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PREDICTION OF THE SPATIO-TEMPORAL GAIT PARAMETERS USING INERTIAL SENSOR

JIAN LIU[*,§], THURMON LOCKHART[†,¶] and SUKWON KIM[‡,‖]

[*]*Division of Applied Science & Technology*
Marshall University, Huntington, WV, USA

[†]*School of Biological and Health Systems Engineering*
Ira A/Fulton Schools of Engineering
Arizona State University, Tempe, AZ, USA

[‡]*Department of Physical Education, College of Education*
Chonbuk National University, Jeonju, South Korea

[§]*Jian.liu@marshall.edu*
[¶]*Thurmon.Lockhart@asu.edu*
[‖]*rockwall@jbnu.ac.kr*

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Monitoring human gait is essential to quantify gait issues associated with fall-prone individuals as well as other gait-related movement disorders. Being portable and cost-effective, ambulatory gait analysis using inertial sensors is considered a promising alternative to traditional laboratory-based approach. The current study aimed to provide a method for predicting the spatio-temporal gait parameters using the wrist-worn inertial sensors. Eight young adults were involved in a laboratory study. Optical motion analysis system and force-plates were used for the assessment of baseline gait parameters. Spatio-temporal features of an Inertial Measurement Unit (IMU) on the wrist were analyzed. Multi-variate correlation analyses were performed to develop gait parameter prediction models. The results indicated that gait stride time was strongly correlated with peak-to-peak duration of wrist gyroscope signal in the anterio-posterior direction. Meanwhile, gait stride length was successfully predicted using a combination model of peak resultant wrist acceleration and peak sagittal wrist angle. In conclusion, current study provided the evidence that the wrist-worn inertial sensors are capable of estimating spatio-temporal gait parameters. This finding paves the foundation for developing a wrist-worn gait monitor with high user compliance.

Keywords: IMUs; gyroscope; wearable sensor; fall-prone; gait; spatio-temporal gait parameters.

1. Introduction

Gait analysis is commonly employed for quantifying gait issues associated with fall-prone individuals as well as other movement disorders. Effective evaluation of

[‖]Corresponding author.

gait features offers valuable information about leg propulsion and control,[1] and provides insight into muscluloskeletal control. In addition, variability in gait characteristics can be used to indicate global stability. It has been found that elderly with higher step variability fell more frequently than nonfallers.[2]

Gait analysis is traditionally a laboratory-based technique, which is associated with various limitations. It is typically required for the subjects to be present at specialized facilities and therefore be removed from their natural environment and daily life. Moreover, the laboratory-based motion analysis systems have been largely bulky, costly, and nonportable. Recognizing such limitations, accurate assessment of spatio-temporal gait parameters using Inertial Measurement Units (IMUs) has long been a research quest. In 1990, a method to detect swing and stance phases during normal walking with a single uni-axial accelerometer attached on the shank was suggested.[3] Temporal gait parameters assessment has been made possible with accelerometers on the low back and on the waist, and gyroscope on the heel.[4–8] For spatial gait parameters assessments, a single pendulum model to calculate step length based on trunk displacement in the vertical direction was developed.[5] Aminian *et al.* further prevented an enhanced double pendulum model with four gyroscopes attached on the shanks and thighs.[9] Beyond ambulatory gait analysis, efforts have also been made to recognize daily activities with inertial sensors.[10–12]

To achieve successful ambulatory gait analysis, sensor attachment site is an important factor to consider because high user compliance can certainly increase the usefulness of the technology. Previous studies have commonly adopted trunk or lower limbs as the site for attaching IMUs. To the author's knowledge, there is limited evidence supporting the feasibility of performing gait analysis with IMUs on the wrist, which has been considered a highly desirable placement site for its superior user compliance.

Therefore, the current study aimed to provide a method for predicting the spatio-temporal gait parameters using the wrist-worn inertial sensors. It was hypothesized that: (1) the temporal gait parameters predicted by the wrist IMU would correlate significantly with the baseline parameters measured by the force-plates and (2) the spatial gait parameters predicted by the wrist IMU would correlate significantly with the baseline parameters measured by the motion capture system.

2. Methods

2.1. *Participants*

A laboratory study was conducted, involving eight younger adults (age $= 24.7 \pm 2.8$ years, weight $= 62.3 \pm 6.9$ kg, height $= 171.7 \pm 4.7$ cm). All participants were required to be in good physical health, and without history of movement disorders that may interfere with their gait function. Local Institutional Review Board has approved the current study. Each participant went through the informed consent process prior to data collection.

