Index of gait stability using inertial measurement unit

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***Abstract*—With an increase in the number of elderly people in the population of most countries, several types of walking-support devices are being developed. At present, the performance of these devices can be measured by using motion capture, however, the evaluation is possible only in a limited environment. Therefore, in this study, we aim to construct an index that allows the device performance to be evaluated conventionally by inputting the measurements obtained from the inertial measurement unit. Therefore, there is an positive correlation between the indices using multisite data and the margin of stability (MoS) for one subject. By contrast, the correlation between the indices using multisite detection, including time delay and MoS, varies significantly depending on the combinations of sensors.**

***Index Terms*—inertial measurement unit, Lyapunov exponent, motion of stability, gait stability**

I. INTRODUCTION

In several countries, the population of elderly people is increasing. In such an aging society, certain companies are developing walking assistance devices for the elderly.

To evaluate the stability for evaluate performance of these devices, we use indices such as the maximum Lyapunov exponent, which represents the periodicity of gait, and the margin of stability (MoS), which represents the margin of time until a fall. However, as the MoS is an indicator of the mechanical properties of gait obtained from the center of gravity, and so on, whereas the Lyapunov exponent is obtained analytically from time series data, it has been thought that the MoS and Lyapunov exponent are two independent indicators of gait. However, because gait is a coordinated action of each part of the body, we hypothesize that the stability margin and periodicity of gait can be related to human motion. Therefore, the purpose of this study is to develop a new index to evaluate gait stability more easily, which correlates with the motion of stability (MoS) using data from the inertial measurement unit (IMU) attached to multiple parts of the body.

II. MAXIMUM LYAPUNOV EXPONENT AND MARGIN OF STABILITY

The Lyapunov exponent expresses the periodicity of gait by inputting the acceleration data of walking [1]. The process to calculate Lyapunov exponent is explained below.

First, the time delay τ is calculated using time series data. The embedded dimension N is also estimated using the global false nearest neighbors (GFNN) method [2]. Thereafter, we construct an $N-$dimensional state space with the accelerations at time t and $t + k\tau(k = 1, 2, ..., N-1)$ as state variables. The distances between these point and each points on the adjacent orbits are calculated along with a time delay and averaged out. As depicted in figure 1, the slope at the 0-0.5 stride is the short-term Lyapunov exponent(λ_s). The MoS is a measure of the respite that causes a fall, and the larger the MoS, the more stable the walk [3].

III. INDEX DEVELOPMENT

In a previous study [4], a new index based on the Lyapunov exponent was proposed. In the following, we denote this index as the multisite (MS) index. For the MS index, a state space was constructed with each of the acceleration waveforms at multiple sites as a state variable to reflect the dynamic nature of the Lyapunov exponent.

We also propose a new index in this study. Hereafter, we denote this index as the multisite time series index (MSTS index). This index is an extension of the MS index using a time delay. In the MSTS index, a state space was constructed with each of the acceleration waveforms at multiple sites expanded with timedelays for each embedding dimensions as a state variabl The number of embedding dimensions of the acceleration waveforms at each site was set to 5, based on the GFNN method.

In this study, the maximum Lyapunov exponents were calculated by constructing 25-, 20-, 15-, and 10-dimensional state spaces for specific combinations of the acceleration waveforms in the forward and lateral directions obtained using the sensors attached at six different locations on the human body, and their correlation with the MoS was investigated.

IV. EXPERIMENTAL METHOD AND ANALYSIS METHOD

The experiment was conducted with the permission of the Institutional Review Board of Nagoya University (approval number 20–22).

To test the relationship between the index and the MoS, we conducted an experiment on two subjects. The subjects walked on a treadmill field at four different speeds (3.0, 3.5, 4.0, and 4.5 km/h) for 120 s each. IMU sensors (ATR-Promotions TSND151) were placed at six locations, namely, on the waist,

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TABLE I
CORRELATION BETWEEN MOS AND λ_s USING MS INDEX

