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RESEARCH ARTICLE

Novel Approach to Analyze All-Round Kinematic Stability During Curving Steps

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ABSTRACT From the viewpoint of the stability of biped walking, the stability for both anteroposterior, lateral, and diagonal directions should be considered owing to the frequent occurrence of turning and curving motions in the daily environment. In this study, a measure called the all-round margin of stability (MoS) is proposed to evaluate the kinematic balance of the all-round direction. A curving experiment was performed to analyze the characteristics of the all-round MoS. The curving gait was recorded with and without the restriction of hip rotation. The all-round MoS of trials were classified using cluster analysis, and the characteristics of curving motion were extracted from gait parameters using factor analysis. By comparing the characteristics of the all-round MoS and factor scores, the features of the all-round MoS were discussed. The results suggest that the effect of the parameters on the MoS, such as the velocity of the center of gravity and step width, matched the characteristics of the all-round MoS. Thus, the effect of the range of motion of hip rotation on curving gait was analyzed using an all-round MoS. The all-round MoS helps visualize the anisotropy of balance, which then enables estimation of the direction with high fall risk. Furthermore, the all-round MoS enables to evaluate and improve the performance of gait assist devices such as exoskeletons. This study proposes the concept of all-round MoS as the method to evaluate balance in diagonal direction especially for complex gait.

INDEX TERMS Curving gait, gait stability, margin of stability, range of motion, exoskeleton.

I. INTRODUCTION

An increase in the aging population requires improvement in the productivity of aged workers and the ability to perform routine activities for the elderly. The risk of falls is a major problem in an aged society because falls are a critical hazard in both industrial and daily living environments [1], [2]. For improving quality of life and productivity, exoskeletons are expected to enhance the mobility of the elderly and workers by assisting with gait motion [3], [4]. These exoskeletons emphasize on walking straight at first because it is the basic requirement of gait. However, the complexity of the daily living environment requires humans to perform various motions. Unlike treadmill training, change in the walking direction is frequently required in real-world environments [5], [6]. Furthermore, a study that observed actual falls in the daily living environment reported a variation in the direction of fall, especially when the body direction is changed [7]. Falls in the lateral direction sometimes cause severe injuries, such as hip fractures [8], [9].

Gait assistant robots are equipped with the degree of freedom (DoF) for hip flexion/extension because they are essential for straight walking. However, the human hip joint has a DoF of internal/external rotation that allows changes in the direction of the foot and adduction/abduction to generate the motion of opening or closing the legs in the frontal

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plane [10]. These DoFs are not only used for straight gait [11], but also play a key role in performing curving motion.

By observing curving gaits, we revealed that humans use approximately 30 deg of hip rotation and 10 deg of abduction when curving corners [12]. Thus, we investigated the effect of the DoFs of the hip joint on the curving gait by restricting rotation and adduction/abduction of the hip joint using a wearable device [13], [14]. The analysis of step positions and joint angles revealed that the restriction of hip rotation decreased the step length but did not decrease the physical margin of fall in both forward and mediolateral direction. Although previous studies revealed the characteristics of stepping motion during curving, conventional indices and methods are insufficient for determining the anisotropy of the stability of curving gait in diagonal directions.

Various aspects of gait motion, such as posture, motion trajectory, joint pattern, variance of motion, and kinematic margin are used to evaluate the stability of gait. The gait parameters such as step length, step time, and CoM speed are used to evaluate the difference of kinematic balance [15]. The statistical method such as factor analysis is also used to extract the factor related to the physical imbalance [16]. Furthermore, among various indices of gait stability, the local dynamic stability and the margin of stability (MoS) are recommended for evaluating the effect of gait perturbation [17]. The MoS is an index used to evaluate the kinematic margin from the fall [18]. Although most stability indices only cover the motion in the anteroposterior direction, the MoS is capable of evaluating the kinematic margin in all the direction of horizontal plane [18]. Thus, some studies evaluated the balance in mediolateral direction of straight walking [19], [20], [21]. Furthermore, other studies suggested that humans cannot maintain balance without stepping outside if the MoS becomes negative in the mediolateral direction [22], [23]. They revealed that MoS is more useful as an index of physical stability in the mediolateral direction than that in the forward direction because the inverted pendulum concept is well applicable.

However, humans sometimes fall in the diagonal direction during curving motion. Thus, the evaluation of balance in anteroposterior or mediolateral direction is insufficient [7]. As curving progresses, the direction of stepping changes in the horizontal plane [24], [25]. Furthermore, the component of ground reaction force increases in the lateral direction, which suggests the change of the direction of velocity vector [11], [26]. An approach to evaluate gait stability in multiple axes using inertia measurement units is proposed. The study reported that the gait stability in yaw direction is low compared to the other axes (i.e., pitch and roll directions) [27]. This suggested the importance to consider the interaction of balance between anteroposterior and mediolateral directions. However, the yaw motion does not directly reflect the balance in diagonal direction, and the study did not consider curving motion. Although we analyzed the MoS of curving steps, it was done in the forward and mediolateral direction separately [14]. Thus, it is necessary to develop a stability index to evaluate kinematic balance in an all-round direction.

