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Walking motions with high margin-of-stability values

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Abstract— **Many researchers studied on gait parameters, such as step width and speed, correlated with gait stability indices. In contrast, to understand stable gait motions against fall, we computed the time-series of joint angles that are correlated with a popular kinetic gait stability index: margin of stability (MoS). A time-series extension of the partial least square regression was applied on the joint angles to construct the principal motions, i.e., motion elements included in gait motions. These principal motions were linearly independent of each other and correlated with MoS. The linear combination of three principal motions produced a quantity that was correlated with the minimal MoS values having a coefficient of 0.87. Interpretation of the obtained principal motions suggests that the stable gait is of the small takeoff and step lengths.**

I. INTRODUCTION

Falling while walking can lead to serious disabilities such as fractures and sprains for the elderly; hence, the reduction of such incidents is a major area of focus to aid the aging society. The clarification of the gait motions with a high risk of falling will be useful for risk assessment, reduction, and practical applications such as the evaluation and development of walking aids. Thus far, there have been several studies on gait stability. England et al. reported that highly stable gaits are observed at slower walking speeds inferring from the correlation between the gait speeds and the maximum Lyapunov exponents calculated from the variability of joint angles [1]. However, if the gait speed is slower than the suitable speed, walking becomes rather unstable [2], [3]. Elderly people tend to exhibit unstable walking motion because of the variability of step length [4]. Thus, it has been reported that gait stability depends on some gait parameters such as gait speed and stride length. Some studies also focused on how humans avoid falling when they stumble or come in contact with obstacles [5], [6].

Margin of stability (MoS) [7], [8] is a popular kinetic index to represent gait stability. MoS represents the kinetic margin against falling. Thus far, many studies have analyzed the relationship between various gait parameters and MoS. For example, the MoS in the medio-lateral direction increases at high cadence [7], [9]. Similarly, the MoS in the forward direction increases when the step length is large and the gait speed is small [10]–[12]. The objectives of these studies are to identify the gait parameters that are correlated with MoS. These gait parameters including step length, cadence, and gait speed are scalar values; however, gait is a redundant multi-degree-of-freedom system and time-series involving the whole body. Gait motions that exhibit large MoS values and are less likely to result in a fall need to be investigated using the time-series of multiple human-limb joints.

In the earlier studies, researchers tried to find gait parameters that are highly correlated with the kinetic stability index. Differing from them, we identify multi-joint time-series during walking that are highly correlated with MoS by using statistical approaches. This difference in the approach may substantially divide earlier studies and ours. For this purpose, we apply partial least squares regression (PLS) [13], which is a supervised multivariate analysis method, to principal motion analysis (PMA) [14], [15], which is an analysis method for multi-variate time-series. This approach is expected to result in a new motion parameter highly correlated with MoS because PLS produces compound quantities for which the correlation coefficients with MoS are maximized. By combining PLS and PMA, we can calculate scores that are highly correlated with the MoS, and we can understand the meaning of them by interpreting the principal motions. We apply this method to a subset of the gait motion database [16] measured by a camera-based motion capture system.

II. GAIT STABILITY INDEX: MARGIN OF STABILITY

MoS is estimated by using the extrapolated center of mass (XCoM) [7], which assumes a walking human body as an inverted pendulum of height l as shown in Fig. 1. The y-axis is positive in the forward direction, and the z-axis is positive in the upward direction. The coordinate vector of XCoM ($\boldsymbol{x}_{com}$), which is computed by the velocity vector of the center of mass (CoM), ($\boldsymbol{v}_{com}$) represents the range of the CoM movement at each instant. The position vector and the velocity vector of CoM at a certain instant are represented as $\boldsymbol{c}_{om}$ and $\boldsymbol{v}_{com}$, respectively. $\boldsymbol{x}_{com}$ is computed as

$$\boldsymbol{x}_{com} = \boldsymbol{c}_{om} + \boldsymbol{v}_{com}\sqrt{\frac{l}{g}} \tag{1}$$

where g is the gravitational acceleration. MoS ($\boldsymbol{m}_{os}$) is computed by using the coordinate vector of the end of the base of support (BoS), ($\boldsymbol{b}_{os}$) and $\boldsymbol{x}'_{com}$, which is the projection of $\boldsymbol{x}_{com}$ on the ground as

$$\boldsymbol{m}_{os} = \boldsymbol{b}_{os} - \boldsymbol{x}'_{com}. \tag{2}$$

As the CoM is outside the BoS and far from its end, the body is unstable and unless a leading step supports the body, a fall occurs [10], [17]. In this study, we only deal with the MoS in the forward direction (y-axis). Generally, the minimum MoS value in the forward direction is observed just before the heel contacts during a gait cycle.

