

Dynamic Gait Stability Estimation Using IMU-Based Kinematic Data

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Abstract—The Margin of Stability is a widely recognized metric for evaluating dynamic gait stability. While its accurate computation typically requires a motion capture system, this study investigates the feasibility of estimating MoS using kinematic data obtained from a single inertial measurement unit (IMU). Sensory data were collected from three adult participants, yielding a total of 107 walking steps, each defined from left heel contact to right heel contact. Anterior MoS values were estimated using Principal Motion Analysis. Estimation performance was compared across IMUs attached to four body locations: the sacral crest, T10 vertebra, right knee, and left knee. Among these, the six-degree-of-freedom motion data from the left knee yielded the highest estimation accuracy, with a root mean squared error of 2.97 cm and a correlation coefficient between the observation and estimation being 0.88. These findings suggest the potential for accessible and cost-effective gait stability assessment tools that do not rely on full-body motion capture systems.

Index Terms—Principal Motion Analysis, acceleration, angular velocity

I. INTRODUCTION

Falls are a major public health concern among older adults, often leading to serious injuries and reduced mobility [1], [2]. Therefore, accurate assessment of dynamic gait stability is crucial for effective fall prevention and early intervention.

The Margin of Stability (MoS) [3]–[5] is a well-established biomechanical metric that quantifies dynamic postural stability during locomotion. However, its estimation typically relies on full-body motion capture systems that measure kinematic and position data across multiple body segments. As a result, MoS assessment has been largely confined to controlled laboratory environments, limiting its practicality for continuous or real-world applications.

Inertial measurement units (IMUs) present a lightweight, cost-effective alternative for motion data collection in daily lives. These sensors can record multi-axis acceleration and angular velocity, making them suitable for estimating gait-related metrics without the need for specialized equipment. Although previous studies have demonstrated that MoS can be estimated using kinematic data from a single body segment [6]–[8], no prior research has attempted to estimate MoS using data from a single IMU.

This study investigates the feasibility of estimating MoS using a single IMU. Specifically, we examine which body location provides the reliable MoS estimation based on IMU

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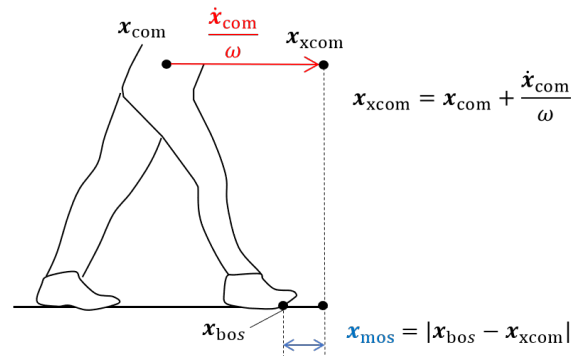


Fig. 1. Margin of stability in anterior direction.

data, thereby contributing to the development of accessible tools for gait stability assessment outside laboratory settings. Although IMUs have been used for assessing gait stability [9], [10], to date, few studies have attempted to estimate MoS using body-worn IMUs, with the notable exception of Akiyama et al. [11]. However, their approach relied on multiple IMUs and differed in both objectives and methodology from the present study.

II. METHODS

A. Gait Data Collection

We measured gait motion using an optical motion capture system (V120:Trio, NaturalPoint, Inc., Corvallis, OR, USA) and IMUs (TSND151, ATR-Promotions Inc., Japan). The optical system was used to compute the MoS in accordance with its biomechanical definition.

IMU sensors were attached to four specific body locations: the sacral crest (the midpoint between the left and right posterior superior iliac spines), the T10 vertebra, and the left and right knees (on the tibial bone just below the knee joint).

Three healthy adults participated in the study. Each participant walked along a 7-meter straight path at a self-selected, comfortable pace to reflect their natural gait. A total of 107 steps, each defined from left heel contact to right heel contact, were recorded and analyzed.

B. Margin of Stability

The MoS [3], [4] represents the distance between the boundary of the base of support (BoS) and the extrapolated

center of mass (XCoM), which accounts for both the position and the velocity of the body’s center of mass (CoM).

As illustrated in Fig. 1, the CoM is projected forward based on the walking speed and natural frequency (ω) of an inverted pendulum approximating a walking human, resulting in a predicted position called XCoM. The boundary of BoS is defined by the most forward point of the foot in contact with the ground, typically the toe or heel of the leading leg.

In this study, we focused on the anterior component of MoS during straight walking. Although reference MoS values were calculated using motion capture data, our goal was to investigate whether IMU sensor data alone could be used to estimate MoS with comparable accuracy.

C. Principal Motion Analysis for MoS Prediction

Principal Motion Analysis (PMA) [6], [12] is a supervised learning algorithm designed for modeling multivariate time-series data. It extends the Partial Least Squares method [13] to handle temporal signals and is particularly effective in extracting common motion patterns, or synergies, across multiple gait samples.

In this study, PMA was applied using acceleration and angular velocity signals from IMU sensors as predictor variables, with the minimum anterior MoS values during a step as the objective variable. The PMA algorithm decomposes these multivariate time-series signals into a small number of shared motion components, referred to as principal motions. Each gait sample is then represented by a set of weights indicating the contribution of each principal motion to the observed signal.

These weights are optimized to maximize their correlation with the corresponding MoS values. By learning this relationship, PMA constructs a linear predictive model capable of estimating MoS for previously unseen gait steps based solely on sensor data.

To evaluate the generalizability of the gait stability prediction model, we employed 10-fold cross-validation. For each condition—defined by the IMU attachment location and whether three- or six-axis data were used—the optimal number of principal motions was determined by minimizing the average prediction error across the folds.