In this study, we newly analyzed the curving motion [14] and proposed an index to measure gait stability in an all-round direction for evaluating gait motion in a daily living environment (i.e., corner curving) by expanding the idea of MoS. Furthermore, the index was applied to evaluate the performance of the gait assist devices. Thus, we compared and analyzed the curving gait under different joint restraint conditions applied by the customized orthosis using the all-round stability index.

II. EXPERIMENTAL METHOD

The data of experiment reported previously [14] were used to develop our balance index, all-round MoS. The experiment was conducted with the approval of the ethics committee of Nagoya University.

A. APPARATUS

The participants walked along the path (Fig. 1 (a)), consisting of a corner section with a radius of 0.5 m and two straight sections used for acceleration and deceleration. The motion of the participants in the corner section was recorded using a motion capture system (Motion Analysis, MAC 3D System). Thirty-five markers were attached to the body of each participant. The motion capture data were smoothed using a sixth-order Butterworth filter. The joint angle and posture were estimated by fitting the positions of the markers to a human body model (SIMM, MusculoGraphics Inc.) [28]. The position of the center of mass (CoM) was calculated using Zatsiorsky's method [29].

The physical assistant robot, MALO [16], was attached to the user by the corset around the torso, belts around the thigh and shank, and shoes. The actuators were not mounted on the robot to evaluate the effect of the DoF of a joint on the curving motion, independent of stabilizing actuation. An overview of the MALO is presented in Fig. 1 (b). MALO has hip, knee, and ankle joints, and all joints can rotate in the sagittal plane, which is generally called flexion/extension. Moreover, the hip joint has an additional sliding mechanism to allow rotation in the horizontal plane by providing an additional DoF, as shown in Fig. 1 (c). This sliding mechanism could be fixed to restrict the hip rotation. The range of motion of the hip rotation was set to 30°, in accordance with previous work [12].

B. PROTOCOL

For the purpose to record the natural curving gait, eleven healthy adult male subjects participated in this study. The average and standard deviation of the age, height, and weight of participants are 22.4±2.4 years old, 171.0±5.1 cm, and 64.5±7.4 kg. The exclusion criteria were gait disorder or lower limb pain, but no participant had these. The participants were fitted to the experimental devices and MALO. Subsequently, the participants walked continuously along the path shown in Fig. 1 (a). The starting position was adjusted such that the curving motion started from the

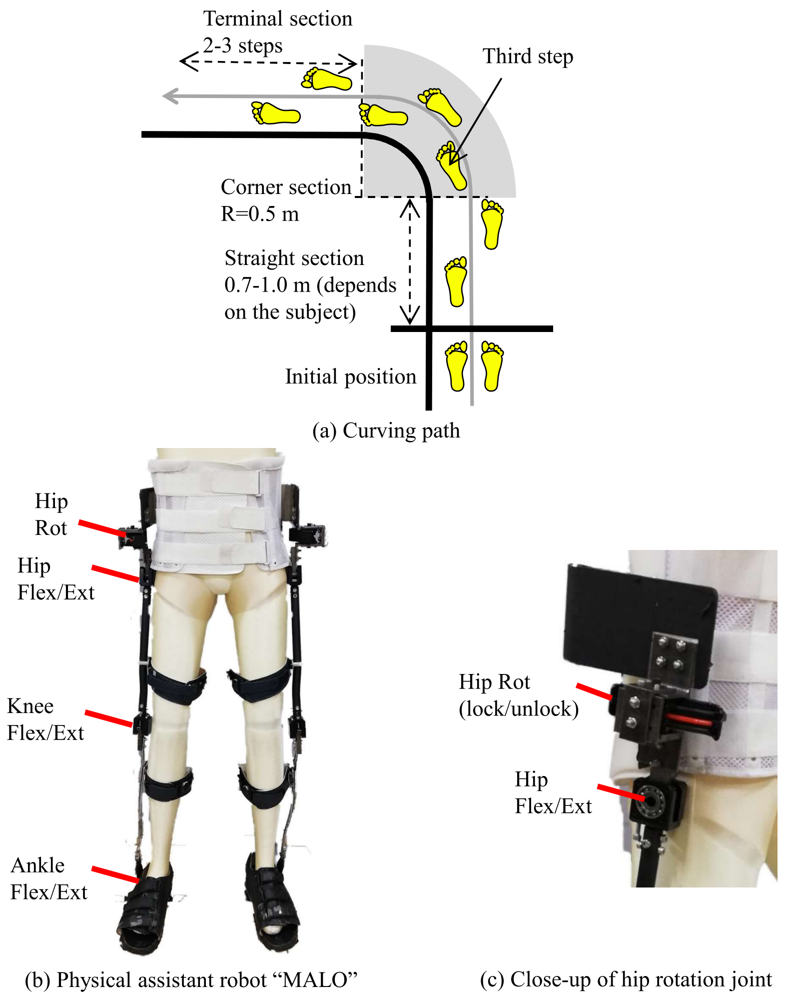


FIGURE 1. **Experimental setups.**

participant's third step. The participants were instructed to follow the path without stepping inside the curve.

