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Relationship between gait stability indices and gait parameters comprising joint angles based on walking data from 288 people

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ABSTRACT

Stability during walking is essential because falling accidents may lead to severe injuries. In this study, we calculated the margin of stability (MoS) and the maximum Lyapunov exponent (λ_s), which are two major stability indices for walking, using a gait database representing 300 healthy people. Previously, the relationships between these indices and other gait parameters, including joint angles, have not been investigated in such a large subject pool. Therefore, we determined the relationships between these stability indices and the gait parameters by calculating correlation coefficients and performing multiple regression analysis. The results indicated that MoS is dominated by walking speed in the forward direction and associated with various joint angles in the lateral direction. Conversely, no relationships were identified between λ_s and the gait parameters. Although both MoS and λ_s are considered as measures of gait stability, they are independent. The results of this study suggest that MoS and λ_s represent different aspects of gait motion.

Keywords: local dynamic stability, margin of stability, gait analysis, gait stability

Abbreviations:
MoS: margin of stability
MoS_f: MoS in the forward direction
MoS_l: MoS in the lateral direction
λ_s: maximum Lyapunov exponent
XCoM: extrapolated center of mass position
HC: heel contact
TO: toe off
COG: center of gravity
BoS: base of support

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INTRODUCTION

Accidents during walking caused by gait instability, particularly among the elderly, can be a major risk factor and cause severe injuries. Therefore, the analysis of gait stability is important for assessing the risk of falls. Various indices have been proposed to evaluate walking stability.[1] The maximum Lyapunov exponent (λ_s)[2] is a major index for evaluating local dynamic gait stability. It quantifies the stability of a person's gait by constructing a limit cycle based on the gait parameters and by calculating the trajectory divergence. Conversely, the margin of stability (MoS) is an index that determines walking stability based on the kinetic margin of the supporting area, which prevents falling.[3,4]

Several studies have investigated various factors that can affect gait stability. Kodesh et al examined gait symmetry and Jordan et al investigated stride-to-stride fluctuations by measuring walking speed.[5,6] Additionally, Espy et al examined the influence of walking speed and step length on gait stability and fall risk.[7] The relationships between gait parameters and gait stability indices, namely, MoS and λ_s, have also been studied. Hak et al have reported that slower walking speeds enhance MoS in the forward direction (MoS_f) and that a greater stride frequency increases MoS in the lateral direction (MoS_l).[8] Additionally, several studies have investigated the relationships between λ_s and walking speed,[9-12] stride length, and stride frequency.[8] However, the stability indexes for gait have not been examined while considering more comprehensive gait parameters such as joint angles during walking. In particular, the relationship between λ_s and MoS is unclear, despite these two indices being prominent measures of gait stability.

In this study, we investigated the relationships between λ_s, MoS, and basic gait parameters,[13,14] such as walking speed, step length, and stride frequency, along with joint angles. We used data from AIST Gait Database 2019,[15] containing gait data from 300 healthy people. Although many gait indices evaluate gait using different parameters, the motion synergy among body links required for gait motion may lead to certain regularities among indices, including MoS and λ_s. Therefore, we aimed to identify statistical relationships between these two indices. Furthermore, because the relationships between gait parameters, including joint angles, and gait stability indices have not been investigated in detail, we aimed to identify the parameters that determine or are correlated with the aforementioned gait stability indices.

METHODS

Dataset

We used data from the AIST Gait Database 2019,[15] which consists of 10 gait trials with approximately 1.5 strides for 300 healthy adults, wherein the left and right strides are included evenly. Measurements were obtained using a motion capture system (Vicon MX, Oxford, UK) and a floor ground reaction force plate (AMTI, Watertown, MA, USA). The sampling frequency was set to 200 Hz, and 55 to 59 reflective markers were attached to different major body parts to obtain positional information. We analyzed data from 288 healthy adult men and women (141 men and 147 women, age range of 20 to 78 years, average age of 49.7 years). The data from 12 subjects were excluded from our analysis as a result of incomplete stride information. Therefore, a total of 2880 trials were analyzed.

Because several studies have reported that gait characteristics are dependent on sex and age,[16-18] we considered various attributes of gait motion in the subjects of this study.

