterns4, 5). Increased in movement variability during walking is associated with a reduction in the coordination required for efficient walking control6). Matsuda et al.7) reported that the stride time variability is associated with muscle strength, flexibility and balance ability in elderly people. Analysis of movement variability during walking may enhance the understanding of motor control and enable the prediction of an individual’s ability to walk.

Movement variability during walking is affected by the walking speed. For example, with respect to stride-to-stride fluctuation, Kang and Dingwell8) reported that variability of the spatiotemporal characteristics and kinematic data were affected by the walking speed in both young and elderly people. They also reported that the effect of walking speed on the variability as measured by frontal hip and knee motions, knee internal/external rotations, and trunk motions were more pronounced at very high or very low speeds. Walking variability must be properly controlled irrespective of the changes in walking speed, to minimize whole-body perturbations. Therefore it is important to clarify the correlation between movement variability and walking speed.

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The accelerometer is commonly used to analyze walking\(^9\)–\(^{11}\). Previous studies have independently examined acceleration variability of the head, lumbar, and/or pelvis independently\(^9\). However, the trunk is well controlled, so that the rotational moments from the lower extremities becomes small\(^{12}\), and the acceleration from the pelvis to the head is absorbed by the spinal column\(^{13}\). In other words, the trunk is adjusted to be vertical (VT) and stable in the course of the transmission of acceleration from the foot to the head. Moreover, the bilateral lower extremities have functional asymmetry, and the non-dominant limb contributes more to support, while the dominant limb contributes more to propulsion\(^{14}\). Thus, variability in the accelerations of the head, lumbar, and bilateral lower extremities may exhibit characteristics unique to each body part. In addition, the acceleration variability measured by accelerometers differs among directions\(^5\). To our knowledge, no prior studies have evaluated the differences in acceleration variability in the head, trunk, and lower extremities as a function of walking speed. By simultaneously evaluating of the acceleration variability of the lower extremities in addition to the head and pelvis, it should be possible to evaluate the direction-dependent differences in variability control.

We hypothesized that the variability of acceleration in the lower extremities during walking would be affected by the walking speed, although those of the head and lumbar were well controlled irrespective of changes in the walking speed. We also hypothesized that the anteroposterior (AP) acceleration variability was affected by walking speed, especially in the lower extremities.

**SUBJECTS AND METHODS**

Ten healthy young male subjects and ten female subjects recruited from the staff of Kurashiki Heisei Hospital participated in this study. The subjects were all right-handed. The exclusion criteria included neurological disorders, joint pain affecting walking and history of surgery to the lower extremities or spine. All procedures were approved by the Ethics Committee at Kurashiki Heisei Hospital, and all participants provided written informed consent prior to enrollment.

Eight wireless multi-function inertia sensors (TSND121; 37 mm width, 46-mm height, 12-mm depth; weight, 22 g; ATR-Promotions Co., Ltd., Kyoto, Japan) were used to measure the head, lumbar, and lower extremity accelerations along three axes (VT, medio-lateral (ML), and AP) at a sampling frequency of 100 Hz and a measurement range of ±8 G. The wireless sensors were placed at the external occipital protuberance (head), L3 processus spinosus (lumbar), bilateral mid-point between the crest of the ilium and the great trochanter (hip), bilateral distal outer thigh (thigh), and bilateral distal outer shank (shank). Data were stored in the internal memory. After the measurement was completed, these data were transferred to a personal computer via Bluetooth.

In the walking trials, all participants were instructed to walk with bare feet, to the end of a 15-m long walkway, and turn around, and walk back. Therefore, a total distance of 30 m was covered. To ensure that the steps and walking motion were stable, the first and last two-to-three steps were excluded from the analysis, because two or three steps are necessary in the transition between the initiation of gait and the steady-state walk of healthy people\(^{15}\). Before collecting any data from the participants, cadence and 10-m walking time during the steady state walking were measured at their preferred speed. Ten meter walking time was recorded in seconds, using a digital stopwatch. The number of steps to walk 10 m was used to calculate the average cadence (steps/min). Referring to the comfortable cadence of walking (100%), the walking speed was prescribed at random.

