EFFECTS OF WALKING SPEED AND AGE ON THE DIRECTIONAL STRIDE REGULARIRY AND GAIT VARIABILITY IN TREADMILL WALKING

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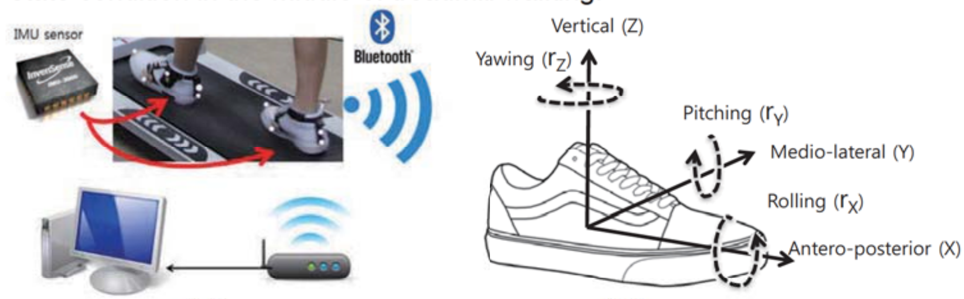
The purpose of this study was to assess the directional stride regularity (SR) and gait variability (GV) of data from shoe-type inertial measurement unit (IMU) sensors during levelled treadmill walking. The DynaStab™ (IMU based gait analysis system) including Smart Balance® (shoe-type data logger) was used to collect normal gait data from forty-four subjects in their 20s (n=20), 40s (n=13), and 60s (n=11). Four different walking speeds (3, 4, 5, and 6 km/h, respectively) on a treadmill were applied for one-minute of continuous levelled walking. Only lateral kinematics (mediolateral acceleration and yawing and rolling angular velocities) revealed significant interactions from walking speed and age, demonstrating lower stride regularity and higher gait variability than the anteroposterior and vertical kinematics.

KEY WORDS: gait stability, inertial sensor, regularity, variability kinematics

INTRODUCTION: While walking, people tend to shift their center of mass (CM) from one leg to the other, resulting in rhythmical lateral and vertical movements with forward translation. This dynamic stability while walking has been interpreted in terms of stride or step regularity and variability of spatio-temporal gait parameters (Li, Haddad, & Hamill, 2005). These parameters are also used for overall quality assessments of normal gait. Gait variability has been represented by temporal parameters of stride time and swing time and spatial parameters such as step length and step width (Hausdorff, Schaafsma, & Balash et al., 2003). Stride regularity is obtained with the use of unbiased autocorrelation procedures on acceleration data (Moe-Nilssen & Helbostad, 2004).
Aging is the process of deterioration of physiological and cognitional functions as people get old. Many elderly people develop a geriatric gait profile due to frailty. One of characteristics of a geriatric gait profile is the increased fall risk (Axer, Axer, Sauer, Witte, & Hagemann, 2010). Many studies have focused on the control of balancing and gait parameters in anteroposterior (A-P) direction, but there is growing evidence that elderly people may be vulnerable to dynamic instability of the frontal plane (Hilliard, Martinez, & Janssen el al., 2008).
The purpose of this study was to investigate the effects of walking speed and age on the directional stride regularity and gait variability of data from shoes-type IMU sensors. We assumed that the stride regularity and gait variability would have directional preference as a result of forward walking. Secondly, the directional stride regularity and gait variability depends on the walking speed and age.

METHODS: Forty-four adults in their twenties (n=20), forties (n=13), and sixties (n=11) voluntarily participated in this study. They had no neuromuscular diseases during the last six months and no physical restrictions to walking on a treadmill. Written informed consent forms were obtained from all subjects.
Gait data were collected with the DynaStab™ (JEIOS, Powell, OH, USA), an IMU sensor-based gait analysis system. The DynaStab™ consists of the Smart Balance SB-1® (data-logger of shoes-type IMU sensors), a treadmill, and a data collecting computer (Figure 1A). The SB-1® can measure three-axial accelerations (up to ± 6 g) and three-axial angular

velocities (up to ±500 °/s) in three orthogonal axes. The IMU sensors were inserted in both out-soles of the shoes. The local axis of the IMU sensor was aligned with the usual orientation of the gait such as the anteroposterior (AP) (X-axis), mediolateral (ML) (Y-axis), and vertical (Z-axis) directions, respectively (Figure 1B). Raw data from sensors were sampled at 100 Hz, filtered at 17 Hz with a low-pass Butterworth filter, and wirelessly transmitted in real time to a computer through a Bluetooth® receiver (Figure 1A). Subjects walked on a treadmill at four different speeds of 3, 4, 5, and 6 km/h (0.83, 1.11, 1.38, and 1.66 m/s), respectively. Data for one-minute continuous and steady walking were collected at each designated treadmill speed when subjects felt comfortable and verbally expressed a steady state condition in the middle of treadmill walking.