III. RESULTS

Table I summarizes the mean and standard deviation of the root mean squared error (RMSE) in MoS estimation for each sensor location, using both 3-axis (acceleration only) and 6-axis (acceleration and angular velocity) IMU data. The effect of incorporating angular velocity is also shown as the Cohen’s d .

Among all sensor placements, the left knee achieved the highest estimation accuracy, with the lowest RMSE of 0.0297 ± 0.0079 m using 6-axis data. The right knee also showed strong performance, with an RMSE of 0.0310 ± 0.0079 m under the same condition. Fig. 2 presents a scatter plot of the estimated versus observed MoS values using data from the left knee.

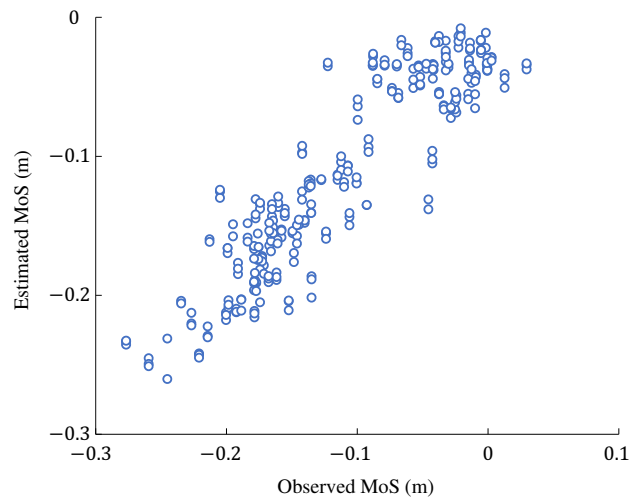


Fig. 2. MoS estimated by using the six-axial data at the left knee. Estimated by 10-fold cross-validation.

TABLE I
MEAN AND STANDARD DEVIATION OF THE RMSE BETWEEN OBSERVED AND ESTIMATED MoS VALUES. NEGATIVE EFFECT SIZE INDICATES AN INCREASE IN ERROR BY INCORPORATING ANGULAR VELOCITY.

Body feature	3-axial	6-axial	Cohen’s d
T10	0.0345 ± 0.0070	0.0363 ± 0.0075	-0.248
Sacral crest	0.0331 ± 0.0089	0.0347 ± 0.0067	-0.203
Right knee	0.0335 ± 0.0087	0.0310 ± 0.0079	0.301
Left knee	0.0377 ± 0.0085	0.0297 ± 0.0079	0.975

Across all body locations, the left and right knees demonstrated improved estimation accuracy when angular velocity data were included. Notably, the left knee exhibited the greatest improvement, with RMSE decreasing from 0.0377 m (3-axis) to 0.0297 m (6-axis), highlighting the added value of incorporating angular velocity in MoS prediction.

IV. DISCUSSION

The overall range of MoS values was approximately 0.3 m, while the average RMSE remained around 0.03 m. Although it is difficult to definitively determine whether this level of accuracy is sufficient, the results provide a useful benchmark for future research.

Notably, the best estimation performance was achieved using 6-axis data from the left knee. Since only steps with the left leg as the stance leg were analyzed, its motion was relatively limited, potentially resulting in reduced noise—factors that may have contributed to the improved accuracy.

Interestingly, the use of 6-axis data did not consistently outperform 3-axis data across all sensor locations, suggesting that the benefit of incorporating angular velocity depends on the IMU placement. Further investigation is needed to understand this location-dependent effect.

Although PMA proved effective under controlled walking conditions, its robustness under more variable gait patterns—such as non-straight walking (curving) or pathological gait—

remains to be explored. Evaluating the model's limitations is essential for developing practical, easy-to-use gait stability assessment tools. Finally, the limited sample size (three participants) constrains the generalizability of the findings. Future studies should incorporate a larger and more diverse population to validate the scalability and applicability of the proposed method.

REFERENCES

- [1] R. Vaishya and A. Vaish, "Falls in older adults are serious," *Indian Journal of Orthopaedics*, vol. 54, no. 1, pp. 69–74, 2020.
- [2] World Health Organization, "Who global report on falls prevention in older age," 2007.
- [3] A. Hof, M. Gazendam, and W. Sinke, "The condition for dynamic stability," *Journal of Biomechanics*, vol. 38, no. 1, pp. 1–8, 2005.
- [4] 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.
- [5] S. Bruijn, O. Meijer, P. Beek, and J. van Dieën, "Assessing the stability of human locomotion: a review of current measures," *Journal of the Royal Society Interface*, vol. 10, no. 83, p. 20120999, 2013.
- [6] 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.
- [7] 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.
- [8] Z. Liu, S. Okamoto, T. Kuroda, and Y. Akiyama, "Estimating the margin of gait stability in healthy elderly using the triaxial kinematic motion of a single body feature," *Applied Sciences*, vol. 14, no. 7, p. 3067, 2024.
- [9] Y.-K. Kim, J.-Y. Joo, S.-H. Jeong, J.-H. Jeon, and D.-Y. Jung, "Effects of walking speed and age on the directional stride regularity and gait variability in treadmill walking," *Journal of Mechanical Science and Technology*, vol. 30, no. 6, pp. 2899–2906, 2016.
- [10] H. Jebelli, C. R. Ahn, and T. L. Stentz, "Comprehensive fall-risk assessment of construction workers using inertial measurement units: Validation of the gait-stability metric to assess the fall risk of iron workers," *Journal of Computing in Civil Engineering*, vol. 30, no. 3, 2016.
- [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.
- [12] 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.
- [13] S. de Jong, "SIMPLS: An alternative approach to partial least squares regression," *Chemometrics and Intelligent Laboratory Systems*, vol. 18, no. 3, pp. 251–263, 1993.