The Change of Gait Motion When Curving a Corner Owing to the Motion Restriction Caused by a Wearable Device

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***Abstract*—Many wearable robots are not fully capable of fitting the motion of the wearer, owing to their limited degrees-of-freedom (DOF). This limitation disturbs motions such as corner curving, which are required in daily life. In this study, the effect of the DOF restriction on the corner curving motion was observed and analyzed. The gait motions, when curving a round corner with and without the restriction of out-of-sagittal plane motion, were compared using a wearable device which could restrict hip adduction/abduction and rotation. The result suggested that the restriction not only decreased the range of motion of hip adduction/abduction and rotation, but also changed the center of mass (COM) trajectory. Owing to the disturbance applied during the stepping motion of the outer leg, the COM trajectory moved further from the corner in the trials with restriction. Thus, the distance between COM and the base of support of the inner foot became larger during the swing phase of the outer leg, which possibly increased the risk of loss of balance. Furthermore, it was also suggested that an assistive torque, which does not consider curving motion, possibly increases such risk.**

I. Introduction

Quality of life for the elderly is an issue being addressed by many countries. It is expected that a wearable robot could improve the quality of life and daily living activities of the elderly. Recently, various types of physical assistant robots (PARs) have been developed and their popularity is increasing. The PARs for gait rehabilitation in hospitals have been developed [1], [2]. Other PARs have been developed aiming for the usage in daily life [3], [4]. There are some studies that focused on abilities for the PARs application [5], [6]. Effects of gait training with PARs have also been studied [7], [8]. Now, because many of these PARs are used for gait rehabilitation in hospitals, the motion which changes walking directions is not considered.

However, the usage of the PAR is gradually expanding to the daily living environment, where curving motions are frequently required. Nonetheless, the PAR that restricts the out-of-sagittal plane motion of the wearer at the lower limb joints, (especially adduction/abduction and rotation of the hip joint) to efficiently apply assist torque and create the mechanism of DOF, is simply not suitable for such an environment. This incompatibility will likely prevent the widespread usage of the PAR as the limitation in curving motions not only decreases the flexibility of daily living activities but also exposes the wearer to the risk of collision, falls, and other accidents. Therefore, for further expanding the adoption of the PAR, it is important to develop a mechanism that enables the wearer to curve easily, even when wearing the PAR.

Although its complexity, some studies focused on the measurement and analysis of curving motion. Hicheur et al. [9] reported that the head adjusted its orientation to the curving direction before the walking direction started changing. They concluded that head movement was part of the mechanism responsible for walking toward the desired direction and also part of the stabilization strategy. Imai et al. [10] also studied the interaction of the body, head, and eyes during turning a 0.5 m radius and 2.0 m radius corner. Courtine and Schieppati [11] studied the curving motion when curving a corner, whose radius was 1.2 m. They compared the gait motion when curving with eyes opened to when curving blindly. Courtine and Schieppati [12] focused on the pitch and roll motion of the lower limb when the curved corner's radius was also 1.2 m. Yamaguchi et al. [13] researched the effect of the turning angle on falling. They induced slipping when the walking direction changed and concluded that the steepness of the turning motion increased the risk of falling. It was because the distance and relative velocity between the center of mass (COM) of the whole body and the COM of the sliding foot increased, which meant that the falling moment subsequently increased. Rogers and Mille [14] investigated lateral falls of the elderly. They suggested that neuromusculoskeletal impairment of disrupted the fall arrest strategy related to lateral stability. Thus, despite some studies analyzed curving motion, the risk of fall during curving motion, which potentially resulted in the lateral fall, was not studied sufficiently.

On the other hand, the study which considered the effect of the motion restriction on curving motion is also insufficient. Some studies focused on the motion restriction of the knee joint. Temel et al. [15] studied the response of the subject when the knee motion was perturbed. However, although the motion restriction of the hip applied by the PAR probably become important for curving, the effect of such restriction on curving motion have rarely been studied. In addition, developing a PAR, which is fully capable of fitting the degree-of-freedom (DOF) of human joints, is not easy from the viewpoint of cost, size, and mass, which also affects the motion stability ([16], [17]). Thus, it is inevitable to tolerate the restriction of DOF

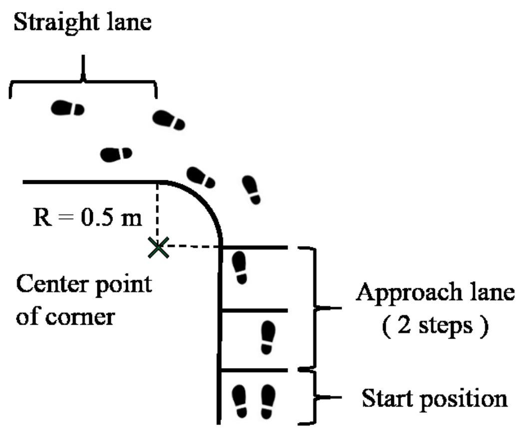

Fig. 1. The straight and curving path and the ideal foot steps

in some degree when using PARs.