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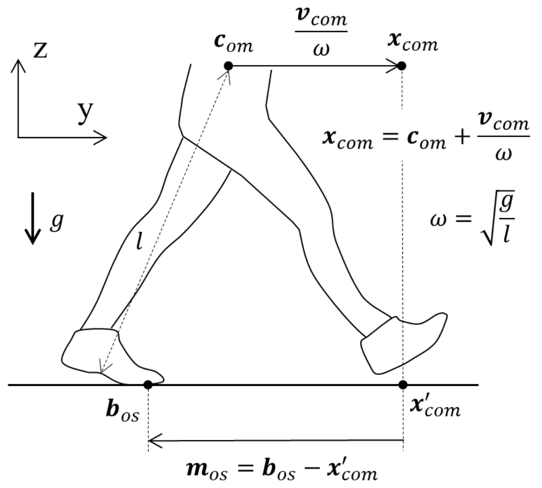

Fig. 1. Definition of MoS along the y-axis. $\boldsymbol{x}'_{com}$ is the projection of $\boldsymbol{x}_{com}$ on the ground. $\boldsymbol{m}_{os}$ is calculated by using $\boldsymbol{b}_{os}$ and $\boldsymbol{x}'_{com}$. Modified from [14].

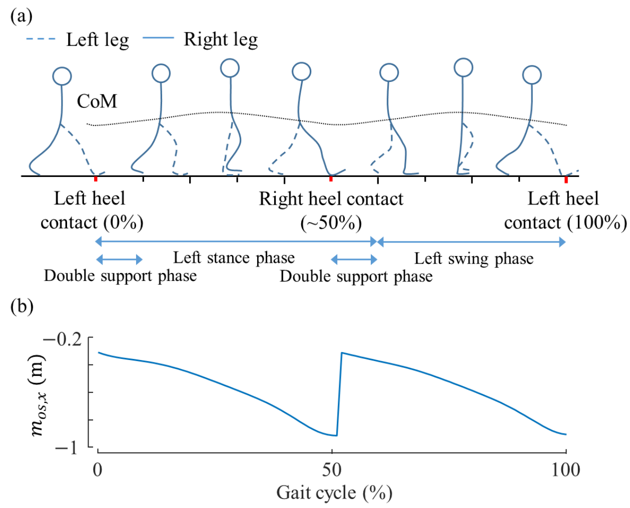

Fig. 2. Gait cycle and MoS value. (a) Gait cycle (defined from the left-heel contact (0%) to the next left-heel contact (100%)) normalized to 0–100%. Modified from [14]. (b) Example of the variation in MoS along the y-axis ($m_{os,y}$) with the gait cycle. Modified from [14].

III. Gait Motion Data

This study used a part of the gait database [16], which included ten elderly participants (age: 67.8±2.5 (mean and standard deviation) years, height: 160.1±8.1 cm, weight: 59.3±7.7 kg) who declared no walking disabilities. They were instructed to walk on a 10 m straight course attached a force measurement sensor at their comfortable gait speeds. An optical motion capture system was used to record the motions of their entire body. The details of the measurement are provided in [16].

We analyzed 50 gait samples in total, i.e., 5 samples for each participant. Each gait sample included two steps starting and ending at left-heel contacts and was normalized to 0–100% (Fig. 2 (a)). The measurement space was defined in the reference coordinate system with the medio-lateral direction on the x-axis (right for positive), the front-back direction on the y-axis (forward for positive), and the vertical direction on the z-axis (upper for positive). Each joint angle is represented as a relative angle of the distal segment seen from the proximal segment. In this study, the direction of the joint flexing and extending from the basic standing posture on the sagittal plane was set as positive and negative, respectively. We analyzed hip flexion, knee flexion, and ankle dorsiflexion angles considering both the legs. An exemplar variation in MoS along the forward direction along a gait cycle is represented in Fig. 2 (b). The minimum MoS value during a gait cycle was recorded immediately before the heel contact at $\sim$50% or $\sim$100%.