(A) (B)

Figure 1: (A) Shoe-type IMU sensor with reflective markers, (B) Directional definitions of six directional kinematic data for normal gait

Stride regularity (SR) is calculated using unbiased autocorrelation procedures. The Pearson product correlation coefficient (*r*) between two adjacent cycles was calculated first. The mean value of correlation coefficients of repeated cycles during one-minute walk was defined as SR (Moe-Nilssen & Helbostad, 2004). Gait variability (GV) was determined by the average standard deviation of spatio-temporal parameters across the gait cycle (Li et al., 2005). GV was defined as the mean value of CV across the entire normalized time frames.

Table 1. Overall scores of directional SR and GV according to three directions of linear motion and three direction of angular motion

			Score	F	*p*
Stride regularirty (SR)	Linear	AP	0.970±0.029	274	<.01* (AP>V>ML)
		ML	0.893±0.075		
		V	0.959±0.035		
	Angular	Roll	0.919±0.053	419	<.01* (Pitch>Roll>Yaw)
		Pitch	0.985±0.013		
		Yaw	0.852±0.079		
Gait variability (GV)	Linear	AP	0.028±0.033	137	<.01* (ML>V>AP)
		ML	0.085±0.074		
		V	0.048±0.049		
	Angular	Roll	0.061±0.049	339	<.01* (Yaw>Roll>Pitch)
		Pitch	0.017±0.016		
		Yaw	0.142±0.088		

AP=anteroposterior, ML=mediolateral, V=vertical, R=rolling, * indicates significant main effect.

RESULTS: Table 1 summarizes the overall results for directional SR and GV. For the linear acceleration components, A-P acceleration had the highest SR (0.970±0.029) and the lowest GV (0.028±0.033) while M-L acceleration had the lowest SR (0.893±0.075) and the highest

GV (0.085±0.074). For the angular velocity components, pitching velocity had the highest SR (0.985±0.013) and the lowest GV (0.017±0.016) while yawing velocity had the lowest SR (0.852±0.079) and the highest GV (0.142±0.088).