Thus, we focused on the effect of restriction of out-of-sagittal plane motion during the curving motion to identify how motion strategy and risk of fall changed. The analysis of the mechanism which changed the curving motion could suggest the priority to add the DOF of adduction/abduction direction for natural curving motion. Furthermore, the observation of the change of COM trajectory helps to improve the safety of PARs by suggesting the necessity of the assist algorithm which reflects the compensation motion against motion restriction.

II. METHODS

An experiment was carried out to analyze the effect on corner curving motion caused by the restriction of out-of-sagittal plane motion, applied by a wearable device. Generally, gait assist robots consist of the pelvis, thigh, and lower thigh links. Although the rotational joint usually connects these links, the DOF of these joints is limited in the sagittal plane, in most cases; therefore, the out-of-sagittal-plane motion was restricted. Because many characteristics of the PAR, such as weight, size, and assist torque, affect the motion of the wearer, in addition to the restriction of the DOF of joints, the effect of these factors should be carefully analyzed. Jan F. Veneman et al. [18] conducted experiments with a method that they limited DOF of hip joint and knee joint rigidly on the sagittal plane. In this study, the focus was on the DOF effect because the effect of that restriction was probably amplified during the curving motion, wherein the risk of falling became higher than that when walking straight. To identify the effect of joint restriction, the results of the two experiments were compared.

A. Apparatus

The experiment was performed with the permission of the institutional review board of the Nagoya University. In this study, the motion when curving a small radius corner was focused on because the effect of restriction probably became larger in steep corner, which was more suitable to the analyze the risk of fall. In addition, such curving motion with small radius is frequently required in the daily living environment (i.e. turning corridor). Therefore, a curved path with a radius of 0.5 m was used. As mentioned above, other studies [9]–[12] adopted larger radii than 0.5 m. Fig. 1 shows the curving path with the position of designed footsteps. The walking lane, which was marked on the floor using tape, consisted of a straight approach line, a quarter of a circle with 0.5 m radius, and a straight line.

The motion of the subject was recorded at 100Hz using a three-dimensional motion capture system (MAC 3D system, Motion Analysis Corporation, U.S.). A set of critical markers of the SIMM Motion Module (SIMM, Mulsculographics Inc., U.S.) and additional markers (sternum, PSIS, shank) were attached to increase the accuracy of human model fitting. The ground reaction force was recorded to detect the timing of gait events, such as heel contact (HC) and toe off (TO), at 100 Hz, using mobile six axis force plates (M3D, Tech Gihan Co., Ltd., Japan); the force plates were fixed under a sole.

Fig. 2 shows the wearable device used in this study. Although this device was originally designed as the PAR, actuators were removed in order to evaluate the DOF restriction effect independently. Because the torso link can be fixed to the wearer tightly, using a belt, the motion of the hip joint in the out-of-sagittal plane could be restricted. However, this restriction could be removed by detaching the connection between torso and hip joint. The subject wore the wearable device, whose abduction/adduction and rotation of the hip joint were restricted under one condition. Under another condition, although the same device was worn, the hip joint of that device was not connected, which meant that the wearer could move their hip joint freely.

The stiffness of the hip joint in the direction of abduction was measured preliminarily. Fig. 3 shows the data of torque and abduction angle. Because the maximum abduction or adduction angles of the hip are approximately $\pm$ 5 degrees during straight walking [19], the restriction was considered enough to restrict joint motion strongly even when the wearer walked straight.