To provide an indication of the variability of acceleration patterns between strides, acceleration signals were divided into individual strides by analyzing the VT component. The identification of particular points that correspond to heel contacts in the acceleration was performed using the method based on a previous study\(^{17}\). The acceleration data during straight line walking were extracted after the initial heel contact was determined in each walking trial. Data for 10 strides were obtained. Stride-to-stride acceleration variability was analyzed using cross-correlation analysis. The acceleration waveform of each walk cycle was treated as independent time series data. Cross-correlation can be useful for investigating the similarity of two-time series data sets\(^{18}\). For the cross-correlation analysis, each stride was time normalized (0–100%). Forty-five combinations of the 10 strides were obtained \((10C_2=45)\). Cross-correlation coefficients were calculated in each pair and normalized using Fisher’s r to z-transform (z-value), which yields variates that are approximately normally distributed, avoiding floor and ceiling effects\(^{19}\). Forty-five z-values were averaged. A high z-value indicates low variability since there is a strong correlation between strides. All calculations were performed using Matlab R2013a (The MathWorks, Inc., Natick, MA, USA).

A two-way analysis of variance with walking speed and directions was used to compare of z-values for each body part. Differences between walking speeds were determined by Tukey’s honest significant difference test. Statistical significance was set at p<0.05. All data were processed by SPSS 18.0 statistical software (SPSS Japan Inc., Tokyo, Japan).

**RESULTS**

The characteristics and the spatiotemporal parameters of the study subjects during comfortable walking are presented in **Table 1**. The z-values of each body part at each speed conditions are shown in **Table 2**. Although there were no significant
interactions between speed and direction in the head, right hip and left hip, there were significant interactions between speed and direction in the lumbar, right thigh, right shank, left thigh and left shank areas. Therefore, these parts were analyzed separately for each direction.

In the head, walking speed factor was not become significant in any directions. This result was consistent with our hypothesis. In the lumbar area, the z-value at very slow condition was significantly larger than the values for the other four walking speeds in the VT direction. Additionally, the z-value at very slow walking speed was significantly larger than the values for slow walking speed in the AP direction. In the right hip, the z-value at very low walking speed was significantly larger than the values for slow, fast and very fast conditions in all directions. In the right thigh, z-value at very slow walking speed was significantly larger than the values for slow, fast and very fast conditions in the VT direction, and the z-value at slow walking speed was significantly lower than the values for fast and very fast conditions in AP direction. In the right shank, the z-values at slow and very fast walking speed were significantly lower than the values for very low and preferred conditions in the vertical direction. In addition, the z-values of the very low and low walking speed were significantly lower than those for the preferred, fast and very fast speed conditions in the ML direction. In the left hip, the z-value at the low walking speed was significantly lower than those for the very low and preferred walking speed in all directions. In the left