2.2. *Apparatus and procedures*

All subjects were involved in a walking study in a biomechanics research laboratory. A published walking study protocol was adopted.[13] Briefly, each subject was provided with a pair of athletic shoes, short and sleeveless shirt. This was to facilitate the attachment of the reflective markers and the IMU, and to reduce the possibility of clothing artifacts. Subjects walked at a normal speed on a straight walking track (1.5 m × 15.5 m) for three trials. Commonly used vinyl floor tile (Armstrong 62311-Signia) material was used to represent a typical living environment. Kinetic and kinematics data was collected at 100 Hz using two Bertec force-plates and a six-camera motion analysis system (Qualysis, Sweden), respectively. A biomechanical model using 27 marker-set was adopted in the kinematics data collection.[14]

One IMU (Inertia-Link, MicroStrain, Inc., USA) was attached to the right wrist (the lateral side). A custom-made Labview program (National Instruments, USA) was used to synchronize between IMU and force-plates. All subjects self-reported to be right dominant. The Inertia-Link IMU is a small orientation sensor, which provides 3D measurements of orientation, acceleration and angular velocity. The technical performance of the Inertial-Link includes: angular resolution within 0.1°, static accuracy within 0.5° and dynamic accuracy within 2.0° RMS.[15] The acceleration and angular velocity output dynamic ranges are ±300°/s and 5 g, respectively.[15] The sampling rate was 100 Hz.

2.3. *Data analysis*

All the experimental data were digitally filtered before further analysis. A zero-phase low-pass filter (Butterworth, 4th order) was adopted with 6 Hz as the cut-off frequency. Heel contact was determined using the force-plate measurements.[13] Baseline stride time (T_B) was defined as the duration between consecutive heel contacts of the same foot. Baseline stride length (L_B) was defined as the heel displacement in the anterio-posterior (AP) direction during (T_B).

Spatio-temporal features of IMU signal on the wrist during T_B were analyzed. The temporal parameters include peak-to-peak duration of gyroscope signals in both AP direction T_{AP} and vertical direction (T_{VT}). The spatial parameters include peak forearm swing angle ($\theta_{\max}$) in the sagittal plane, peak acceleration in the AP direction (α_{AP}), peak resultant acceleration ($\alpha_{\max}$), and peak acceleration in the vertical direction (α_{VT}).

One stride was extracted from each of the three walking trials for each subject. Mean gait parameters for each subject were analyzed in this study.

2.4. *Statistical analysis*

All the baseline gait parameters and the IMU parameters were analyzed using pair-wise linear correlation analysis. Pairs between the baseline parameters and the IMU parameters with fair correlation strength ($R > 0.6$) were selected for multivariate correlation analysis. The hypotheses were tested with a significance level of $p \leq 0.05$. JMP 7.0 (SAS Institute, USA) was used for all statistical analyses.

3. Results

A representative walking cycle with both kinetic and IMU measurements is presented in Fig. 1. The measurements from IMU included acceleration, orientation and angular velocity. A clear cyclic pattern (Fig. 1) was found in the vertical (VT) wrist acceleration. Specifically, the peak-to-peak duration closely corresponded to one gait step. The angular velocity in AP direction shows similar cyclic pattern, with one gait stride (2 gait steps) roughly corresponding to the peak-to-peak