The hip rotation was sequentially set as free and fixed (rot-free and rot-restriction) in each trial to observe the influence of joint restriction on curving motion. Furthermore, the leg used for the first step (left/right) was alternated between trials for each hip rotation condition. Thus, each participant was tested under four conditions. Ten trials were recorded per condition for each participant in a random order.

III. DATA PROCESSING

A. PARAMETER DEFINITION AND CALCULATION

To evaluate the curving motion, the gait parameters that represent the posture and balance in the diagonal direction were determined, as shown in Table 1. In addition to our previous study [14], several parameters were newly determined to evaluate the kinematic balance in the all-round directions of the curving step.

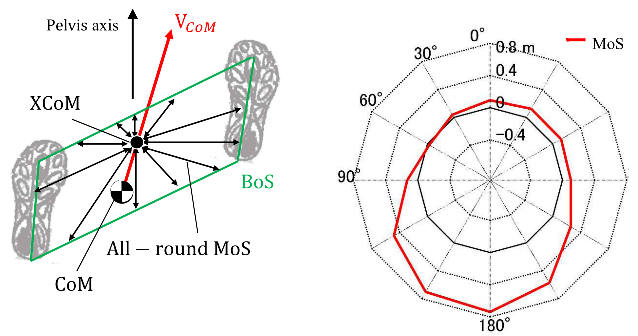
The timing of heel contact (HC) was determined by detecting the bottom height of the heel marker in a time series. Direction perpendicular to line consisting of the anterior superior iliac spine (ASIS) markers was determined as the direction of the sagittal plane, whereas the direction of the frontal plane was that of the line comprising the ASIS markers. The direction of the sagittal plane was defined as 0°, and the inner direction of the corner was set as the positive direction for CoMV-dir and Foot-dir in the horizontal plane.

The positive direction of HipAng was toward the outside of the body. The direction of the thigh was determined from the line of markers attached to the front and rear of the thigh. The angle offset was adjusted using the its value recorded in the upright posture.

Furthermore, the MoS, which is the index of kinematic margin from fall, was determined in all-round directions in this study. Originally, the MoS was calculated as the distance between the expanded CoM (XCoM), which consists of the position and velocity of the CoM to account for dynamic balance and the base of support (BoS) [19], [20], [21]. A larger MoS indicates greater stability. Although the MoS is capable of evaluating the balance of

TABLE 1. Curving parameters.

Parameter name	Definition
StLeng	The step length is the distance between the heel markers of both feet at the time of heel contact (HC) in the sagittal plane.
PelAng	The pelvis yaw angle is the change in the frontal direction of pelvis in the horizontal plane of the global coordinate system between the HCs.
HipAngFront HipAngBack	The hip rotation angle of front and rear leg is defined as the rotation of the thigh with respect to the pelvis in the horizontal plane at HC.
StWid	The step width is the distance between the heel markers of both feet at the time of HC in the frontal plane.
CoMV-norm CoMV-dir	The center of mass (CoM) velocity is the velocity of the CoM at HC timing. The direction of CoM motion is the CoM velocity direction.
Foot-dist Foot-dir	The foot distance is the distance between heel marker of stepping foot and CoM at the HC timing. The foot direction is the direction of stepping foot from the CoM
BoS-area	The BoS area is determined as the area of support polygon consists of heel and toe markers of both feet at the timing of toe contact.



(a) Geometry of all-round MoS (b) Graph of all-round MoS

FIGURE 2. Definition of the all-round MoS.

any direction in horizontal plane, it was used only for the anteroposterior and mediolateral direction [14]. In this study, to evaluate the kinematic margin in diagonal directions, MoS was calculated every 30°. Therefore, we totally obtained value in 12 directions. A geometrical image of the all-round MoS is shown in Fig. 2. The direction in the sagittal plane is defined as 0°, and counterclockwise is defined as the positive direction.

B. STATISTICAL ANALYSIS

The all-round MoS of the trials was classified using a cluster analysis. In parallel, a factor analysis was conducted for the set of gait parameters shown in Table 1 to extract the characteristics of the curving gait. By comparing factor scores across cluster groups, the relationship between the all-round MoS and the features of the stepping motion were discussed.

Both the all-round MoS and gait parameters of each stepping foot (left and right steps) were analyzed separately. Then, the all-round MoS and factor scores with and without joint restraints were compared. Multivariate analysis of variance (MANOVA) and the Tukey-Kramer method were used for comparison.