IV. Calculation of the Gait Motion Correlated with Margin of Stability

We identified the gait motions correlated with MoS by using the motion data of the joint angles during walking. For this purpose, we applied PLS [13] to PMA [14], [15]. PLS determines a quantity as the correlation with the objective variable which is maximized by a linear synthesis of the explanatory variables. Using this method, we can calculate some principal motions whose scores are highly correlated with the minimum MoS value. That is, the minimum value of MoS was estimated by a linear synthesis of multiple principal motions that are independent of each other. The principal motion was the time-series of the angles of the six lower-limb joints. The minimum value of MoS was standardized (z-score) among all trials. Joint angles were standardized across all trials after discretizing every 1% of the gait cycle.

For the joint i ($i \in 1, ..., 6$) at the k-th trial ($k \in 1, ..., k'$), let $\boldsymbol{j}_{i,k}$ be the time-series vector of the joint angles of 101 discretized moments (one value every percent of gait cycle):

$$\boldsymbol{j}_{i,k} = (j_{i,k,1}, j_{i,k,2}, ..., j_{i,k,101}). \tag{3}$$

By using this, we constructed an extended column vector $\boldsymbol{a}_k$ ($\in \mathbb{R}^{606\times 1}$) as

$$\boldsymbol{a}_k = (\boldsymbol{j}_{1,k}, \boldsymbol{j}_{2,k}, ..., \boldsymbol{j}_{6,k})^{\mathrm{T}}. \tag{4}$$

The time-series data of all the motions are represented by the matrix $\boldsymbol{A}$ ($\in \mathbb{R}^{k'\times 606}$) as follows:

$$\boldsymbol{A} = (\boldsymbol{a}_1, ..., \boldsymbol{a}_k, ..., \boldsymbol{a}_{k'})^{\mathrm{T}}. \tag{5}$$

Here, k' is the number of gait samples and $k' = 50$ in the present study.

The model formulas of PLS in this problem are as follows:

$$\boldsymbol{A} = \sum_{i=1}^{n} \boldsymbol{t}_i \boldsymbol{p}_i^{\mathrm{T}} + \boldsymbol{E}_A \tag{6}$$

$$\boldsymbol{m}_{os,min} = \sum_{i=1}^{n} q_i \boldsymbol{t}_i + \boldsymbol{e}_b \tag{7}$$

Here, $\boldsymbol{m}_{os,min}$ ($\in \mathbb{R}^{k'\times 1}$) represents the vector of the minimum MoS values obtained from each trial. n is the number of principal motions, $\boldsymbol{t}_i$ ($\in \mathbb{R}^{k'\times 1}$) is the score vector for the i-th principal motion, $\boldsymbol{p}_i$ ($\in \mathbb{R}^{606\times 1}$) is the loading of the i-th

TABLE I
CORRELATION COEFFICIENTS BETWEEN $\boldsymbol{m}_{os,min}$ AND PRINCIPAL MOTION SCORES.

First principal motion	0.68
Second principal motion	0.44
Third principal motion	0.37
Forth principal motion	0.25

principal motion, and q_i is the regression coefficient for the i-th principal motion. $\boldsymbol{E}_A$ and $\boldsymbol{e}_b$ are the residuals of $\boldsymbol{A}$ and $\boldsymbol{m}_{os,min}$, respectively. First, using these formulas, $\boldsymbol{t}_1$ was determined to maximize the covariance of $\boldsymbol{t}_1$ and $\boldsymbol{m}_{os,min}$. $\boldsymbol{p}_1$ and q_1 are calculated so that the sum of the squares of the elements of $\boldsymbol{E}_A$ and $\boldsymbol{e}_b$ are minimized, respectively. Then, $\boldsymbol{t}_2$ was determined to maximize the covariance of $\boldsymbol{t}_2$ and $\boldsymbol{m}_{os,min} - q_1\boldsymbol{t}_1$. The third and subsequent principal motions are also determined in this way. In each principal motion, the motion with a high score is a stable motion with a large MoS. Adopting up to n-th principal motion, the minimum value of MoS is estimated as follows;