The midpoints of both the anterior superior iliac spine marker and sacral marker were considered as centers of mass. Additionally, heel and toe markers were used to determine foot contact and calculate the position of the base of support (BoS). Various gait parameters were considered in our analysis. The data were analyzed using the software MATLAB R2020b (MathWorks, Inc, Natick, MA, USA).

Gait parameters

Table 1 presents the gait parameters considered in this study. The posture angle of each body link was determined based on the marker positions. In this study, in addition to the parameters identified in our previous study,[19] stride frequency was newly identified as the inverse of single-stride time, which is calculated as walking speed divided by stride length.

Table 1 List of gait parameters

	Gait parameters	Definitions
1	Step length (m)	Distance between the heel markers of the right and left legs in the forward direction at HC
2	Step width (m)	Lateral distance between the right and left heels at HC
3	MFC (m)	Height of the sole when the foot becomes parallel to the ground during the swing phase
4	Thigh tilt (HC) (°)	Angle between the thigh and horizontal axis in the sagittal plane
5	Thigh tilt (TO) (°)	Thigh tilt at TO
6	Knee angle (HC) (°)	Angle between the thigh and shank at HC
7	Knee angle (TO) (°)	Knee angle at TO
8	Shank tilt (HC) (°)	Angle between the shank and horizontal direction at HC
9	Shank tilt (TO) (°)	Shank tilt at TO
10	Foot angle (°)	Angle between the vector from the distal end to the proximal end of foot in the horizontal direction at TO
11	Tilt of upper body (°)	Inclination of the line connecting the midpoint between C7 and the upper body margin of the sternum
12	Ratio of COG position (lateral)	Ratio of the COG positions and the area of the BoS in the lateral direction at HC
13	Ratio of COG position (forward)	Ratio of the COG position in the forward direction at HC
14	Walking speed (m/s)	Average value of the velocity of the center of mass in the forward direction
15	Stride frequency (Hz)	Inverse of one stride time calculated as walking speed/ stride length

HC: heel contact
TO: toe off
MFC: minimum foot clearance
COG: center of gravity

Margin of stability

The MoS evaluates the gait stability using an inverted pendulum model.[3,4] Initially, the extrapolated center of mass position (*XCoM*) is calculated using the position and velocity of the center of mass, which are denoted as *CoM* and V_{CoM}, respectively.

$$XCoM = CoM + V_{CoM} / \sqrt{\frac{g}{l}} \quad (1)$$

Here, l denotes the height of the center of mass, and g is the acceleration due to gravity. Additionally, we calculated the BoS based on the position of the toe marker. The margin between BoS and $XCoM$ defines MoS, which is obtained as follows:

$$MoS = BoS - XCoM. \quad (2)$$

A system is mechanically stable when $MoS > 0$ and unstable when $MoS < 0$. Figure 1 presents the MoS in the stable state. MoS_f is calculated as the distance between the position of the toe marker and $XCoM$, as shown in Equation (2), where the toe marker of the forward foot is considered as BoS. MoS_l is calculated as the distance between the position of the toe marker and $XCoM$ in the lateral direction. In this study, the smallest margin at the beginning of the double-stance phase, which appears after heel contact (HC), was selected as the representative MoS value in the forward and lateral directions of each stride, respectively.

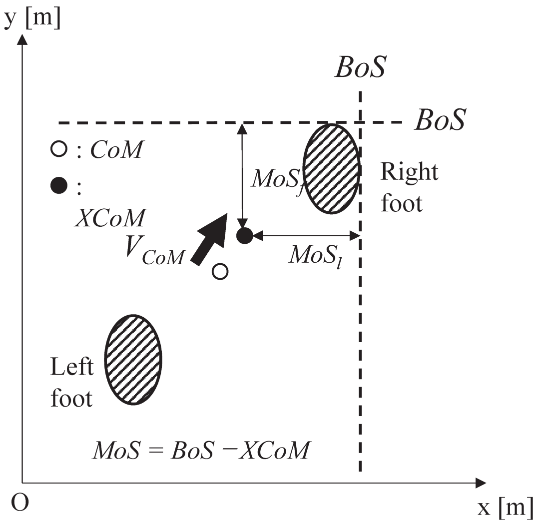


Fig. 1 Schematic of XCoM, BoS, and MoS in the stable state
The foot is grounded in the direction the body is moving. The minimum value of MoS in the beginning of the double-stance phase is used as the representative value of MoS.
CoM: center of mass
XCoM: extended center of mass
BoS: base of support
MoS: margin of stability

