Prediction of Dynamic Gait Stability using Kinematic Motion of Center of Mass: Enhancement by Stratified Learning

Hiroki Watanabe
Tokyo Metropolitan University
Hino, Japan

Shogo Okamoto
Tokyo Metropolitan University
Hino, Japan

Haoyun Peng
Tokyo Metropolitan University
Hino, Japan

Yasuhiro Akiyama
Shinshu University
Ueda, Japan

***Abstract*—The Margin of Stability (MoS) is a key metric for assessing dynamic postural stability during human walking. Although MoS is typically calculated using motion capture systems, this study aims to predict the minimum mediolateral MoS using only center of mass (CoM) velocity data. Time-series data of tri-axial CoM velocities during single steps were analyzed using Principal Motion Analysis, a stochastic learning method for multivariate time-series data. To account for variability in gait patterns, unsupervised clustering was applied, and separate predictive models were developed for each cluster. The results demonstrated that stratified learning significantly improved prediction accuracy compared to a single-model approach, reducing the root mean square error (RMSE) from 21.6 mm to 18.5 mm. These findings indicate that incorporating gait stratification into predictive modeling can enhance the accuracy of MoS estimation based solely on kinematic data.**

***Index Terms*—principal motion analysis, fall risk, motion capture**

I. INTRODUCTION

The Margin of Stability (MoS) [1], [2] is an index used to evaluate postural stability and has demonstrated both construct validity [3] and criterion-related validity [4]. Given its importance, MoS has been widely studied in recent years. However, its measurement typically requires specialized equipment such as motion capture systems, limiting its applicability in daily life settings. To overcome this limitation, previous studies have attempted to estimate MoS using accelerations or velocities measured by inertial measurement sensors, including those embedded in smartphones [5], [6]. In this study, we aim to predict the minimum mediolateral MoS using tri-axial center of mass (CoM) velocity data.

The use of CoM velocity as the sole input feature was a deliberate design choice. If MoS can be accurately estimated from velocity data alone, it opens up possibilities for real-world implementation using a single inertial measurement unit (IMU), such as those found in smartphones. This minimalist input requirement facilitates broader applicability in everyday environments where motion capture systems are impractical.

Given the variability in gait characteristics across individuals and between left and right steps, we propose clustering gait patterns using principal component analysis (PCA), followed by the construction of separate prediction models for each cluster to improve accuracy. To the best of our knowledge, no prior study has applied a stratified learning approach to enhance MoS prediction.

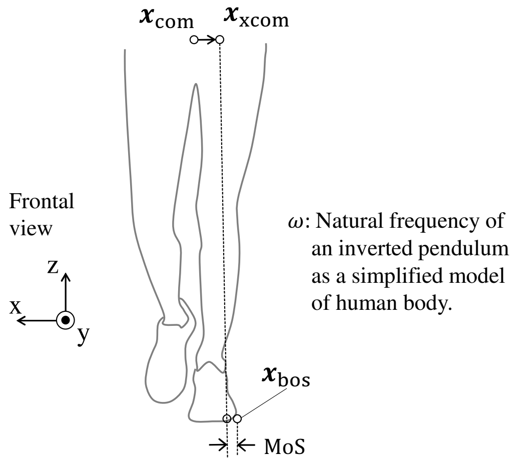

Fig. 1. Margin of stability in mediolateral direction.

II. DATA COLLECTION OF MARGIN OF STABILITY

The MoS is conceptually similar to the classical stability margin, which is defined as the distance between the center of mass (CoM) and the boundary of the base of support (BoS). Under dynamic conditions such as walking, it is more appropriate to consider the extrapolated center of mass (XCoM)—the projected position of the CoM in the near future—rather than its instantaneous position [1], [2].