TABLE 2. Number of samples in each cluster of inner (left) step.

	1st cluster	2nd cluster	3rd cluster	Total
Rot-free	37	141	26	204
Rot-restriction	19	21	169	209
Total	56	162	195	413

TABLE 3. Number of samples in each cluster of outer (right) step.

	1st cluster	2nd cluster	3rd cluster	4th cluster	Total
Rot-free	20	69	73	42	204
Rot-restriction	19	32	73	85	209
Total	39	101	146	127	413

IV. RESULTS

The single inner (left) step and single outer (right) steps were obtained from each trial. Trials in which the motion capture markers were entirely obstructed from the view were omitted. Thus, six to ten trials were analyzed based on the test conditions for each participant. In total, 204 and 209 trials were analyzed for rot-free and rot-restriction conditions, respectively.

A. CLUSTER ANALYSIS

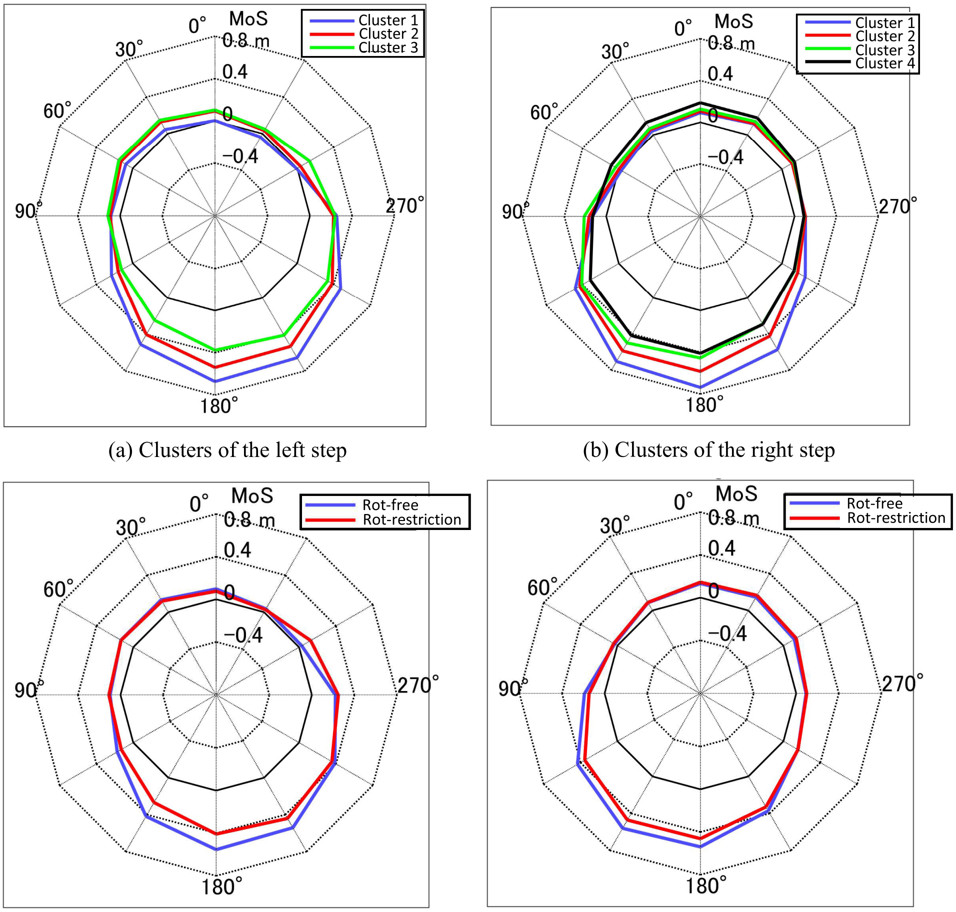
The all-round MoS, consisting of MoSs in twelve directions, at the time of HC was classified using cluster analysis. The inner and outer steps were analyzed separately.

The inner step cases were separated into three clusters, and the outer step cases were separated into four clusters considering the number of samples included in each cluster. The number of samples in each group is shown in Tables 2 and 3, respectively.

The average all-round MoS of each cluster is shown in Fig. 3 (a) and (b). In the left step, the MoS increased in the front-left direction, which is the direction of the footstep. Moreover, the MoS in the posterior right direction, which is the direction of the support limb, was also high. The differences among clusters appeared in the MoS of the posterior half. In the right step, as in the left step, MoS increased in the direction of the footstep and support limb. The differences among the clusters also appeared in the posterior half. Furthermore, in few trials, the MoS became negative in a specific direction (i.e., 60° on the right step). In addition, the all-round MoS is compared between the restriction conditions in Fig. 3 (c) and (d). In the rot-free condition, the MoS increased in the posterior half. Occasionally, it decreased in the anterior half. The result of MANOVA suggested that the all-round MoS of each cluster differed significantly. The *p*-values of each pairs of clusters are shown in Tables 4 and 5.