Maximum Lyapunov exponent

The λ_s evaluates local dynamic stability, which quantifies the divergence of small perturbations in a state space.[1,2,9,20] An m-dimensional state space S with time delay τ is reconstructed using the center of mass velocity $v(t)$ based on the Takens theorem[21] as follows:

$$S = [v(t)\ v(t+\tau) \cdots v(t+(m-1)\tau)]. \quad (3)$$

The values of the embedding dimension m and time delay τ must be appropriately selected for Equation (3). Therefore, we calculated the optimal m using the false nearest neighbor algorithm.[22]

In this algorithm, the false nearest neighbor of a cyclic signal is determined as the point at which the distance from the closest point of the neighboring cycle changes significantly when m changes. Typically, m is identified as the minimum value at which the false nearest neighbors converge. We obtained average values of $m = 3$ and $m = 5$ for all participants in the forward and lateral directions, respectively.

Additionally, the time delay τ was calculated using average mutual information.[23] Typically, τ is determined as the minimum value at which the mutual information exhibits a local minimum. For each τ, we determined the amount of mutual information between the original time series data and the time series data delayed by τ. Consequently, average values of 13 and 6 time points for all participants were calculated in the forward and lateral directions, respectively. Therefore, the state space was reconstructed using the derived values of m and τ, and divergence was calculated using Rosenstein's algorithm.[24]

The average logarithmic rate of divergence was obtained by computing the Euclidean distances between neighboring trajectories in the state space. The slope of the obtained divergence curve is the maximum Lyapunov exponent. In this study, a stride of 0.5 to 1.0 steps was considered as the short-term maximum Lyapunov exponent, which is denoted as λ_s. Although the optimal stride length was not identified for computing λ_s,[25] we selected this short stride length based on its applicability to real-time scenarios. A positive λ_s indicates that a system is unstable.

Statistical analysis

The correlation coefficients between the gait stability indices and the gait parameters were calculated. We performed multiple regression analysis considering the two types of stability indices and gait parameters as the objective and explanatory variables, respectively. Additionally, the parameters were standardized (z-score) based on the original data distribution to facilitate the interpretation of regression coefficients.

RESULTS

Correlation coefficients between gait parameters and stability indices

Table 2 lists the value of the correlation coefficients between the two calculated stability indices and each gait parameter. As indicated in Table 2, no meaningful correlation exists between λ_s and the gait parameters. Additionally, the correlation coefficients obtained between λ_s and MoS are nearly negligible at $r = -0.02$ and $r = 0.03$ in the forward and lateral directions, respectively.

However, the correlation coefficient between the walking speed and MoS_f is negative ($r = -0.69$). Additionally, a negative correlation ($r = -0.42$) can be observed between the step length and MoS_f. Furthermore, weak correlations were identified between several joint angles and MoS_l. The correlation coefficients between MoS_l and the step width are small and positive ($r = 0.25$). Additionally, the correlation coefficients between MoS_l and the thigh tilt at HC and between MoS_l and the tilt of the upper body are small and negative at $r = -0.24$ and $r = -0.27$, respectively. Negative correlation coefficients were also observed between MoS_f and the foot angle and MoS_f and the ratio of the center of gravity (COG) position (forward) at $r = -0.33$ and $r = -0.25$, respectively. Furthermore, the correlation coefficients between MoS_f and the thigh tilt at toe off (TO) and MoS_f and the shank tilt at TO are positive and small at $r = 0.26$ and $r = 0.27$, respectively.

Regression analysis of gait parameters and stability indices

Figure 2 presents the coefficient values and their 95% confidence intervals obtained through