This approach is based on the inverted pendulum model, where the body is modeled as an inverted pendulum pivoting around the stance foot. In this model, the natural frequency ω is defined as $\omega = \sqrt{g/l}$, where g is the acceleration due to gravity and l is the pendulum length (height of the center of mass in the upright position). The extrapolated CoM (XCoM) is then calculated as:

$$\boldsymbol{x}_{\mathrm{xcom}} = \boldsymbol{x}_{\mathrm{com}} + \frac{\boldsymbol{v}_{\mathrm{com}}}{\omega}$$

As illustrated in Fig. 1, MoS is defined as the distance between the edge of the BoS ($\boldsymbol{x}_{\mathrm{bos}}$) and the XCoM ($\boldsymbol{x}_{\mathrm{xcom}}$),

This study was supported by The Okawa Foundation (24-12).

i.e.,

$$\text{MoS} = |\boldsymbol{x}_{\text{bos}} - \boldsymbol{x}_{\text{xcom}}|.$$

This study focuses on the minimum MoS value in the mediolateral direction during a single step. This value has been used as a representative barometer of dynamic gait stability [5]–[8]. A larger MoS indicates greater postural stability, while values approaching zero suggest an increased risk of falling.

Motion data were recorded using an optical motion capture system (V120:Trio, NaturalPoint Inc., OR), measuring the positions of the CoM and the center of the second and third metatarsal bones of each foot. The CoM was defined as the midpoint between the left and right anterior superior iliac spines. The edge of the BoS was defined at the fifth metatarsal. Straight-ahead walking was recorded from three healthy adult males, yielding a total of 273 steps in which the left leg served as the supporting leg.

Recordings were obtained under three conditions: normal walking, and restricted conditions affecting either the left or right side. In the restricted conditions, a commercially available orthotic device (Simulated Experience Material for Elderly People, Sanwa Manufacturing Co., Ltd., Japan) was used to limit the range of motion of one knee joint. Additionally, a 2.0 kg ankle weight was attached on the same side to simulate physical burden.

III. PREDICTION OF MOS USING KINEMATIC DATA OF COM

A. Principal Motion Analysis

The minimum mediolateral MoS was predicted using Principal Motion Analysis (PMA) [5], [9]. PMA is a time-series extension of partial least squares regression, suitable for handling redundant multivariate time-series data. As explanatory variables, we used the time-series data of the three-axis velocity of the CoM during a single step, resampled to 100 discrete points.

Each step was segmented from the heel contact of one foot to the heel contact of the opposite foot, representing a single step that covers roughly half of a gait cycle. This segmentation ensures that important gait events such as heel strike and the single-support phase are naturally included in the input time-series data, even though explicit event markers were not used as features.

The number of principal components for the regression analysis was set to three. Leave-one-out cross-validation was performed to evaluate the prediction accuracy of the model.

B. Stratified Learning by Hierarchical Clustering

Principal component analysis (PCA) was applied to the explanatory variables of the PMA, and all samples were clustered based on their principal component scores. Hierarchical clustering using Ward's method was employed. The number of principal components was set to three, and the number of clusters to four. Following clustering, a separate PMA model was constructed for each cluster.

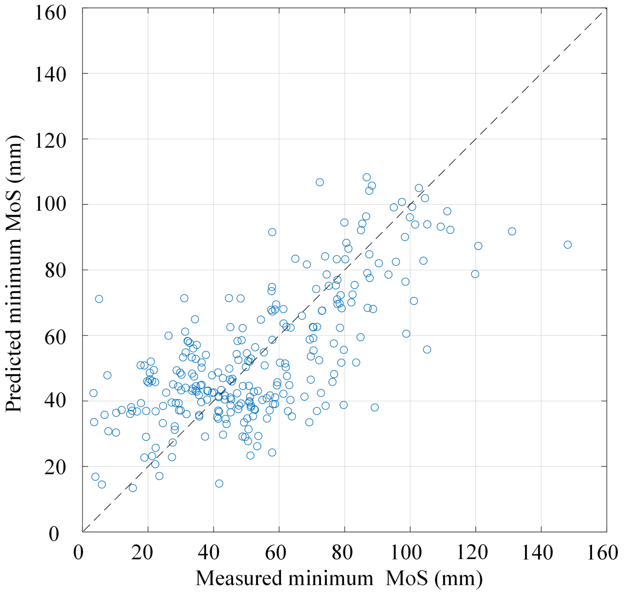

Fig. 2. Predicted MoS in mediolateral direction.

To evaluate the effects of stratified learning, we compared the predictive accuracy of MoS between the stratified models and the non-stratified model.

IV. RESULTS

Clustering based on principal component scores resulted in four clusters (Clusters 1–4), comprising 42, 124, 22, and 85 samples, respectively. These clusters were primarily differentiated by the scores on the first principal component.