$$\bar{\boldsymbol{m}}_{os,min} = \sum_{i=1}^{n} q_i \boldsymbol{t}_i. \tag{8}$$

V. RESULTS

Correlation coefficients between $\boldsymbol{m}_{os,min}$ and the principal motion scores are summarized in Table I. The principal motions exhibited strong to moderate relationships, i.e., 0.68–0.25, with the minimum MoS. In our analysis, we considered motions up to the third principal motion considering the magnitude of the correlation coefficients. We approximated the gait motions by a linear combination of the three principal motions;

$$\bar{\boldsymbol{m}}_{os,min} = 0.08\boldsymbol{t}_1 + 0.04\boldsymbol{t}_2 + 0.06\boldsymbol{t}_3. \tag{9}$$

As shown in Fig. 3, which is the scatter plot of $\boldsymbol{m}_{os,min}$ and $\bar{\boldsymbol{m}}_{os,min}$, the linear synthesis of the three principal motions was highly correlated with the minimum value of MoS. Further, Fig. 4 shows the distribution of the first and second principal motion scores. Clusters were formed for each participant, indicating that the principal motions well represent the gait characteristics of each individuals.

VI. DISCUSSION

Herein, we interpret the implications of the principal motions based on their time-series profiles. Fig. 5 shows the contents of the first–third principal motion vectors that represent the time-series of the standardized joint angles. When the motion load is positive, the joint flexes more than the mean value of all trials at a certain instant because the motion is standardized.

Fig. 5 (a) shows the first principal motion. The hip and knee joints of both legs tend to extend (negative) through the entire phase. The right ankle joint tends to dorsiflex (positive) between ∼90% (immediately before the left-heel contact) to ∼50% (at the right heel contact). Similarly, the

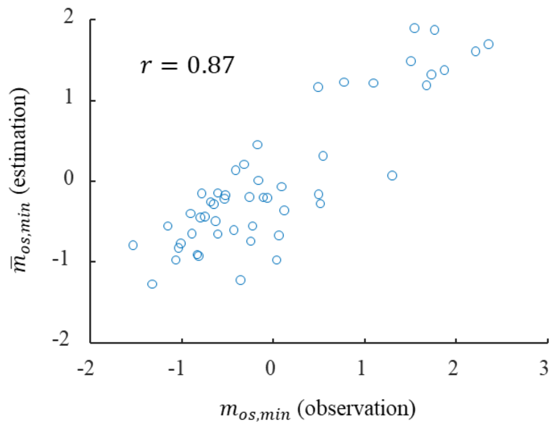

Fig. 3. Correlation between $\boldsymbol{m}_{os,min}$ and $\bar{\boldsymbol{m}}_{os,min}$.

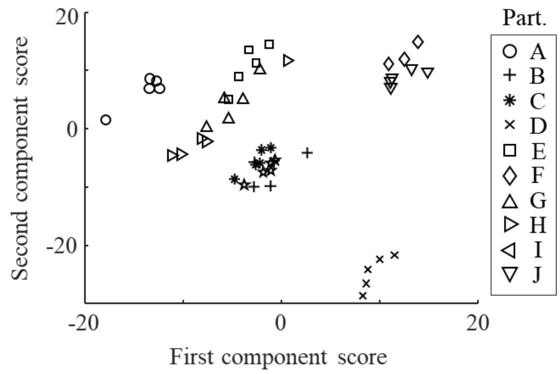

Fig. 4. Scatter plot of the first and second principal motion scores. Trials of the same participant are denoted by the same symbols.

left ankle joint tends to dorsiflex (positive) between ∼40% (immediately before the right heel contact) to ∼100% (at the left-heel contact) of the gait cycle. These characteristics suggest that the first principal motion expresses the gait with weak takeoffs, i.e., weak kicking motions at toe-off. As these characteristics are prominent, the minimum MoS values are high and the gait motions are more stable.

Note that people with the small takeoff walk slowly. Previous studies have shown that when the walking speed is slow, the gait stability is large in terms of the short-term Lyapunov exponent [1], [18], [19], which is consistent with the first principal motion. However, in contrast, it is reported that slow walking directly increases the risk of fall [20] and lowers clinical balance scales [21]. The effects of gait speed on stability are not fully consistent among earlier studies.