| Z values | Very low | Low | Preferred | Fast | Very fast |
|----------|----------|-----|-----------|------|-----------|
| Head VT  | 2.75 (0.19) | 2.51 (0.21) | 2.51 (0.29) | 2.31 (0.29) | 2.28 (0.24) |
| AP       | 1.80 (0.65) | 1.74 (0.60) | 1.79 (0.66) | 1.78 (0.60) | 1.66 (0.67) |
| ML       | 1.58 (0.37) | 1.30 (0.31) | 1.53 (0.31) | 1.42 (0.30) | 1.41 (0.35) |
| Lumbar VT| 2.76 (0.23) | 2.41 (0.21) | 2.53 (0.24) | 2.40 (0.20) | 2.32 (0.20) |
| AP       | 1.62 (0.27) | 1.33 (0.25) | 1.56 (0.37) | 1.48 (0.24) | 1.43 (0.30) |
| ML       | 1.10 (0.23) | 0.95 (0.18) | 1.13 (0.30) | 1.13 (0.26) | 1.10 (0.23) |
| Rt. Hip VT| 2.51 (0.24) | 2.27 (0.22) | 2.32 (0.19) | 2.23 (0.32) | 2.15 (0.23) |
| AP       | 1.29 (0.28) | 1.07 (0.34) | 1.36 (0.25) | 1.28 (0.37) | 1.27 (0.24) |
| ML       | 2.04 (0.49) | 1.79 (0.49) | 2.01 (0.60) | 1.91 (0.56) | 1.88 (0.70) |
| Rt. Thigh VT | 2.45 (0.29) | 2.16 (0.22) | 2.25 (0.22) | 2.22 (0.26) | 2.11 (0.27) |
| AP       | 1.36 (0.24) | 1.12 (0.26) | 1.39 (0.28) | 1.49 (0.30) | 1.44 (0.25) |
| ML       | 1.40 (0.40) | 1.22 (0.35) | 1.37 (0.33) | 1.46 (0.27) | 1.42 (0.29) |
| Rt. Shank VT | 2.27 (0.27) | 2.02 (0.22) | 2.29 (0.20) | 2.18 (0.21) | 2.05 (0.20) |
| AP       | 1.27 (0.21) | 1.14 (0.22) | 1.54 (0.21) | 1.52 (0.22) | 1.52 (0.25) |
| ML       | 1.13 (0.15) | 1.03 (0.15) | 1.27 (0.18) | 1.21 (0.18) | 1.24 (0.19) |
| Lt. Hip VT | 2.48 (0.19) | 2.22 (0.24) | 2.37 (0.35) | 2.35 (0.26) | 2.32 (0.33) |
| AP       | 1.19 (0.25) | 1.05 (0.22) | 1.33 (0.30) | 1.29 (0.31) | 1.25 (0.32) |
| ML       | 1.66 (0.55) | 1.46 (0.39) | 1.59 (0.50) | 1.56 (0.37) | 1.45 (0.46) |
| Lt. Thigh VT | 2.36 (0.20) | 2.20 (0.24) | 2.24 (0.33) | 2.15 (0.30) | 2.18 (0.29) |
| AP       | 1.28 (0.21) | 1.19 (0.21) | 1.45 (0.24) | 1.39 (0.32) | 1.52 (0.26) |
| ML       | 1.45 (0.20) | 1.35 (0.23) | 1.43 (0.25) | 1.40 (0.23) | 1.53 (0.23) |
| Lt. Shank VT | 2.29 (0.25) | 2.06 (0.21) | 2.31 (0.27) | 2.21 (0.33) | 2.08 (0.29) |
| AP       | 1.31 (0.21) | 1.17 (0.21) | 1.55 (0.25) | 1.57 (0.30) | 1.57 (0.28) |
| ML       | 1.36 (0.24) | 1.23 (0.20) | 1.38 (0.22) | 1.33 (0.24) | 1.31 (0.22) |

Values are shown as mean (SD).
thigh, the z-values at the very low and low walking speed were significantly lower than those for the very fast speed, while the z-value at the low walking speed was significantly lower than those for preferred walking speed in the AP direction. In the left shank, the z-values of the very low and low walking speeds were significantly lower than those for the preferred, fast and very fast speed conditions in the AP direction. These results were partially consistent with our hypothesis.

Regarding the effects of direction, the z-values of the VT direction were significantly higher than those for the AP and ML directions in all body parts. In contrast, the z-values of the AP direction of the head, lumbar, and bilateral shank areas were significantly higher than those for the ML direction, while the z-values of the ML direction of the bilateral hip were significantly higher than those for the AP direction, although those of the bilateral thigh were not significantly different between the AP and ML directions.

**DISCUSSION**

This study investigated the walking variability by simultaneously evaluating acceleration of the head, trunk, and lower extremities as a function of walking speed in order to clarify whether the effect of walking speed on the variability of acceleration pattern differs among the body parts. Variability of the VT acceleration pattern on the lumbar, right lower extremity, and left hip was clearly affected by the walking speed, and tended to be smaller at very slow walking speed. In contrast, VT acceleration variability of the head and left lower extremity was not affected by the walking speed. Therefore, there is laterality in the effect of walking speed on the VT acceleration variability. The VT accelerations reflect the degree of support during walking, and the VT trunk acceleration variability is associated with the step time variability. Because it relies on central and peripheral inputs and feedback, as well as on neuropsychological function, the stride time can be viewed as the final, integrated output of the locomotor system. It has been reported that the bilateral lower extremities have functional asymmetry, and that the non-dominant limb contributes more to support. The subjects of this study were all right-handed. Since the left lower extremity of the study subjects had the role of providing more support, VT acceleration variability on the left thigh and shank might have been less affected by the walking speed. In contrast, VT acceleration variability on the right lower extremity was affected by the walking speed, and the variability increased during very slow. Moreover, VT acceleration variability at all body parts was smaller than that of the AP or ML direction. These findings suggested that because the variability of acceleration pattern in the VT direction was clearly low, the VT acceleration might be strictly controlled so as to stabilize the walking behavior.