						λ_s-MoS_{Max}				λ_s-MoS_{min}			
Combination of sensors						forward		lateral		forward		lateral	
Bk	Ws	Ll	Rl	Li	Ri	A	B	A	B	A	B	A	B
○	○	○	○	○		0.21	0.23	0.41	0.44	0.65	0.36	0.38	0.50
○	○	○	○		○	0.21	-0.22	0.47	-0.05	0.68	-0.29	0.33	0.01
○	○	○		○	○	0.27	-0.01	0.38	0.38	0.70	0.06	0.40	0.40
○	○		○	○	○	0.30	0.01	0.44	0.38	0.72	0.12	0.41	0.42
○		○	○	○	○	0.31	-0.03	0.42	0.35	0.73	0.09	0.43	0.45
	○	○	○	○	○	0.30	-0.14	0.42	-0.14	0.73	-0.06	0.41	-0.01
○	○	○	○			0.01	-0.36	0.42	0.25	0.25	-0.35	0.25	0.31
○	○	○		○		0.31	0.59	0.38	0.45	0.68	0.73	0.38	0.43
○	○	○			○	0.02	-0.18	0.30	-0.21	0.38	-0.29	0.09	-0.10
○	○		○	○		0.25	-0.19	0.38	0.55	0.66	-0.18	0.34	0.48
○	○		○		○	0.31	-0.23	0.45	0.01	0.66	-0.24	0.30	0.03
○	○			○	○	0.29	-0.11	0.42	0.58	0.70	-0.07	0.39	0.51
○		○	○	○		0.25	0.33	0.40	0.62	0.67	0.49	0.43	0.68
○		○	○		○	0.30	-0.08	0.45	0.10	0.69	-0.15	0.36	0.20
○		○		○	○	0.25	0.05	0.34	0.49	0.67	0.14	0.43	0.50
○			○	○	○	0.31	0.15	0.42	0.40	0.74	0.30	0.42	0.48
	○	○	○	○		0.25	0.12	0.40	0.24	0.68	0.17	0.37	0.33
	○	○	○		○	0.24	-0.41	0.47	-0.46	0.72	-0.51	0.36	-0.43
	○	○		○	○	0.26	-0.13	0.35	0.20	0.71	-0.07	0.37	0.31
	○		○	○	○	0.30	-0.28	0.41	-0.20	0.73	-0.23	0.40	-0.13
		○	○	○	○	0.30	-0.09	0.40	-0.08	0.70	-0.01	0.44	0.04

Bk: Back, Ws: Waist, Ll: Left leg, Rl: Rignt leg, Li: Left instep, Ri: Right instep

TABLE II
CORRELATION BETWEEN MOS AND λ_s USING MSTS INDEX

						λ_s-MoS_{Max}				λ_s-MoS_{min}			
Combination of sensors						forward		lateral		forward		lateral	
Bk	Ws	Ll	Rl	Li	Ri	A	B	A	B	A	B	A	B
○	○					-0.06	-0.15	-0.05	0.12	-0.06	-0.03	-0.04	-0.07
○		○				0.00	0.08	0.37	0.00	0.44	0.25	0.34	0.09
○			○			-0.11	0.07	0.34	-0.40	0.10	0.23	0.47	-0.35
○				○		-0.30	0.13	-0.04	-0.39	-0.39	0.31	0.24	-0.48
○					○	-0.32	0.26	0.20	-0.58	-0.43	0.41	0.37	-0.42
	○	○				-0.10	-0.19	0.19	-0.41	-0.01	-0.08	0.21	-0.28
	○		○			-0.20	0.25	0.29	-0.49	-0.12	0.44	0.40	-0.39
	○			○		-0.27	0.18	-0.12	-0.13	-0.26	0.34	0.17	-0.28
	○				○	-0.31	0.09	-0.05	-0.56	-0.40	0.14	0.15	-0.39
		○	○			-0.17	0.10	0.23	-0.37	-0.01	0.22	0.39	-0.15
		○		○		-0.05	0.04	0.06	-0.75	-0.15	0.19	0.30	-0.64
		○			○	-0.21	-0.01	0.22	-0.60	-0.38	0.08	0.37	-0.41
			○	○		-0.20	0.01	0.16	-0.68	-0.37	0.11	0.37	-0.57
			○		○	0.03	0.21	0.26	-0.72	0.28	0.31	0.42	-0.58
				○	○	-0.28	0.04	0.03	-0.74	-0.50	0.20	0.28	-0.61
○	○	○				0.00	-0.11	0.31	-0.05	0.19	-0.05	0.24	-0.04
○	○		○			-0.03	0.02	0.48	-0.03	0.26	0.17	0.47	-0.08
○	○			○		-0.15	0.16	0.03	0.14	-0.04	0.32	0.30	-0.01
○	○				○	-0.23	0.06	0.18	-0.46	-0.11	0.15	0.19	-0.38
○				○	○	-0.26	0.08	0.07	-0.61	-0.46	0.25	0.31	-0.46
○	○	○	○			0.23	0.41	0.40	0.29	0.53	0.56	0.40	0.41
○	○	○		○		-0.05	0.09	0.03	-0.35	-0.08	0.20	0.29	-0.29
○	○	○			○	-0.04	0.39	0.21	-0.54	-0.04	0.55	0.30	-0.39
○	○		○	○		-0.01	0.02	0.24	0.07	0.00	0.13	0.42	0.08
○	○		○		○	0.22	0.33	0.44	-0.46	0.60	0.50	0.37	-0.35
○	○			○	○	-0.21	0.09	0.13	-0.76	-0.38	0.26	0.35	-0.71
○	○	○	○	○		0.06	0.10	0.15	-0.04	0.09	0.22	0.37	0.08
○	○	○	○		○	0.23	0.31	0.44	-0.50	0.50	0.48	0.45	-0.33
○	○	○		○	○	-0.12	0.15	0.08	-0.74	-0.29	0.31	0.31	-0.65
○	○		○	○	○	-0.04	0.08	0.27	-0.64	-0.08	0.24	0.41	-0.56