B. Protocol

In total, three healthy young adult males, who were not authors and did not know the intention of the experiment, participated in our experiment. First, the subject wore well-fitted sportswear and the wearable device with reflective markers for recognition by the motion capture system. Then, the subject had walked with the robot until he came to be able to walk naturally. Following adaptation trials, the motion of the subject was recorded when walking along a curved path, with or without the restriction. At the beginning of the trial, the subject stood at a start position. In order to record the step, which was most affected by curving, the side of the leg which started walking was randomly ordered in order to observe the curving motion using a different leg. The subject was instructed to start curving a corner at the third step. The line of approach was adjusted to the subjects' step length and they were also asked to walk as naturally as possible and at their

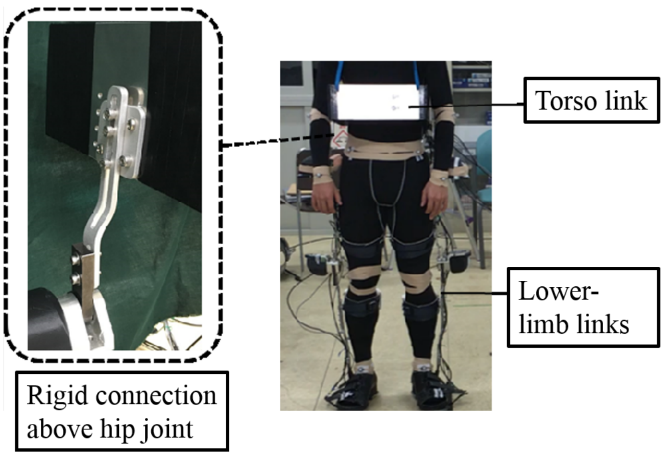

Fig. 2. The exoskeleton and its fixation part which restricts out-of-sagittal-plane motion

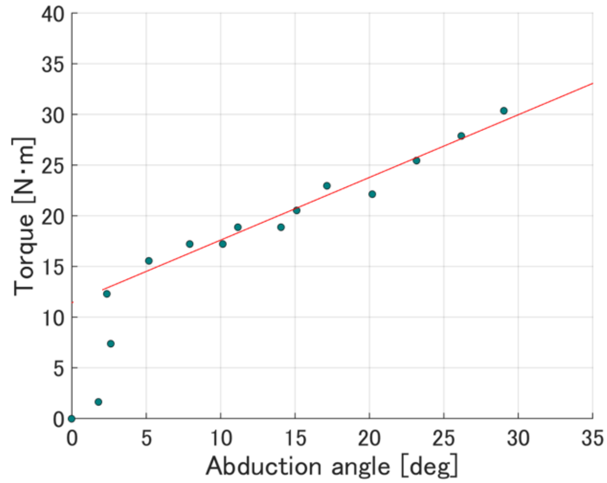

Fig. 3. The resistance torque of the exoskeleton against abduction angle

preferred pace. After all the trials under a restricted or non-restricted condition were recorded, the torso link connection of the robot was attached or detached in order to change the restriction condition. Then, the motion of the subject, who walked under a different restriction condition, was recorded following additional adaptation trials.

The trials were restricted to two DOF conditions (both with and without abduction/adduction and rotation restriction) and two stepping conditions (start with left or right leg). The same restriction condition was used in the first twenty trials. The stepping conditions were alternated. Then, another twenty trials were conducted under another restriction condition, in a similar manner. The order of restricted and non-restricted conditions was randomized for each subject. A total of forty trials, which could be separated to four combinations of different conditions, were carried out for each subject.

C. Data processing

As our study focused on the curving motion, analysis was mainly carried out for the step motion at a corner section. The motion data were smoothed using a 6 Hz Butterworth filter. The timing of HCs and TOs were detected by ground reaction forces with a threshold of 10 N. The angles of each joint and the position of the COM were calculated with SIMM, based on marker positions. *The speed of the center pelvis*, which was the mean velocity of the center position between the left and right anterior inferior iliac spine (ASIS) in a stride at the corner section, indicated the velocity of the curving motion and was used to validate the restriction.

III. Result

The speed of the center pelvis of subject A, in non-restricted trials was 0.79±0.03 m/s and decreased to 0.55±0.02 m/s when the restriction was applied. The restriction also decreased the speed of subject B from 0.93±0.04 m/s to 0.75±0.02 m/s. However, *the speed of the center pelvis* of the other subject did not differ between different restriction conditions. As it seemed that the restriction affected the successive non-restricted condition, the data of the subject, for which the trial started from the restricted condition, were omitted.