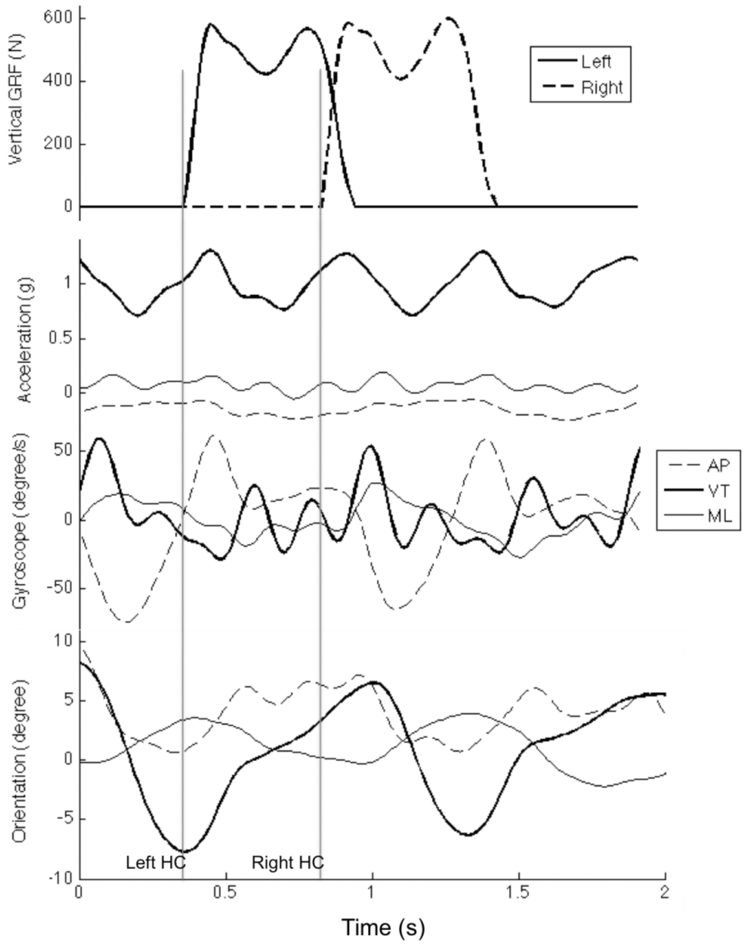

Fig. 1. Representative profile of ground reaction force (GRF) and wrist inertial measurements during walking (AP: anterio-posterior, VT: vertical, ML: medio-lateral, HC: heel contact).

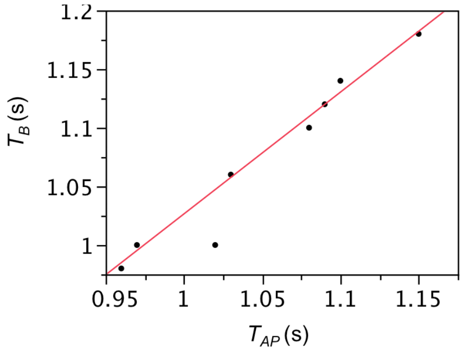

Fig. 2. Linear correlation between baseline stride time (T_B) and peak-to-peak duration of gyroscope measurement in AP direction (T_{AP}).

duration. In terms of gait events, peak wrist angles appear to coincide with the contralateral heel contacts.

With respect to the temporal gait parameters, the linear correlation between T_B and T_{AP} (Fig. 2, Table 1) was found to be strong and significant ($p < 0.0001$, $R = 0.99$). Based on the temporal parameter prediction model (Eq. (1)), the absolute residual error between T_B and T_{AP} was, on average, 0.0069 s or 0.6% of the mean stride time (1.08 s). The T_B and T_{VT}, however, had a rather weak and insignificant linear correlation ($R = 0.57$, $p < 0.1063$).

$$T_B = 1.0383 \times T_{\mathrm{AP}} - 0.0119, \tag{1}$$

Table 1. Baseline and predicted gait features.

	Stride time (s)			Step length (mm)		
	Mean (SD)			Mean (SD)		
Subject	T_B	T_{AP}	RMSE	L_B	L_P	RMSE
S01	0.98 (0.08)	0.96 (0.07)	0.14	643.91 (157.39)	515.56 (73.76)	11.33
S02	1.00 (0.06)	1.02 (0.04)	0.14	940.99 (120.97)	654.90 (94.22)	16.91
S03	1.12 (0.03)	1.09 (0.03)	0.17	702.33 (45.69)	627.20 (106.19)	8.66
S04	1.10 (0.05)	1.08 (0.06)	0.14	787.29 (29.29)	802.48 (176.26)	3.89
S05	1.06 (0.08)	1.03 (0.12)	0.17	773.97 (33.48)	610.97 (170.30)	12.76
S06	1.00 (0.09)	0.97 (0.12)	0.13	830.04 (37.04)	450.39 (91.70)	19.48
S07	1.16 (0.03)	1.20 (0.05)	0.20	833.72 (44.96)	270.54 (391.10)	23.73
S08	1.14 (0.03)	1.10 (0.04)	0.20	767.80 (14.01)	391.66 (304.61)	19.39
Mean	1.07 (0.07)	1.05 (0.08)	0.12	780.01 (89.36)	540.46 (168.17)	15.63

Notes: T_B: Baseline stride time measured from force-plate.
T_{AP}: Predicted stride time predicted.
L_B: Baseline step length measured from motion capture system.
L_P: Predicted step length.