B. FACTOR ANALYSIS

As a result of factor analysis, three factors were extracted for each step. The factor loading vectors, weighted by the contribution rate, are shown in Fig. 4. The characteristics of clusters of all-round MoS are investigated using factor



(a) Clusters of the left step

(b) Clusters of the right step

(c) Restriction conditions of the left step

(d) Restriction conditions of the right step

FIGURE 3. All-round MoS of each step.

TABLE 4. Statistical comparison of all-round MoS of of inner (left) step.

	0 deg	30 deg	60 deg	90 deg	120 deg	150 deg	180 deg	210 deg	240 deg	270 deg	300 deg	330 deg
1-2 clusters	**	**	**	0.18	**	**	**	**	**	**	**	**
1-3 clusters	**	**	**	**	**	**	**	**	**	0.10	**	**
2-3 clusters	0.29	*	**	**	**	**	**	**	**	**	**	**
Rot-free/ Rot-Restriction	**	*	0.74	**	**	**	**	**	**	**	**	0.11

$*\leq 0.05$, $**\leq 0.01$

TABLE 5. Statistical comparison of all-round MoS of of outer (right) step.

	0 deg	30 deg	60 deg	90 deg	120 deg	150 deg	180 deg	210 deg	240 deg	270 deg	300 deg	330 deg
1-2 clusters	0.16	*	**	**	**	**	N/A	**	**	1.00	0.50	0.82
1-3 clusters	**	**	**	**	**	**	N/A	**	**	*	*	**
1-4 clusters	**	**	**	1.00	**	**	N/A	**	**	*	**	**
2-3 clusters	**	0.13	**	**	**	**	N/A	**	**	**	**	**
2-4 clusters	**	**	**	**	**	**	N/A	**	**	**	**	**
3-4 clusters	**	**	**	**	**	**	N/A	0.96	0.8	0.95	*	**
Rot-free/ Rot-Restriction	*	0.59	*	**	**	**	N/A	**	0.84	*	**	**

$*\leq 0.05$, $**\leq 0.01$

TABLE 6. Factor score of each cluster and condition of inner (left) step.

		1st factor	2nd factor	3rd factor
Rot-free	1st cluster	-0.26 (± 0.72)	1.65 (± 0.61)	-0.59 (± 0.90)
	2nd cluster	0.01 (± 1.18)	0.23 (± 0.53)	-0.67 (± 0.69)
	3rd cluster	-0.29 (± 0.67)	-0.55 (± 0.68)	-0.38 (± 0.78)
Rot-restriction	1st cluster	0.38 (± 0.61)	2.12 (± 0.35)	1.27 (± 0.67)
	2nd cluster	-0.29 (± 0.30)	0.48 (± 0.43)	-0.31 (± 0.32)
	3rd cluster	0.08 (± 1.04)	-0.76 (± 0.67)	0.64 (± 0.82)
All	1st cluster	-0.04 (± 0.74)	1.81 (± 0.58)	0.04 (± 1.21)
	2nd cluster	-0.03 (± 1.11)	0.26 (± 0.53)	-0.62 (± 0.67)
	3rd cluster	0.03 (± 1.00)	-0.74 (± 0.67)	0.50 (± 0.88)

TABLE 7. Factor score of each cluster and condition of outer (right) step.

		1st factor	2nd factor	3rd factor
Rot-free	1st cluster	-0.14 (± 0.66)	1.81 (± 0.46)	0.94 (± 0.71)
	2nd cluster	0.07 (± 1.37)	0.91 (± 0.75)	0.00 (± 0.73)
	3rd cluster	0.00 (± 0.83)	0.23 (± 0.62)	-0.98 (± 0.71)
	4th cluster	-0.61 (± 0.57)	0.18 (± 0.71)	0.61 (± 0.91)
Rot-restriction	1st cluster	0.58 (± 0.47)	0.96 (± 0.29)	1.86 (± 0.56)
	2nd cluster	-0.12 (± 0.74)	-0.16 (± 0.30)	0.60 (± 0.54)
	3rd cluster	0.46 (± 1.30)	-0.40 (± 0.66)	-0.59 (± 0.60)
	4th cluster	-0.20 (± 0.62)	-1.26 (± 0.54)	0.18 (± 0.85)
All	1st cluster	0.21 (± 0.68)	1.40 (± 0.57)	1.38 (± 0.79)
	2nd cluster	0.01 (± 1.21)	0.57 (± 0.81)	0.19 (± 0.73)
	3rd cluster	0.23 (± 1.11)	-0.09 (± 0.71)	-0.78 (± 0.68)
	4th cluster	-0.34 (± 0.63)	-0.79 (± 0.91)	0.32 (± 0.89)

scores associated with each cluster. The factor scores of each cluster are shown in Fig. 5 (a)(b). The comparison of factor scores with and without joint restraint conditions is shown in Tables 6 and 7, and Fig. 5 (c) and (d).