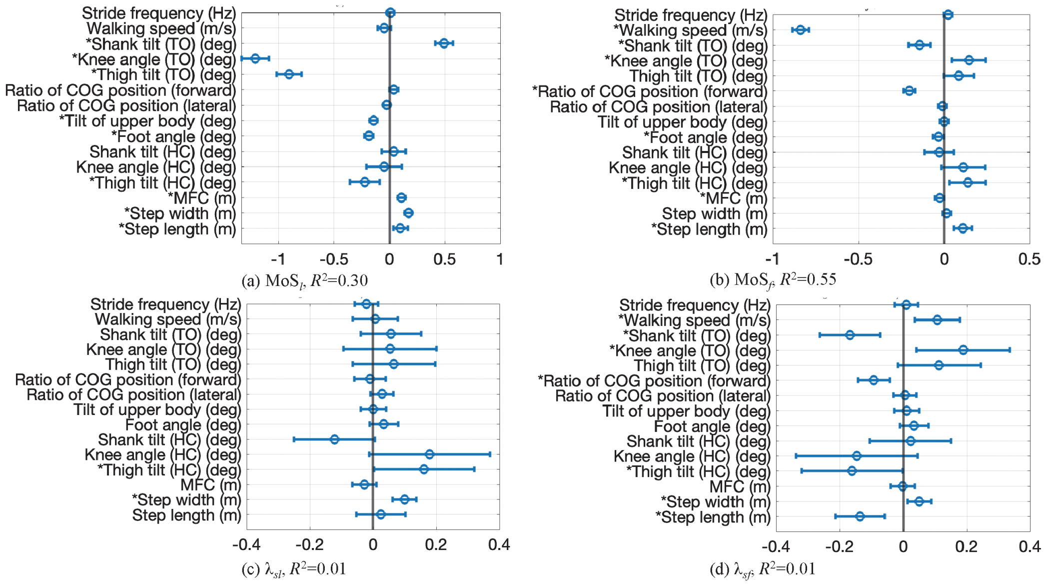
Table 2 Computed Pearson's correlation coefficients between gait parameters and MoS and λ_s

Variables	mean	std	r			
			MoS_l	MoS_f	λ_{sl}	λ_{sf}
Step length (m)	0.66	0.06	–0.05**	–0.42**	0.01	–0.01
Step width (m)	0.07	0.03	0.25**	–0.04*	0.09**	0.04*
MFC (m)	0.02	0.01	0.14**	–0.13**	–0.02	0.00
Thigh tilt (HC) (°)	117.5	3.42	–0.24**	–0.16**	–0.01	0.04
Knee angle (HC) (°)	8.3	4.14	0.10**	0.07**	0.02	–0.05**
Shank tilt (HC) (°)	109.9	2.56	–0.12**	–0.11**	0.01	–0.03
Foot angle (°)	69.1	8.99	–0.17**	–0.33**	–0.01	0.04*
Tilt of upper body (°)	17.1	7.38	–0.27**	–0.02	0.00	0.01
Ratio of COG position (lateral)	0.50	0.13	–0.03	–0.02	0.02	0.00
Ratio of COG position (forward)	0.65	0.03	0.11**	–0.25**	–0.01	–0.02
Thigh tilt (TO) (°)	80.5	4.10	0.09**	0.26**	0.00	0.01
Knee angle (TO) (°)	41.1	5.03	–0.18**	–0.07*	0.03	–0.03
Shank tilt (TO) (°)	38.4	2.80	–0.01	0.27**	0.05*	–0.07**
Walking speed (m/s)	1.34	0.15	–0.11**	–0.69**	0.00	0.03
Stride frequency (Hz)	1.07	0.07	0.01	0.01	–0.02	–0.00

Mean and standard deviation values are also presented. _l and _f denote the lateral and forward directions, respectively. The p-values are indicated as follows: *>0.05, **>0.01.
HC: heel contact
TO: toe off
MFC: minimum foot clearance
COG: center of gravity
MoS: margin of stability
λ_s: maximum Lyapunov exponent

the multiple regression analysis of the gait parameters and stability indices. As shown in this figure, MoS_f is negatively affected by the walking speed, shank tilt at TO, and ratio of the COG position (forward). Additionally, the step length has a positive effect on MoS_f. In the lateral direction, MoS_l is negatively affected by the knee angle and the thigh tilt at TO. In contrast, the shank tilt at the TO exhibits a positive effect on MoS_l. Additionally, MoS_l is positively affected by the step width, step length, and minimum foot clearance (MFC). The large R^2 value (R^2 = 0.55) of MoS_f indicates that it can be predicted to a certain extent using these gait parameters. Additionally, a relatively large R^2 value can be observed in the case of MoS_l with R^2 = 0.30.