When all samples were analyzed using a single (non-stratified) estimation model, the root mean squared error (RMSE) was 21.6 mm. In contrast, applying stratified learning reduced the RMSE to 18.5 mm. Stratified learning significantly reduced the variance of the estimation error ($F(272, 272) = 1.36$, $p = 0.011$).

Fig. 2 illustrates the relationship between the predicted and measured MoS values using stratified learning.

V. DISCUSSION

This study showed that the use of stratified learning can improve the accuracy of PMA-based models. By building separate models for each cluster, the prediction of MoS was better adapted to walking samples with distinct characteristics.

In the present analysis, the first principal component—mainly related to walking speed—explained most of the variance and had a strong influence on the clustering results. It is important to note that clustering was done only based on principal component scores, not on who the participant was or whether motion was restricted or not. The best method to group samples to improve prediction accuracy is still unclear and should be explored in future research.

Although hierarchical clustering divided the samples into four groups, these clusters were not intended to reflect biomechanical or constraint-based differences. Rather, clustering was employed purely as a data-driven strategy to improve MoS prediction accuracy. Interpreting the physical meaning of each cluster lies beyond the scope of this study but represents a promising direction for future research.

The use of CoM velocity alone as input was a deliberate design to reflect real-world scenarios where a single inertial measurement unit (IMU), such as that in a smartphone, can be used [10], [11]. This minimal input requirement offers a practical advantage in daily environments lacking access to motion capture systems.

Although the RMSE was significantly reduced from 21.6 mm to 18.5 mm, the practical or clinical significance of this improvement remains unclear. Future research should pursue methods achieving higher accuracy.

This study primarily aimed to evaluate the feasibility of stratified learning for MoS prediction; therefore, the number of experimental samples was intentionally limited. Rather than pursuing immediate generalizability, we focused on verifying the method's effectiveness under controlled motion capture conditions. Future research should extend this approach to larger and more diverse datasets, including gait patterns associated with frailty, aging, and pathological conditions. Such efforts are essential for assessing the method's applicability in clinical and real-world environments.

REFERENCES

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

[2] 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.

[3] S. M. Bruijn, O. G. Meijer, P. J. Beek, *et al.*, "Assessing the stability of human locomotion: A review of current measures," *Journal of the Royal Society Interface*, vol. 10, no. 83, p. 20120999, 2013.

[4] H. Ohtsu, S. Yoshida, T. Minamisawa, *et al.*, "Does the balance strategy during walking in elderly persons show an association with fall risk assessment?," *Journal of Biomechanics*, vol. 103, p. 109657, 2020.

[5] T. Iwasaki, S. Okamoto, Y. Akiyama, and Y. Yamada, "Gait stability index built by kinematic information consistent with the margin of stability along the mediolateral direction," *IEEE Access*, vol. 10, pp. 52832–52839, 2022.

[6] T. Kuroda, S. Okamoto, and Y. Akiyama, "Prediction of margin of gait stability by using six-dof motion of pelvis," *Sensors*, vol. 24, no. 22, p. 7342.

[7] T. Yamaguchi and K. Masani, "Effects of age on dynamic balance measures and their correlation during walking across the adult lifespan," *Scientific Reports*, vol. 12, p. 14301, 2022.

[8] L. Hak, H. Houdijk, F. Steenbrink, A. Mert, P. van der Wurff, P. J. Beek, and J. H. van Dieën, "Speeding up or slowing down?: Gait adaptations to preserve gait stability in response to balance perturbations," *Gait & Posture*, vol. 36, no. 2, pp. 260–264, 2012.

[9] C. Qiu, S. Okamoto, Y. Akiyama, and Y. Yamada, "Application of supervised principal motion analysis to evaluate subjectively easy sit-to-stand motion of healthy people," *IEEE Access*, vol. 9, pp. 73251–73261, 2021.

[10] P. Haoyun, S. Okamoto, H. Watanabe, and Y. Akiyama, "Dynamic gait stability estimation using IMU-based kinematic data," in *IEEE Global Conference on Consumer Electronics*, 2025.

[11] Y. Akiyama, K. Kazumura, S. Okamoto, and Y. Yamada, "Utilizing inertial measurement units for detecting dynamic stability variations in a multi-condition gait experiment," *Sensors*, vol. 24, no. 21, p. 7044, 2024.