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The Usefulness of a New Gait Symmetry Parameter Derived from Lissajous Figures of Tri-axial Acceleration Signals of the Trunk

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Abstract. [Purpose] Tri-axial accelerometers have advantages, including portability, in clinical gait analysis. However, the gait parameters calculated by accelerometers cannot be used visualize the symmetry of trunk movement. The purposes of this study were to visualize the acceleration signals of the trunk during gait and to assess the usefulness of a new gait symmetry parameter derived from Lissajous figures of acceleration of the trunk. [Subjects and Methods] Trunk accelerations of 38 healthy young and 38 healthy elderly subjects were measured with a tri-axial accelerometer while walking at their preferred speed. Gait parameters assessed included: the symmetry index of the Lissajous figure (Lissajous Index; LI), and the root mean square (RMS) and harmonic ratio (HR) of the acceleration signals. [Results] Walking speed did not significantly differ between the two groups. However, LI was significantly higher, indicating less symmetry of motion, in the elderly subjects (young: 23.0%, elderly: 35.4%). RMS of the acceleration signals in the vertical and mediolateral directions were also significantly higher in the elderly subjects. [Conclusion] These results suggest that the LI may be useful for the evaluation of trunk movement in the frontal plane during gait analysis.
Key words: Gait analysis, Accelerometer, Symmetry

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INTRODUCTION

Recent studies have reported that gait analysis using tri-axial accelerometers has many advantages, including reliability of measurement and low operational costs[1–4]. In particular, portability is one of the representative advantages of the tri-axial accelerometer. A gait analysis system employing an accelerometer consists of a miniature wired-sensor (weight 4 grams), a data logger (including a transmitter; weight 90 grams) and a laptop computer. Various gait parameters, as well as the regularity and smoothness of the gait, can be computed from data gathered by accelerometers[3, 5]. For example, Menz et al. used tri-axial accelerometers to investigate the differences between healthy elderly and healthy young adults of the root mean square (RMS) and harmonic ratio (HR) of the acceleration during walking[6]. The RMS, which represents the average of trunk acceleration amplitudes, was significantly higher, and HR, which represents the smoothness of the gait, was significantly lower in the elderly subjects. Thus, gait analysis using tri-axial accelerometers is suitable for assessing qualitative differences in gait. In spite of this, gait parameters obtained using tri-axial accelerometers are not generally considered to recognize trunk movement. To facilitate the recognition of the lateral deviation of the trunk during walking, a Lissajous figure (LF), a planar figure composed of two types of simple oscillations, has been proposed[7, 8]. LF has the advantage of allowing easy and instant visual recognition of the lateral deviations of the trunk during gait, but its ability to quantify those deviations has not been previously assessed.

In this study, in order to evaluate the symmetry of trunk movement during walking, we quantified the LF of the acceleration signals of the trunk to obtain a Lissajous Index (LI) using the formula for the symmetry index described by Robinson et al.[9]. In addition, we also evaluated other gait parameters for the amplitude of the acceleration signals and investigated age-related changes in the smoothness of gait at the preferred walking speeds of the subjects, to determine the usefulness of LI as a new gait symmetry parameter.

$$\text{Lissajous Index (LI)} = \left| \frac{2\,(R_{\text{right}} - R_{\text{left}})}{(R_{\text{right}} + R_{\text{left}})} \times 100 \right|$$

R : rectangle area

Fig. 1. Formula used to calculate LI. An LI of 0 indicates perfect symmetry.

SUBJECTS AND METHODS

Thirty-eight healthy young and 38 healthy elderly subjects volunteered to participate in this study. The young subjects were all university students and the elderly subjects were community-dwellers. All subjects were free of neurological and musculoskeletal disorders or injuries at the time of testing. This study was approved by the Medical Ethics Committee of Kobe University, and written informed consent was obtained from all subjects prior to their participation.

All the subjects were instructed to walk at their preferred speed on a 20-meter walkway in their bare feet. A piezoresistive tri-axial accelerometer (MicroStone, Co., Ltd., Nagano, Japan) was used to measure the vertical (VT), anteroposterior (AP), and mediolateral (ML) acceleration of the trunk during gait. The accelerometer system consisted of a wired-sensor (MA3-04AC) that was attached directly over the spinous process of the third lumbar vertebra and a data logger (MVP-RF-AC) that was fixed to the body using an elastic bandage with a hook-and-loop fastener. The initial contact event was identified by a positive peak in VT acceleration. The acceleration signals were sampled at a rate of 200 Hz. After analog to digital transformation, the signals were collected by the logger and transmitted to a laptop computer over a Bluetooth personal area network.