Conversely, the value of R^2 for λ_s is extremely small and the gait parameters do not appear to affect the value of λ_s. Although several gait parameters exhibited significant effects, as shown in Fig. 2(d), wide confidence intervals were observed with significant differences between individual subjects and between trials. Additionally, the observed trends were common among the young, middle-aged, and elderly groups. We examined the inter-correlations among the gait parameters to identify multicollinearity in the regression analysis, but none of the gait parameters were highly correlated with each other (r > 0.8).



(a) MoS_l, R^2=0.30 (b) MoS_f, R^2=0.55

(c) λ_{sl}, R^2=0.01 (d) λ_{sf}, R^2=0.01

Fig. 2 Partial correlation coefficients of multiple regression analysis

Two stability indices MoS and λ_s are modeled using gait parameters. Error bars represent 95% confidence intervals. R^2 values are also indicated. The *p*-value is indicated on the left side (*>0.05).

HC: heel contact

TO: toe off

MFC: minimum foot clearance

COG: center of gravity

MoS: margin of stability

λ_s: maximum Lyapunov exponent

DISCUSSION

Effects of gait parameters on MoS

Forward direction. Based on the results of multiple regression analysis presented in Fig. 2(b), we conclude that the effect of the walking speed on MoS_f is dominant and that a negative relationship exists between them. Furthermore, the values of the correlation coefficients between the walking speed and MoS_f are large. Compared to the walking speed, the other parameters exhibit weaker effects on the MoS_f value. This trend matches the results of a previous study,[8] which reported a positive relationship between the walking speed and the MoS in the backward direction. This is because the XCoM moves forward as the walking speed increases, which reduces MoS_f.

Additionally, the parameter that determines the BoS, namely, the partial regression coefficient of the step length, is positive. Furthermore, a negative correlation and effect are identified between the ratio of the COG position and MoS_f based on the narrowing of the margin as the COG position moves forward.

Additionally, the partial regression coefficients of the shank tilt, knee angle, and thigh tilt significantly affect MoS_f. This can be attributed to the greater values of the knee angle, thigh tilt, and step length increasing BoS, which in turn increases MoS_f. Additionally, we analyzed the effects of the joint angles on MoS_f by considering the HC parameters. We observed that the effects of the joint angles detected at the TO on MoS_f were similar to those detected during

HC. This represents the effect of the kicking motion at TO on the stability of the stance phase.

Lateral direction. As shown in Fig. 2(a), MoS_l is significantly affected by the knee angle, thigh tilt, and shank tilt at TO, which implies that lateral stability relies heavily on the joint angles at TO. In contrast, the contributions of the step width and ratio of the COG position (lateral), which affect MoS_l directly, are relatively small. This implies that the joint angles are stronger indicators of lateral gait stability than the gait parameters. Furthermore, the effects of the joint angles at the TO are significantly greater than those observed at HC. This is probably because the kicking motion at TO is strongly reflected in MoS_l, similar to the forward direction.

Furthermore, we found that the walking speed and the stride frequency did not affect MoS_l and that stability improved when the step length was increased. A previous study[8] has reported that walking speed and step length are not associated with lateral stability but are positively related to stride frequency. Another study has reported that faster walking speed helps maintain lateral gait stability.[26] The reported relationships between these three gait parameters, namely, the stride frequency, walking speed, and step length, and lateral gait stability are inconsistent. However, our findings verify that the joint angles in the sagittal plane contribute to lateral gait stability more significantly than the aforementioned basic gait parameters. Furthermore, existing studies have considered the balance between the forward, backward, and mediolateral directions independently. However, as shown in Fig. 2(a), our results suggest that the kicking motion in the sagittal plane (ie, tilt angles at TO, knee angle (at TO), and foot angle) affects stability in the mediolateral direction.

Effects of gait parameters on λ_s

The coefficients of determination for the gait parameters were extremely low, indicating that they did not influence the value of λ_s significantly. Although our results revealed a weak positive trend between the walking speed and λ_s, the confidence intervals were large based on the individuality and the variance between trials. In other words, the results indicate that λ_s is not directly associated with the gait parameters. However, previous studies have reported that λ_s can be used to distinguish the gait sets of the young and elderly,[27] and is associated with fall history.[28] These results indicate that although λ_s may reflect the properties of gait motion, it is not directly associated with basic gait parameters.