On the bilateral shank, the influence of walking speed on AP acceleration variability was observed. The z-values of the bilateral shank in the very low and low walking speeds were significantly smaller than those for the preferred, fast, and very fast speeds. The AP accelerations reflect the degree of braking, and propulsion, and leg swing during walking. These are generated by the flexion-extension movement of the lower extremity. Plotnik et al. reported that the bilateral coordination of the left-right stepping was deteriorated when humans intentionally walk slowly. Because the walking speed effect on the AP acceleration variability was the largest in the distal shank, the step timing might have been controlled by the shank movement. Since the AP acceleration variability of the bilateral shank was larger in the slower walking speed, the adjustment of stride by the shank was not constant during slow walking.

In the ML direction, the z-values of the bilateral hip alone were significantly higher than those of the AP direction. Dynamic lateral balance is affected by the foot placement and the mediolateral moments generated by the ankle, and the hip abductor moments to ensure trunk orientation. Therefore, the pelvis motion in the ML direction might be important for controlling lateral movements during walking, because the bilateral hip predominates the control of the acceleration variability in the ML rather than in the AP direction. There were differences in the acceleration variability in the ML direction of the hip between the values for the low and very low speeds. The z-values of both hips in the very low speed condition were significantly higher than those in the low speed condition. These values became small in the AP direction as well, when they walked at an even slower speed. A previous study reported that the elderly individuals had lateral instability in the lateral direction related to the risk of falling. In contrast, Kobzar et al. reported that there were age-related differences in the step regularity or symmetry in the AP direction, and no difference in these values were observed in the VT and ML directions in the lumbar area.

Lateral balance during walking in the elderly may differ by walking speed. Further studies are need to clarify the control of lateral balance while walking in the elderly.Moreover, the acceleration variability of the right shank was affected by walking speed. The z-values of the right shank in the low speed condition were significantly lower than those in the preferred, fast and very fast speed conditions. This result suggests that there is laterality in the lateral control of the shank, and that it may be equally important for the evaluation of balance to examine ML accelerations of the distal side in addition to ML accelerations of the proximal side.

Walking speed had no effect on acceleration variability of the head. Movement variability is thought to be a function of neurological integration and feedback processing of numerous sensory inputs that occur during the generation of each gait cycle. The head and eyes exhibit compensatory rotations in response to perturbations generated by the lower extremity movements to maintain stable head position and gaze. Moreover, the vestibular system detects motion of the head and stabilizes the gaze by the vestibulo-ocular reflex. As a result, the acceleration variability of the head was less affected by walking speed in order to stabilize the gaze.
The present study has several limitations. First, walking speed was prescribed by a metronome in this study. Walking speed can generally be controlled consistently as a function of walking cadence. The subjects in this study could walk at a steady speed of five levels to the beat of a metronome. In contrast, Hunt et al.\(^{28}\) reported that auditory stimulation during walking affected the walking fluctuations. Therefore, the auditory stimulation by the metronome might have affected stride-to-stride acceleration variability in this study. Second, this study evaluated the acceleration variability of the head, trunk, and lower extremities at several different walking speeds, but it was not possible to identify the mechanical interaction between body parts in relation to walking speeds. Further studies are needed to determine the correlation between the acceleration waveform and walking speed. Third, this study revealed the correlation between walking speed and acceleration variability of the head, lumbar, and lower extremities in young people. Movement variability is associated with the ability to walk in elderly people\(^{7}\). Thus, further studies are required to determine the effects of age-related alternations in the acceleration variability, particularly in the ML direction, through simultaneous evaluations of the head, lumbar, and lower extremities of elderly people.

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