As shown in Fig. 5 (b), in the second principal motion, the hip joints tend to flex (positive) through the entire gait cycle. The knee joints tend to flex (positive) in the stance leg. This motion represents a small step length with bending knees and stooping hip. As mentioned in Section 1, with smaller stride lengths, the MoS values in the forward direction are greater [10]–[12]. As such, the second principal motion reasonably pertains to the MoS value.

As in Fig. 5 (c), in the third principal motion, the minimum

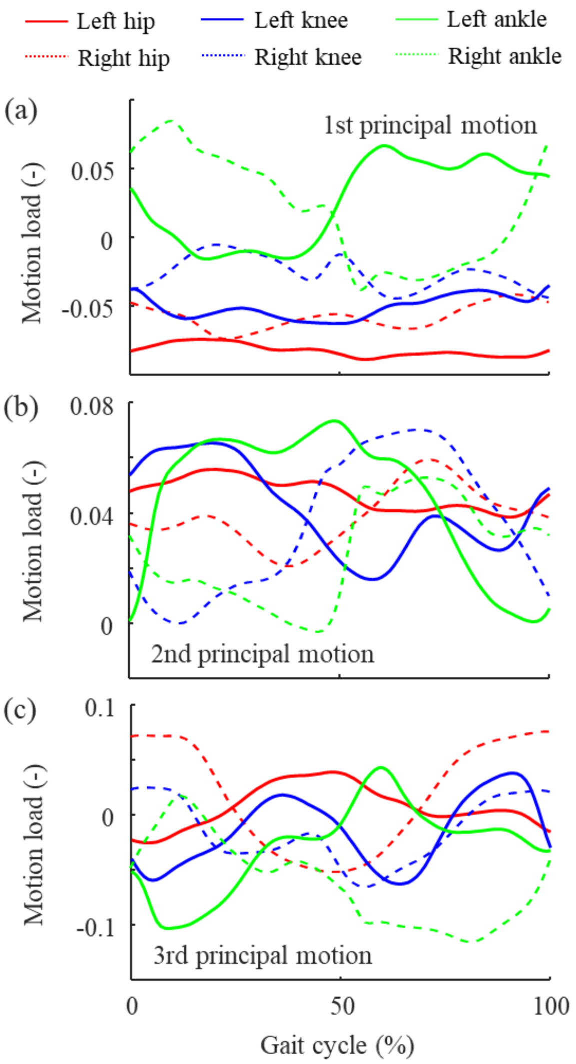

Fig. 5. Substance of each principal motion. (a): first principal motion. (b): second principal motion. (c): third principal motion. A positive value at an instant indicates that the angle is greater than the average angle among all trials.

angle for the left hip and maximum angle for the right hip are observed at left-heel contact (∼0%). Similarly, the maximum angle for the left hip joint and the minimum angle for the right hip joint are observed at right heel contact (∼100%). This motion indicates small angular changes in the hip joints. The knee joints in both legs tend to extend (negative). The ankle joint tends to planterflex (negative) in the stance leg, and dorsiflex (positive) in the swing leg. Therefore, this motion may represent a small step length without stooping.

VII. Conclusion

This study computed the lower-limb gait motions that are correlated with MoS values using a method of principal motion analysis. From the obtained principal motions, we may interpret that the first principal motion expresses the level of takeoff, and the second and third principal motions express the walking motions with small steps with and without stooping, respectively. The walking motions including these principal motions can be kinetically stable, referring to earlier studies on stable walking. Although we analyzed the data of ten participants in the present study, the original gait motion database included more participants. To obtain better results, the data of a greater number of participants should be included in future studies. Further, in future studies, our approach will be applied along the medio-lateral direction as well as the frontal-back direction.

References

[1] S. A. England and K. P. Granata, "The influence of gait speed on local dynamic stability of walking," *Gait and Posture*, vol. 25, no. 2, pp. 172–178, 2007.

[2] S. M. Bruijn, J. H. van Dieen, O. G. Meijer, and P. J. Beek, "Is slow walking more stable?" *Journal of Biomechanics*, vol. 42, no. 10, pp. 1506–1512, 2009.