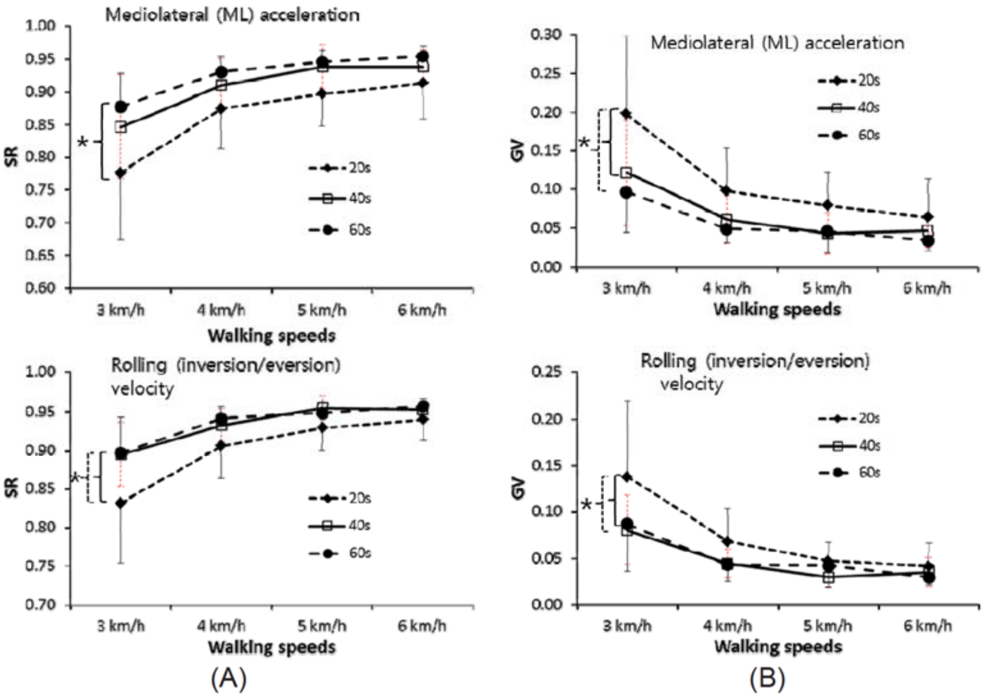


Figure 2: Effects of walking speed and age on stride regularity (A) and gait variability (B).

Two-ways repeated measures mixed ANOVA found significant interactions with age and walking speed for only M-L acceleration (F=2.48, *p*=.027) and rolling angular velocity (F=3.80, *p*=.002, Figure 2A). In M-L acceleration and rolling angular velocity, post-hoc analysis revealed that the significant difference of SRs between the 20s and 60s age groups at 3 km/h significantly decreased at 6 km/h. Statistical analysis detected significant interactions with GVs from age and walking speed in M-L acceleration (F=2.42, *p*=.031) and rolling angular velocity (F=2.65, *p*=.019, Figure 2B). In M-L acceleration and rolling angular velocity, GVs were reduced by increased walking speeds. The M-L acceleration GV for the 20s age group was significantly higher than those for the 40s and 60s age groups.

DISCUSSION: Regarding the directional preference the lateral SR and GV, represented by M-L acceleration, yawing angular velocity (abduction/adduction), and rolling angular velocity (inversion/eversion), were worse than the A-P and vertical angular velocities. Specifically, the SRs were lower and the GVs were higher in lateral kinematics. For maintaining gait stability, higher SR and lower GV are necessary.

There are a few reasons why lateral stability is weak compared to fore-aft stability during walking. It is reported that the fore-aft dynamics of walking is likely to be controlled passively by gravity and the subcortical system (Bauby & Kuo, 2000), since there is a large linear momentum in the fore-aft direction because of higher directional velocity. The lateral dynamics, however, is actively controlled by the neuromuscular system. Therefore, it requires more consideration and is sensitive to external perturbations (Bauby & Kuo, 2000). Another reason is partially attributed to the fact that the yawing motion of the foot is coupled with a rolling motion. Anatomically, the ankle joint provides coupled motions of inversion/adduction and eversion/abduction, which tend to induce motions in the frontal and transverse planes simultaneously. Mechanically the displacement and the velocity of the center of mass (CM) must be regulated with respect to the base of support defined by the feet in order to maintain postural stability (Pai & Patton, 1997). The A-P base of support, represented by the step length, is larger than the M-L base of support represented by the step width. Therefore, the SRs and GVs in lateral kinematics are relatively worse than the SRs and GVs in A-P kinematics.

Regarding the effects of walking speed and age, significant interactions from walking speed and age were found with only lateral SRs and GVs (i.e., M-L acceleration and rolling angular velocity). There was no significant interaction in A-P and vertical kinematics, which indicated insensitivity to walking speeds and ages. The primary cause of interaction with lateral kinematics was attributed to differences in SRs and GVs between the twenties and sixties age groups. These differences were very large at 3 km/h but were significantly reduced at 5 km/h and 6 km/h.

These results gave rise to a couple of neuromechanical related speculations. First, the difference in preferred walking speed according to different ages would contribute to the lateral SRs and GVs significantly (Brach, Berthold, Craik, Van Swearingen, & Newman, 2001). Secondly, the adapted linear gait parameters (e. g., shorter step length and faster step rate for the elder) for different ages would determine their stable range of walking speeds. According to the results, the elderly subjects (the forties and sixties age groups) showed a small drop in GV from 3 to 4 km/h and their GVs were relatively maintained regardless of increased speed up to 6 km/h.

CONCLUSION: The walking speed and age significantly affected the lateral SRs and GVs while walking in comparison with A-P and vertical variables. Since lateral stability is well associated with fall risk and gait problems, people need to pay more attention to the lateral dynamics of normal gait.

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Acknowledgement

This research project was supported by the Sports Promotion Fund of Seoul Olympic Sports Promotion Foundation from Ministry of Culture, Sports and Tourism.