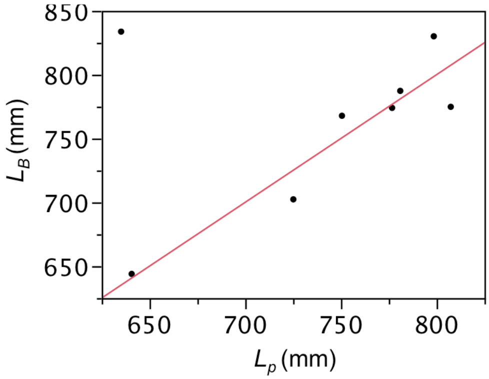

Fig. 3. Linear correlation between baseline step length (L_B) and predicted step length (L_P).

where T_B is the baseline stride time and T_{AP} is the peak-to-peak duration of gyroscope measurement in AP direction.

For the spatial parameters, L_B was found to be significantly correlated with peak resultant wrist acceleration ($\alpha_{\max}$) ($R = 0.85$, $p = 0.0146$). In addition, L_B was also moderately correlated with peak sagittal forearm swing angle ($\theta_{\max}$) ($R = 0.67$, $p = 0.1008$). Subsequently, a multivariate regression analysis was performed with L_B as the dependent variable and $\alpha_{\max}$ and $\theta_{\max}$ as the independent variables. Based on the spatial parameter prediction model (Eq. (2)), a strong and significant correlation was achieved ($R = 0.93$, $p = 0.0167$). The prediction performance was illustrated in Fig. 3.

$$L_P = 3.52 \times \theta_{\max} + 443.73 \times \alpha_{\max} + 434.16, \quad (2)$$

where L_P is the predicted stride length, $\theta_{\max}$ is the peak sagittal forearm swing angle, and $\alpha_{\max}$ is the peak resultant wrist acceleration.

4. Discussion

The objective of the current study was to develop a method using wrist-worn inertial sensors to predict the spatio-temporal gait characteristics. The study results supported our hypotheses that both stride time and stride length can be predicted by the signal features of IMU with fairly high accuracy.

From the perspective of temporal parameters, all three types of inertial features of the right wrist exhibited a similar cyclic pattern as the vertical GRF. Various peak-to-peak duration parameters can be extracted and among these, the parameter derived from the AP gyroscope output correlated with the baseline stride time with a nearly perfect strength ($R = 0.99$). Thus, the peak-to-peak duration from AP gyroscope can be considered as the best predictor for gait stride time. The stride time prediction RMSE in the current study was found to be on average 0.12 s, which is slightly higher than those reported in the literature. For example, the stride time prediction RMSE from Aminian *et al.*[9] ranged from 0.026 s to 0.1 s. Aminian's method required gyroscopes attached to the shank and the thigh segments. Therefore, the discrepancy in RMSE is likely to be attributed to the sensor location differences.

For the spatial gait parameter prediction, none of the wrist IMU features can be used to satisfactorily predict stride length alone in the current study. Nevertheless, a combination model of peak resultant wrist acceleration and peak sagittal wrist angle was found to be a viable solution for stride length estimation. Acceleration signals of various locations of human body have been used for assessing spatial gait parameters.[5,7] The step length prediction results in the current study (RMSE = 15.63 mm) compare favorably with those reported in the literature (RMSE = 70 mm).[9] Such results may be due to the strong correlation between the arm swing motion and the lower limb motion during walking, as indicated by previous studies.[11,16] The more recent study by Park[17] further demonstrated that by limiting the allowable foot reaction moment and minimizing the whole-body motion, the arm swing motion can be generated. In this context, the current findings add to the body of knowledge that the wrist motion features can also be used to assess walking characteristics.

As a pilot study, the current study includes several limitations. First is the limited sample size, which means the generalization of the current findings has to be made with caution. Second, current study only involved younger adults with no pathological arm movement. Future studies with diverse subject populations including elderly and patients with movement disorders are warranted.

5. Conclusions

In conclusion, present research provided the evidence that the wrist-worn inertial sensors are capable of estimating spatio-temporal gait parameters. This finding paves the foundation for developing a wrist-worn gait monitor with high user compliance. With the capability of evaluating an individual's gait outside the laboratory, the proposed technology could substantially improve the access to clinical gait analysis, and extend the utilization of gait analysis to longitudinal monitoring of an individual's gait features particularly in the field of physical rehabilitation and remote health care.

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