[3] J. M. Hausdorff, "Gait variability: methods, modeling and meaning," *Journal of Neuroengineering and Rehabilitation*, vol. 2, no. 1, pp. 1–9, 2005.

[4] T. M. Owings and M. D. Grabiner, "Variability of step kinematics in young and older adults," *Gait and Posture*, vol. 20, no. 1, pp. 26–29, 2004.

[5] Y. Akiyama, Y. Fukui, S. Okamoto, and Y. Yamada, "Effects of exoskeletal gait assistance on the recovery motion following tripping," *Plos One*, vol. 15, no. 2, p. e0229150, 2020.

[6] Y. Akiyama, K. Mitsuoka, S. Okamoto, and Y. Yamada, "Experimental analysis of the fall mitigation motion caused by tripping based on the motion observation until shortly before ground contact," *Journal of Biomechanical Science and Engineering*, vol. 14, no. 1, pp. 18–00 510, 2019.

[7] A. Hof, M. Gazendam, and W. Sinke, "The condition for dynamic stability," *Journal of Biomechanics*, vol. 38, no. 1, pp. 1–8, 2005.

[8] H. Vallery, A. Bögel, C. O'Brien, and R. Riener, "Cooperative control design for robot-assisted balance during gait," in *Automatisierungstechnik*, vol. 60, no. 11, 2012, pp. 715–720.

[9] A. Hof, "The 'extrapolated center of mass' concept suggests a simple control of balance in walking," *Human Movement Science*, vol. 27, no. 1, pp. 112–125, 2008.

[10] D. D. Espy, F. Yang, T. Bhatt, and Y.-C. Pai, "Independent influence of gait speed and step length on stability and fall risk," *Gait and Posture*, vol. 32, no. 3, pp. 378–382, 2010.

[11] D. Espy, F. Yang, and Y.-C. Pai, "Control of center of mass motion state through cuing and decoupling of spontaneous gait parameters in level walking," *Journal of Biomechanics*, vol. 43, no. 13, pp. 2548–2553, 2010.

[12] P. M. M. Young, J. M. Wilken, and J. B. Dingwell, "Dynamic margins of stability during human walking in destabilizing environments," *Journal of biomechanics*, vol. 45, no. 6, pp. 1053–1059, 2012.

[13] S. Wold, M. Sjöström, and L. Eriksson, "PLS-regression: a basic tool of chemometrics," *Chemometrics and Intelligent Laboratory Systems*, vol. 58, no. 2, pp. 109–130, 2001.

[14] T. Iwasaki, S. Okamoto, Y. Akiyama, T. Inagaki, and Y. Yamada, "Kinematic gait stability index highly correlated with the margin of stability: Concept and interim report," in *Proceedings of IEEE/SICE International Symposium on System Integration*, 2021, pp. 347–350.

[15] T. Iwasaki, S. Okamoto, Y. Akiyama, and Y. Yamada, "Principal motion ellipsoids: Gait variability index invariant with gait speed," *IEEE Access*, vol. 8, pp. 213 330–213 339, 2020.

[16] Y. Kobayashi, N. Hida, K. Nakajima, M. Fujimoto, and M. Mochimaru, "2019: AIST gait database," 2019.

[17] Y.-C. Pai and J. Patton, "Center of mass velocity-position predictions for balance control," *Journal of Biomechanics*, vol. 30, no. 4, pp. 347–354, 1997.

[18] J. B. Dingwell and L. C. Marin, "Kinematic variability and local dynamic stability of upper body motions when walking at different speeds," *Journal of Biomechanics*, vol. 39, no. 3, pp. 444–452, 2006.

[19] L. Li, J. M. Haddad, and J. Hamill, "Stability and variability may respond differently to changes in walking speed," *Human Movement Science*, vol. 24, no. 2, pp. 257–267, 2005.

[20] R. L. Cromwell and R. A. Newton, "Relationship between balance and gait stability in healthy older adults," *Journal of Aging and Physical Activity*, vol. 12, no. 1, pp. 90–100, 2004.

[21] H. L. Rogers, R. L. Cromwell, and R. A. Newton, "Association of balance measures and perception of fall risk on gait speed: a multiple regression analysis," *Experimental Aging Research*, vol. 31, no. 2, pp. 191–203, 2005.