Suitability of Sacrum Motion in Computing Dynamic Gait Stability Indices

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***Abstract*—Gait stability indices are expected to preemptively detect people at high risk of falling. Among these, the margin of stability (MoS) is known as a valid index. Usually, the computation of MoS requires the motion-related information of multiple feature points of the body; however, we have been pursuing the use of only one feature point. We estimated the anterior and mediolateral MoS values from the velocity time series of the sacrum, knee, or toe using principal motion analysis. Based on open gait data for 60 people over 60 years of age, the sacrum was best suited for computing MoS in the anterior and mediolateral directions. The correlation coefficients between the estimated and observed values were 0.77 and 0.73, respectively. Our findings will help establish an easy-to-access and accurate measurement of MoS values using an inertial measurement unit attached to a body feature.**

***Index Terms*—Gait stability, sacrum, knee, toe, margin of stability**

I. INTRODUCTION

Gait stability indices are expected to preemptively identify people at a high risk of falling [1]. Among these, the margin of stability (MoS) [2] evaluates dynamic balance stability during walking with good construct validity. MoS can be used for normal and perturbed walking and provides omnidirectional fall risks [3], [4]. Hence, MoS has been used by many researchers for various applications.

The computation of MoS values requires the time-series position data of the center of mass (CoM) of the body as well as those of the feet, implying that at least three feature points are needed. Hence, MoS has been largely measured in laboratory settings and rarely used in daily living. As a new challenge in computing MoS values, only the translational and angular velocities of the pelvis or CoM were used in our previous studies [5], [6]. If MoS values can be estimated solely from the time-series data of a single-body point, then smartphones with an inertial measurement unit installed can be utilized to provide a reliable gait stability index in an easy-to-access manner. However, it remains unknown which body parts are suitable for accurate estimation. In this study, we compared three body features—the sacrum, knee, and toe—to estimate anterior and mediolateral walking stability. Using an open gait database of 60 people aged over 60 years, we determined which body part was best to estimate MoS values.

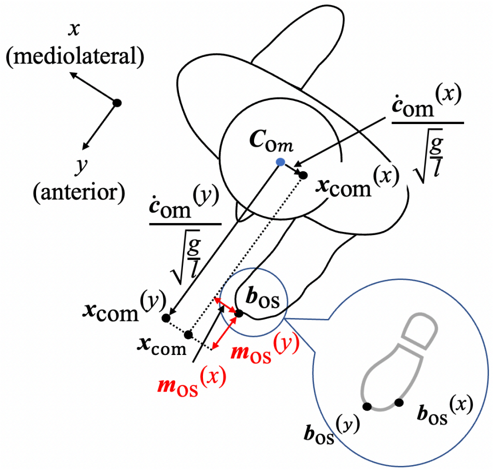

Fig. 1. Anterior and mediolateral margins of stability from the overhead viewpoint. Adapted from [7].

II. MEDIOLATERAL MARGIN OF STABILITY (MOS)

As shown in Fig. 1, MoS [2] is the distance between the predicted position of the CoM and the tip of the base of the support in the transverse plane at moment t. The predicted CoM position $\boldsymbol{x}_{\mathrm{com}}(t)$ is its prospective position in the near future and is calculated as

$$\boldsymbol{x}_{\mathrm{com}}(t) = \boldsymbol{c}_{\mathrm{om}}(t) + \dot{\boldsymbol{c}}_{\mathrm{om}}(t)\sqrt{\frac{l}{g}}, \tag{1}$$

where $\boldsymbol{c}_{\mathrm{om}}(t)$ and $\dot{\boldsymbol{c}}_{\mathrm{om}}(t)$ are the position and velocity vectors of the CoM, respectively. Here, g is the gravitational acceleration and l is the height of the CoM from the floor in an upright body posture.

The MoS is defined as

$$\boldsymbol{m}_{\mathrm{os}}(t) = \boldsymbol{b}_{\mathrm{os}}(t) - \boldsymbol{x}_{\mathrm{com}}(t) \tag{2}$$

where $\boldsymbol{b}_{os}(t)$ is the position vector of the tip of the base of the support area. The y and x components of $\boldsymbol{m}_{\mathrm{os}}(t)$ are the anterior and mediolateral MoS values, respectively. The minimum values in each direction during the gait cycle were used as the MoS values for the most critical condition. As these values are large, it is unlikely that people would lose balance or fall during walking.