1) INNER STEP

According to the factor loading shown in Fig. 4, the first factor is strongly related to PelAng, CoMV-norm, and negative CoMV-dir. This factor contributes to rapid walking and alteration of body direction. Furthermore, the CoM did not move in the inner direction of the pelvis. The second factor consists of StWid, CoMV-norm, CoMV-dir, and Foot-dir. A larger second factor corresponds to the step towards the inner direction of the corner, implying that the body moves to the left side without altering the pelvis direction. The third factor was characterized by positive PelAng, Foot-dist, and negative StLeng. However, the magnitude of PelAng was less than that of the first factor.

2) OUTER STEP

Unlike the inner step, the first factor of the outer step is strongly related to the positive StLeng and related to the CoMV-norm. These parameters represent the strong forward step. Furthermore, a positive PelAng indicates body rotation towards the corner. The second factor is strongly related to the positive StWid as the inner step. However, the effect on CoMV-dir and Foot-dir is negative, implying that the body moves toward relatively outside of corner. The third factor is related to the PelAng, BoS-area, and negative HipAngBack. The positive PelAng suggests that this factor works similar to the first factor.

V. DISCUSSION

A. RELATIONSHIP BETWEEN ALL-ROUND MoS AND STEPPING MOTION

1) INNER STEP

According to Fig. 3 (a), the first cluster of the all-round MoS can be characterized by a short MoS in the forward direction. Especially in the front right direction, the MoS became negative, which sometimes occurred in the forward direction during gait [30]. Meanwhile, the factor score and factor loading of each factor shown in Figs 4 (a) and 5 (a) suggest that this cluster tends to perform large rotation with high speed according to the large positive first factor. The high speed can be directly related to the short MoS in the forward direction [31]. Furthermore, the negative CoMV-dir indicates the direction of CoMV towards relatively outside of the corner, which decreases the MoS in the front right direction.

The second cluster of the all-round MoS was placed between the first and third clusters, excluding the second factor. Although the CoMV tends to move to the front-right direction as the first cluster, the slower speed diminishes the effect of CoMV-dir.

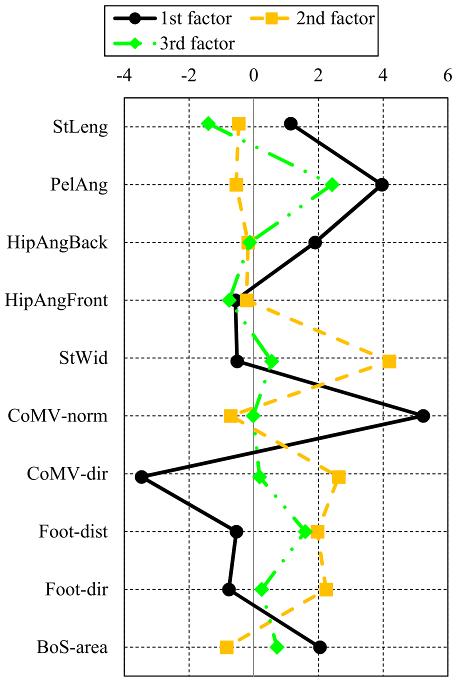
The characteristics of the third cluster of the all-round MoS are opposite to those of the first cluster. The slower speed, suggested by the negative first factor, corresponds to the larger MoS in the anterior half. Furthermore, the positive second factor indicates a large step width that results in a large MoS in the lateral direction.

2) OUTER STEP

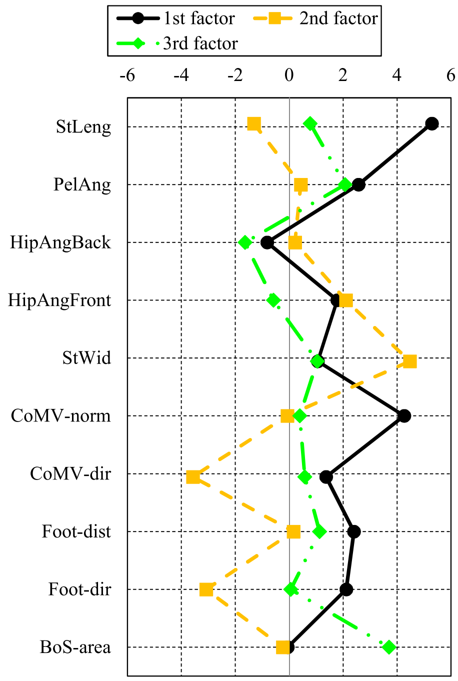
The first cluster of the all-round MoS is characterized by a short MoS in the front-left direction, as shown in Fig. 3 (b). The scores of the first and second factors shown in Figs. 4 (b) and 5 (b) suggest high speed, long step length, small step width, and CoMV toward the inner direction. As mentioned above, in the frontal direction, the fast speed decreases the MoS [31]. Furthermore, the long step length also decreases the MoS in the forward direction according to the gait experiment [31] whereas the short step width does not affect the MoS in the lateral direction [32]. In addition, pelvic rotation is also high according to the first factor. Therefore, the results of this cluster suggest that the rapid curving motion causes a decrease in MoS in the front-left direction. In contrast, the second cluster of the all-round MoS was placed in the middle of other clusters, and did not have notable characteristics.