Bk: Back, Ws: Waist, Ll: Left leg, Rl: Rignt leg, Li: Left instep, Ri: Right instep

back, left and right feet, and left and right insteps to measure the acceleration data in the forward and lateral directions for the MS and MSTS indices. The measurement frequency of the IMU was set to 200 Hz. In addition, motion capture markers were attached to the motion analysis, and the IMU and motion capture measurements were performed simultaneously.

We now describe the analysis method. Stability margins were analyzed at two points: immediately after heel-ground contact, which was the most stable point, and immediately before heel-ground contact, which was the most unstable fixed point. Short-term Lyapunov exponents were calculated for each index, and their correlations with the most stable and least stable points of the MoS were investigated.

V. RESULT

The results obtained in this experiment are presented in Tables I and II. In these tables, λ_s is the short-term Lyapunov exponent, MoS_{max} is the MoS at most stable point, and MoS_{min} is the MoS at most unstable point.

The correlations between the MoS and MS index are depicted in Table I. For subject A, the MS index was positively correlated with the Lyapunov exponent and MoS at the least stable point in the forward direction regardless of the number of embedded dimensions. However, positive correlations were slightly found for subject B.

The correlations between the MoS and MSTS index in the forward and lateral directions are shown in Tables II. The tables indicate that, for subject B, negative correlations were found only for certain combinations of the sensors in the lateral direction. This correlation did not depend on the number of embedded dimensions. In contrast, for subject A, there were no correlations for the combination of all the sensors.

VI. DISCUSSION

The MS index and MoS demonstrated a positive correlation for subject A in forward direction. On the other hand, for subject B, there was a positive correlation for specific combinations of sensors. This result is different from those of previous research [4]. These findings indicate that the relationship between the MS index and MoS varies widely among subjects. The correlations between the MSTS index and MoS varied significantly depending on the combination of sensors for subject B, but no correlation for subject A. Furthermore, the strongest correlation between indicators with the MoS was not identified for the largest number of sensors selected. Therefore, it is necessary to determine an appropriate number and combination of sensors for each of the MS and MSTS indices by increasing or changing the location and combination of sensors.

VII. CONCLUSION

To conveniently evaluate the performance of the gait-assist device, we developed a new index using acceleration data from the IMU. We identified a positive correlation between the MoS values and MS index for certain sensor combinations, and a negative correlation between the MoS values and MSTS index for certain sensor combinations. However, the difference of trend among subjects suggests that it is neccesary to evaluate indices with increasee numbers of subject.

REFERENCES

[1] M. T. Rosenstein, J. J. Collins, and C. J. De Luca, "A practical method for calculating largest Lyapunov exponents from small data sets," *Physica D: Nonlinear Phenomena*, vol. 65, no. 1, pp. 117–134, 1993.

[2] M. B. Kennel, R. Brown, and H. D. Abarbanel, "Determining embedding dimension for phase-space reconstruction using a geometrical construction," *Physical review A*, vol. 45, no. 6, p. 3403, 1992.

[3] L. Hak, H. Houdijk, P. J. Beek, and J. H. van Die ¨ en, " Steps to take to enhance gait stability: the effect of stride frequency, stride length, and walking speed on local dynamic stability and margins of stability," *PLoS One*, vol. 8, no. 12, p. e82842, 2013.

[4] T. Naganeo, Y. Akiyama, S. Okamoto, and Y. Yamada, " Examination of walking stability evaluation index using inertial measurement unit," *JSME Conference on Robotics and Mechatronics*, vol. 06, no. 20, pp. 27–30, may 2020.