Furthermore, variations in the data used to calculate λ_s complicate the comparison of the results reported in related studies.[29] For example, Hak et al used a combination of three-axis walking speeds to calculate λ_s and reported a negative relationship between λ_s and the walking speed.[8] In contrast, Dingwell et al used body acceleration and reported a quadratic positive relationship between λ_s and the walking speed.[9] Furthermore, England et al reported that λ_s calculated using joint angles exhibited a positive correlation with the walking speed.[10] Another study identified a negative relationship between λ_s calculated using time series velocity data and the walking speed in the forward direction.[12]

Additionally, the number of strides considered in this study is small compared to the numbers used in previous studies.[25] Although the λ_s value calculated from a small stride number can be applied in real-time scenarios, the results of this study suggest that it is not associated with the MoS and the gait parameters. However, the λ_s values calculated using a large stride number may be more relevant, but this requires further investigation.

Relationship between λ_s and MoS

The correlation coefficient between λ_s and MoS in the forward direction is small, and no relationship is identified between the two indices. Furthermore, no correlation exists between λ_s

and MoS in the lateral direction. Therefore, we can conclude that MoS and λ_s represent different aspects of walking and that no direct relationship exists between the two indices. Additionally, the differences between MoS and λ_s in terms of their responses to gait parameters suggest that they are independent of each other. However, a greater number of strides may affect these results based on the sensitivity of λ_s to stride length.

Effects of outliers in our analysis

To investigate the effects of outliers on the MoS and λ_s, Spearman's rank correlation coefficients, which are more robust to outliers than Pearson's correlation, were calculated. The results are shown in Table 3. According to Tables 2 and 3, the differences between Spearman's correlations and Pearson's correlations are small, except for the relationships between the stride frequency and the MoS and λ_s. Considering the small standard deviation of the stride frequency, it is nonlinearly related to the stability indices.

We also plotted the frequency distributions and skewness of the MoS and λ_s, respectively Fig. 3. The frequency distributions are approximately normally distributed, and the skewness value is inconsequential. Therefore, the effects of outliers are assumed to be small.

Table 3 Computed Spearman's correlation coefficients between gait parameters and MoS and λ_s

Variables	mean	std	r			
			MoS_l	MoS_f	λ_{sl}	λ_{sf}
Step length (m)	0.66	0.06	–0.03*	–0.55**	–0.01	–0.01*
Step width (m)	0.07	0.03	0.23**	–0.02*	0.10**	0.04*
MFC (m)	0.02	0.01	0.13**	–0.17**	–0.02*	0.01
Thigh tilt (HC) (°)	117.5	3.42	–0.23**	–0.19**	–0.01	0.05**
Knee angle (HC) (°)	8.3	4.14	0.12**	0.08**	0.01*	–0.07**
Shank tilt (HC) (°)	109.9	2.56	–0.10**	–0.15**	0.01	–0.02*
Foot angle (°)	69.1	8.99	–0.16**	–0.42**	–0.01	0.04*
Tilt of upper body (°)	17.1	7.38	–0.29**	–0.03*	–0.01	0.01*
Ratio of COG position (lateral)	0.50	0.13	–0.11**	–0.10**	–0.07**	0.03*
Ratio of COG position (forward)	0.65	0.03	0.12**	–0.29**	–0.01	–0.03*
Thigh tilt (TO) (°)	80.5	4.10	0.08**	0.32**	0.02*	0.01
Knee angle (TO) (°)	41.1	5.03	–0.17**	–0.07**	0.02*	–0.03*
Shank tilt (TO) (°)	38.4	2.80	–0.02*	0.32**	0.04*	–0.08**
Walking speed (m/s)	1.34	0.15	–0.08**	–0.84**	0.01	0.04*
Stride frequency (Hz)	1.07	0.07	0.10**	–0.63**	–0.01*	0.07**

Mean and standard deviation values are also presented. *_l* and *_f* denote the lateral and forward directions, respectively. The p-values are indicated as follows: *>0.05, **>0.01.
HC: heel contact
TO: toe off
MFC: minimum foot clearance,
COG: center of gravity
MoS: margin of stability
λ_s: maximum Lyapunov exponent