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TABLE I
CORRELATION COEFFICIENT BETWEEN THE OBSERVED AND ESTIMATED MoS VALUES USING DIFFERENT BODY FEATURES

Body Features	Mediolateral	Anterior
Sacrum	0.73	0.77
Knee	0.64	0.76
Toe	0.63	0.79

III. METHODS

A. Gait motion data

The three-dimensional motion data of various body points of 60 people over 60 years of age were used for the analysis, including 30 males and 30 females. They were adopted from an open gait motion database [8]. Thus far, this database has been used by various researches, e.g., [9]. For each person, five gait cycles were analyzed, and 300 gait samples were included in the analysis.

B. Principal motion analysis

Principal motion analysis is a supervised multivariate time series analysis [5], [10], [11]. It determines the basis time-series of multiple variables called principal motions so that their linear combinations approximate any sample in a learning dataset. The principal motions are determined such that their score, which indicates the degree to which a sample includes that principal motion, exhibits the greatest correlation coefficients with the anterior or mediolateral MoS values. We used the minimum MoS values along these two directions in a gait sample comprising two successive steps as the objective values. The time series of triaxial velocities of the sacrum, knee, and toe served as predictors of the minimum MoS values, as described in Section III-C.

C. Body features used to compute MoS

We used the tri-axial velocities of three lower-body features—the sacrum, right knee, and right toe—to compute MoS values. The sacrum and toe are close to the CoM and tips of the base of the support, respectively; hence, these feature points can help estimate the MoS values. The knee is nearly the central point between the sacrum and the toe. The knee and toe are referred to as the lateral condyle of the femur and the center of the second and third metatarsals, respectively. The sacrum was referred to as the median sacral crest. In addition to this, the reason we chose these parts of body features is because it is easier to recognize skeletal features from the body surface.

IV. RESULTS

We computed the three principal motions for each of the three body features. We estimated the minimum mediolateral and anterior MoS values using regression analysis, with the scores of the three principal motions as explanatory variables. The correlation coefficients between the observed and estimated minimum mediolateral MoS were 0.73, 0.64, and 0.63 for the sacrum, knee, and toe, respectively, and those for the anterior MoS were 0.77, 0.76, and 0.79, respectively. These values are summarized in Table I. Fig. 2 shows a scatter plot of the observed and estimated mediolateral MoS values when the motion data of the sacrum were used for the prediction. Among the three feature points, the sacrum was the best for the mediolateral MoS values, whereas all three were comparable for the anterior MoS values.

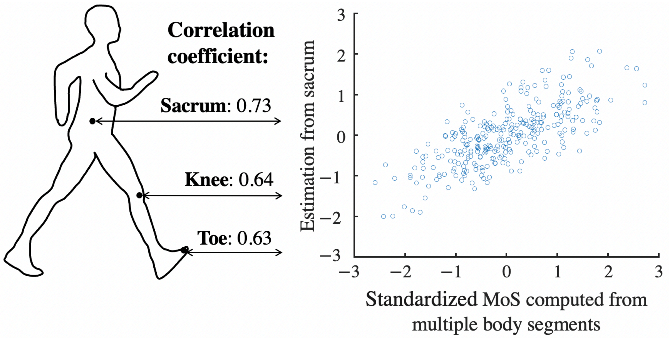

Fig. 2. Results. Left) Correlation coefficients for each body feature point. Right) Scatter plot of observed mediolateral MoS values and those estimated by using the motion data of sacrum. The MoS values are standardized.

V. CONCLUSION

MoS is a popular gait stability index that indicates fall risk. We estimated the minimum mediolateral and anterior MoS values during a gait cycle by using the triaxial translational velocities of each of the three body feature points, considering the potential use of an inertial measurement unit. In the mediolateral direction, the sacrum was the best among the three features for estimating MoS values. There were no substantial differences in the accuracy of estimation in the anterior direction. The sacrum is a good position for estimating MoS values.

In the future, we need to compare a variety of body features in addition to the three investigated in this study. Furthermore, we experiment with inertial measurement units for estimating the MoS values, whereas the motion data of this study were recorded using an optical motion capture system.

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