The symmetry index of the LF (LI) was calculated using the formula shown in Figure 1. LI of the trunk acceleration during walking was obtained from the rectangular area of the quadrants. In the frontal plane, LI of the 1st and 2nd quadrant was calculated as the product of the maximal absolute X value by the maximal absolute Y value during walking. An LI of 0 indicates perfect symmetry.

RMS of the trunk acceleration was computed in each direction during 10 strides as previously described by Latt et al[10]. HR was obtained by frequency analysis of the acceleration data in all directions of 10 random strides via Fourier transformation as previously described by Menz et al[5]. All signal processing was performed using commercially available software (MATLAB, The MathWorks Co., Release 2007b, Cybernet Systems Co., Ltd., Tokyo, Japan). Before analysis, all acceleration data were low-pass filtered (dual pass zero-lag Butterworth) with a cutoff frequency of 20 Hz. The method of sampling and filtering of the acceleration signal followed a previously established protocol[11].

Walking speed, HR, and RMS were normally distributed and between-group differences were assessed using Student's unpaired t-test. LI was not normally distributed and was analyzed using the Wilcoxon signed-rank test. All statistical analyses were performed with JMP7.0 (SAS Institute Japan Co., Tokyo, Japan), and differences were considered statistically significant if the P-value was lower than 0.05.

RESULTS

The mean age of the young participants was 22.1 ± 3.3 years (22 males, 16 females), and that of elderly participants was 70.1 ± 6.0 years (22 males, 16 females). There was a significant difference between the young and elderly groups in height (young: 166.9 ± 9.0 cm, elderly: 158.7 ± 7.7 cm, $p < 0.001$), but not in weight (young: 58.6 ± 8.9 kg, elderly: 60.1 ± 12.3 kg).

A typical LF of the acceleration signals of the trunk during walking is shown in Figure 2. The LF of the acceleration signal is shaped like a butterfly. Briefly, the acceleration signal during one stride in each direction undergoes a cyclic trajectory from a positive to a negative peak. The trajectory of the trunk movement during one step, as shown in the LF, begins at zero, moves to a positive peak in the 1st quadrant, and then returns to 0 before moving to a negative peak in the 3rd quadrant and finally back to zero again. The LF is completed in one stride by drawing the trajectory on the other side as well. Although walking speed was not significantly different between the two groups (young: 1.29 ± 0.12 m/sec; elderly: 1.31 ± 0.15 m/sec) (Table 1), LI was significantly greater in the elderly subjects (23.0% for the young, 35.3% for the elderly, $p < 0.05$, Table 1). As shown in Table 2, RMS of both the VT and ML directions was significantly higher in the elderly subjects than in the young subjects (VT: 1.76 ± 0.40 for the young, 2.35 ± 0.34 for the elderly, $p < 0.05$; ML: 1.18 ± 0.29 for the young, 1.60 ± 0.41 for the elderly, $p < 0.05$). HR of the VT (young: 3.27 ± 0.67; elderly: 2.61 ± 0.60, $p < 0.05$) and AP (young: 3.41 ± 0.70, elderly: 2.80 ± 0.72, $p < 0.05$) direction were lower in the elderly than in the young subjects.

DISCUSSION

In clinical gait analysis it is desirable to assess spatiotemporal gait parameters such as walking speed, stride length, and cadence. Accelerometers can compute not only these essential parameters[11–13] but also RMS and HR, which better reflect the qualitative differences in gait. However, these parameters cannot be easily and quickly visualized. Therefore, it would be useful to establish a new easily recognizable parameter reflecting the symmetry of trunk movement during gait.

In this study, we used parameters including LI to compare the gait of young and elderly subjects. LI was significantly higher in the elderly subjects. A low LI value indicates good symmetry of motion. Similarly, RMS of the VT and ML directions were significantly higher in the elderly than in the young. Marigold et al. reported that the ML trunk acceleration, trunk angle variability, and trunk movement during gait of young subjects were significantly lower than those of elderly subjects[14]. LI in the frontal plane is derived

Table 1. Walking speed and LI of young and elderly subjects

walking speed (m/sec)				LI (%)			
Young		Elderly		Young		Elderly	
mean	SD	mean	SD	median	range	median	range
1.29	0.12	1.31	0.16	23.0	1.2–55.4	35.4*	0.2–111.0

* p<0.05

Table 2. HR and RMS of the acceleration of the trunk while young and elderly subjects walked

	HR				RMS			
	Young		Elderly		Young		Elderly	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
VT								
Prefer	3.27	0.67	2.61*	0.60	1.76	0.40	2.35*	0.30
ML								
Prefer	2.15	0.47	2.09	0.62	1.18	0.29	1.60*	0.40
AP								
Prefer	3.41	0.76	2.80*	0.72	1.68	0.27	1.98	0.40