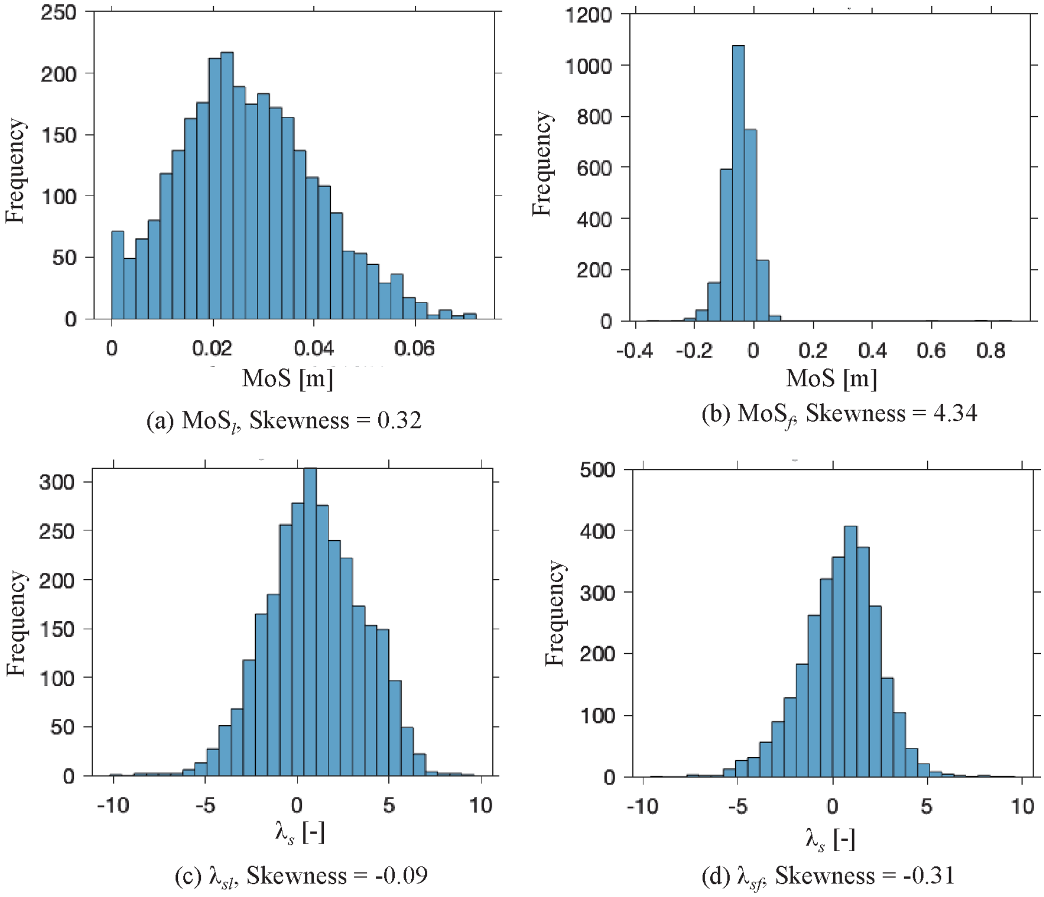


Fig. 3 Histograms of MoS and λ_s
Skewness of each frequency distribution is also shown.
MoS: margin of stability
λ_s: maximum Lyapunov exponent

Limitations

Elderly individuals sometimes have underlying conditions that come with aging, and such diseases may affect gait ability.[30] It is important to investigate the relationship between these diseases and gait characteristics. However, participant histories of disorders were not included in the database used in this study. Therefore, we could not analyze the effects of underlying conditions on the gait characteristics in this study.

CONCLUSIONS

This study aimed to identify the relationships between the gait stability indices MoS and λ_s and various gait parameters using 10 trials of walking data from 288 subjects. We investigated the effects of various parameters on the values of the MoS and λ_s based on the calculation of the correlation coefficients and multiple regression analysis. The relative contributions of individual gait parameters such as walking speed, walking frequency, step length, and several joint angles to the values of MoS and λ_s were determined.

The results indicate that no meaningful correlations exist between λ_s and MoS. Based on our analysis, we conclude that MoS is dominated by the negative effect of the walking speed and is closely associated with various joint angles, whereas no relationships exist between λ_s and most of the gait parameters. Although these two indices are used as measures of gait stability, the results of our study indicate that they can be used to examine different aspects of gait. Further investigation of the relationships between MoS and various gait parameters (ie, effects of symptoms or lower-limb injuries) will facilitate the development of a measure that quantifies the risk of falls and gait stability. This index is expected to be useful as an indicator for gait rehabilitation.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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