The MoS of the third cluster was large on the left side. The large second factor suggests a large step width that increases the MoS in the lateral direction [31]. The weaker internal motion amplifies this tendency.

The MoS of the fourth cluster was large in the anterior half area. According to the factor score, a smaller speed and short step length increased the MoS [31]. This is the likely reason for the largest margin among all clusters.



(a) Factor loadings of the left step



(b) Factor loadings of the right step

FIGURE 4. **Factor loadings.**

B. EFFECT OF JOINT RESTRAINT

1) INNER STEP

Based on the distribution of samples for each condition in the clusters shown in Table 6, some clusters probably represent the characteristics of each of the restriction conditions. The second and third clusters mainly consist of strides with rot-free and rot-restriction conditions, respectively as shown in Table 2. Thus, the characteristics of these clusters represent one condition each. The factor scores of each condition shown in Fig. 5 (c) correspond to those of each cluster, as shown in Fig. 5 (a). According to Fig. 3 (a) and (c), the all-round MoS of the rot-restriction condition is large in the front-right direction, which corresponds to the third cluster. In contrast, it appears that the first cluster consists of a rapid curving motion, regardless of the restriction.

2) OUTER STEP

Unlike the inner step cases, none of the clusters reflected the characteristics of the restriction conditions because both rot-free and rot-restriction conditions were not prominent for all clusters of the outer step, as shown in Table 3. Furthermore, the difference in the shape of the all-round MoS in the anterior half between the conditions is slight, as shown in Fig. 3 (d).

However, Fig. 5 (d) suggests that the factor scores differ significantly between the two conditions. Compared to the rot-free condition, a smaller first factor and a larger second factor suggest a shorter step length and step width in the rot-restriction condition. Furthermore, the CoMV and pelvic rotation were small. These characteristics correspond to the result of direct comparison of gait parameters with and without restriction of hip rotation [14].

C. MEANING OF ALL-ROUND MoS

The all-round MoS is an idea that expanded the MoS to all the direction of horizontal plane. The all-round MoS of each direction consists of the distance between the edge of BoS and XCoM, respectively. According to this definition, the faster the component of gait speed, the smaller the MoS becomes. Furthermore, the MoS tends to become small towards the short axis direction of BoS. If the MoS becomes negative, an additional step is required to prevent fall.

We determined the all-round MoS to evaluate the kinematic margin of the curving gait. Because the walking direction gradually changes between the forward and lateral directions during curving, the definition of the margin in diagonal direction becomes an advantage in this method to analyze the imbalance of curving steps. As a general trend, the shape of the all-round MoS was small on the opposite side of the stepping foot of the anterior half. This trend matches the fall in the lateral direction, reported as actual falls [7]. Because the direction of fall affects the severity of fall injuries, it is important to estimate the fall direction of a specific gait motion. Furthermore, the results suggested that the all-round MoS reflected the difference in gait motion caused by gait variability and restriction conditions, as shown in Figs. 3 and 5. This result encouraged us to develop an index to estimate not only the risk of falls, but also the severity of fall injury during the curving gait.