* p<0.05

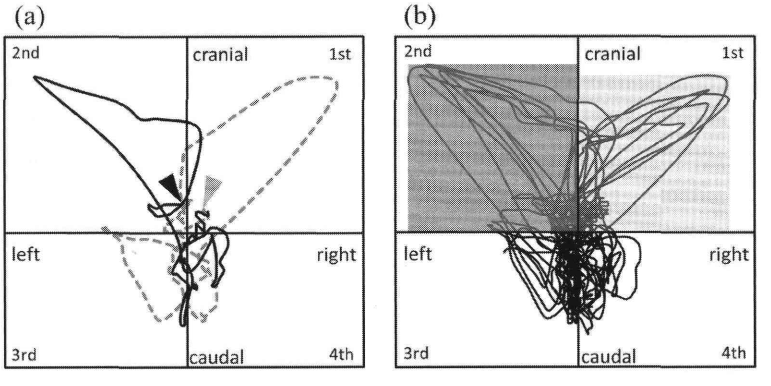

Fig. 2. A typical example of an LF of the acceleration of the trunk. The ordinal number in each corner represents the quadrant. (a) The bold line and the dashed line describe the right step and the left step, respectively. The gray triangle shows the initial contact (IC) of the right step, and the black triangle indicates the left IC. The trajectory of the LF begins at the gray triangle and moves to a positive peak in the 1st quadrant and then to a negative peak in the 3rd quadrant. The LF is completed in one stride by drawing the trajectory on the other side as well. (b) The rectangular area of the Lissajous figure in the frontal plane. The LI was calculated as the absolute symmetry index from the rectangular area of the 1st and 2nd quadrants, shown by the light gray rectangle and the dark gray rectangle, respectively, in the frontal plane over 10 strides.

from the acceleration in the VT and ML directions. Thus, LI and RMS might reflect the lateral sway of the trunk, and our results suggest that gait symmetry of healthy elderly subjects is inferior to that of young subjects, in spite of their ability to walk at similar speeds.

Walking speed was not significantly different between the two groups. It has been reported that the walking speed of elderly subjects is slower than that of young subjects[14, 15]. However, it has been also reported that there were no significant differences in the walking speeds of young and elderly subjects (young: 1.30 m/sec, elderly: 1.29 m/sec, reported by Kang et al.[16]; young: 1.33 m/sec, elderly: 1.34m/sec reported by Lowry et al.[17]). Although the preferred walking speed of the elderly subjects was 1.31 m/sec (mean age

70.1 years) in the present study, it was not significantly different from these reported by Kamide et al. (1.32 m/sec; mean age 74.1years)[18] and by Lindsey et al (1.36 m/sec; mean age 68.3years)[19]. Thus, the walking speed of elderly subjects may not necessarily be slower than young subjects.

HR was significantly less in the elderly subjects. Brach et al. reported, in a study assessing the validity of HR measurements, that older adults have a "less smooth" gait than young adults[20]. Our results suggest that even healthy elderly subjects whose gait speeds are as fast as young subjects have a less smooth gait than young subjects.

All the subjects in this study were instructed to walk at their preferred walking speed without modulation with a metronome or a treadmill. This method was in accordance with previous studies of gait analysis using tri-axial accelerometers[1–5, 10, 11]. In addition, Helbostad et al. suggested that the range of speeds in heterogeneous samples may not always contain the common standardized speed[21]. They recommended that gait analysis at a normalized walking speed using a treadmill or a metronome should not be performed for heterogeneous populations, because the free gait characteristics would be affected by the control speed. For these reasons, we instructed all the subjects to walk at their preferred walking speed in this study.

One of the limitations of this study was the sampling of the elderly subjects. The elderly subjects in this study were exemplary healthy elderly who performed daily exercises such as walking, because the results of our previous study demonstrated that the average of their daily steps were more than 10,000 steps[4]. Although the elderly subjects in this study were not the exactly the same subjects as in our previous study, they lived in the same local community. Therefore, although the results of this study should not be generalized, comparison between the two groups does have some validity.

The other limitation of the present study is the lack of comparison with reference data of the real spatial coordinates of the trunk during walking by our subjects. Further work will be necessary to assess the association between LI determined by the tri-axial accelerometer and the spatial coordinates of the trunk determined using a 3D motion capture system.

In summary, to determine if LF might be appropriate for the visualization of acceleration of the trunk during gait analysis, we used data obtained with a tri-axial accelerometer to compute the LI of the acceleration of the trunk during walking by young and elderly subjects. We found that, in spite of the lack of a significant between-group difference in walking speed, LI was significantly higher for the elderly subjects, as was RMS of the VT and ML acceleration. This higher LI might reflect increased lateral sway of the trunk in the elderly, which suggests that the LI may be a useful parameter for evaluating the symmetry of trunk movements in the frontal plane during gait analysis.

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