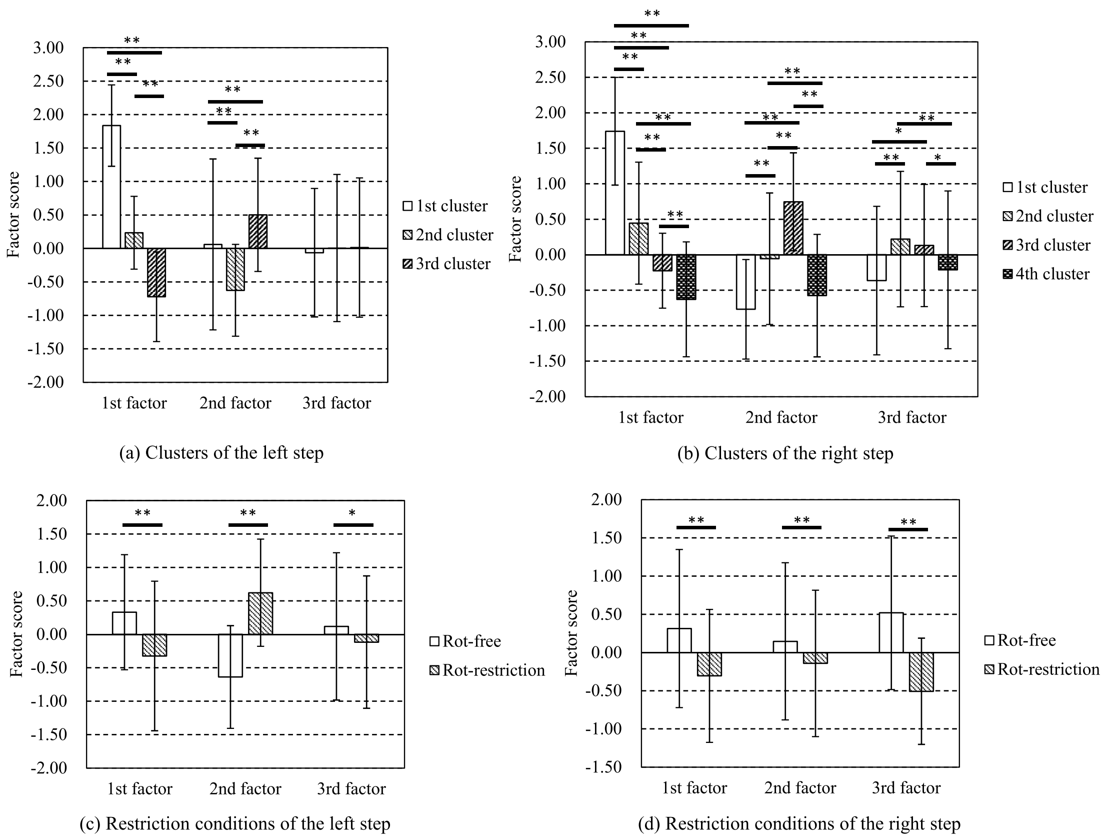


FIGURE 5. **Factor scores.**

However, when calculating the all-round MoS, the direction of the CoM velocity vector and the direction of the MoS were mismatched in the backward direction. The all-round MoS was simply determined as the distance between the XCoM and BoS in each direction. However, the posterior half of the all-round MoS may not have reflected the kinematic margin against backward fall because the subject could move the CoM forward by decreasing the ground reaction force, which decelerates the CoM motion. However, the margin for the backward fall could be evaluated using MoS. Yang et al. used the rear edge of the supporting leg as the BoS to evaluate the backward margin of the swing phase [33]. Furthermore, Sivakumaran et al. evaluated the kinematic margin in the anteroposterior and mediolateral directions during the swing phase as well as during the double stance phase [34]. Furthermore, the expansion of the MoS to evaluate the kinematic margin in the backward direction is another challenge to estimate the risk of backward fall.

D. LIMITATIONS

In this study, the BoS was determined as a quadrangle that connected the position of the toe and heel markers of both feet. Although the results of our analysis were consistent with the characteristics of gait parameters, the simplification of the BoS shape made the area of the BoS narrower than the actual support polygon. For the actual usage of all-round MoS such as diagnosis of gait balance, an elaborate model of support polygon consists of feet may be required. Thus, the BoS should be expanded considering the shape of the foot, especially in the lateral direction of the foot.

In this study, the variance of gait motion used was limited compared to that of general population because the gait motion of only healthy young men was observed. Thus, the development of the general classification model of the all-round MoS is another work for future. In the current analysis, the trials of each subject tended to belong to several clusters together. It can be considered that the characteristics of the gait of individuals was reflected to the classification. For the analysis of all-round MoS in the general population, the affiliation of subjects should be considered for the classification, whereas we focused on the correspondence between clusters of all-round MoS and gait characteristics.

VI. CONCLUSION

It is difficult to evaluate the risk of fall of the motion that changes the walking direction because the current stability measures can evaluate the kinematic stability in the anteroposterior or mediolateral direction independently. In this study, the novel all-round MoS is developed and introduced to quantify the kinematic margins in all directions and analyze the kinematic instability in the diagonal direction of the body during curving gait.

By expanding the concept of the margin of stability, we determined the all-round MoS as a measure of the kinematic margin in the diagonal direction in addition to the forward and lateral directions. Curving gait was observed with and without the restriction of hip rotation. Furthermore, the gait parameters were calculated and analyzed using factor analysis. By comparing the all-round MoS and gait parameters, the characteristics of the all-round MoS were discussed.

In this study, the effects of the range of motion of hip rotation on curving gait were analyzed using the all-round MoS. The results confirmed that the characteristics of groups classified according to the all-round MoS could be described by their stepping motions involved in the factor scores. The investigation of change of the all-round MoS caused by the exoskeleton enables evaluation and improvement of its performance.

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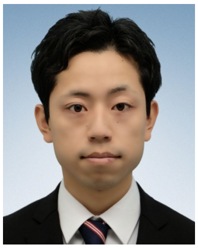

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