Figs. 4 and 5 show the trajectory of a representative curving motion, under restricted and non-restricted conditions, respectively for Subject A. The red points in the figures represent COM positions at HC; the discontinuous red line represents the COM trajectory. The first footprint was one step before curving started. Then, the second to fourth footprints comprised the curving motion. The motion between the second and third footprints was included in the corner section. This motion corresponded to the inner swing approximately.

Further, Figs. 6 and 7 show the curving motion trajectory, from which the outer swing was extracted. According to Figs. 4 through 7, the COM trajectory in restricted cases usually passed between the footprints of both legs; in non-restricted cases, however, it got closer to the inner foot.

Then, the peak adduction/abduction angle was extracted from both inner and outer swings to identify the effect of the restriction on the range of motion.

Tables I and II give the peak adduction/abduction angles during inner and outer swings. The peak angle of one side direction (adduction or abduction), whose peak angle increased, was selected from each leg. In all cases, the peak joint angle decreased under the restricted condition. In most cases, this

TABLE I
MAXIMUM ADDUCTION/ABDUCTION ANGLE OF HIP JOINT OF INNER FOOT STEPS

Subject	direction	side	restricted	non-restricted
A	Abduction	Left	4.9± 1.4	7.2± 1.9
	Adduction	Right	1.2± 1.0	3.2± 1.9
B	Abduction	Left	2.5± 0.7	3.8± 1.0
	Adduction	Right	-2.9± 0.7	-0.6± 1.5

note : Value is mean ± SD.

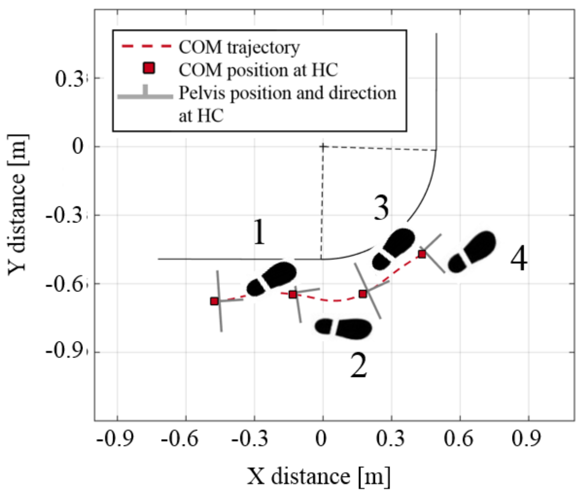

Fig. 4. The motion trajectory of an inner swing trial in the restricted condition

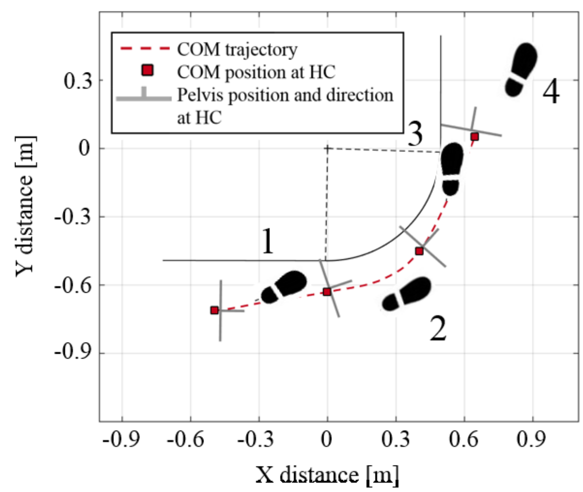

Fig. 5. The motion trajectory of an inner swing trial in the non-restricted condition

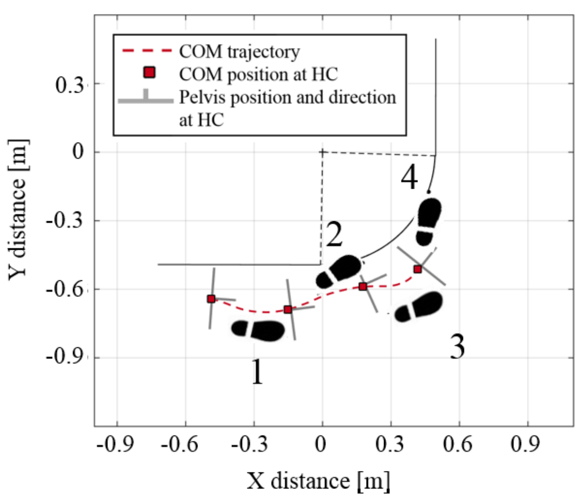

Fig. 6. The motion trajectory of an outer swing trial in the restricted condition

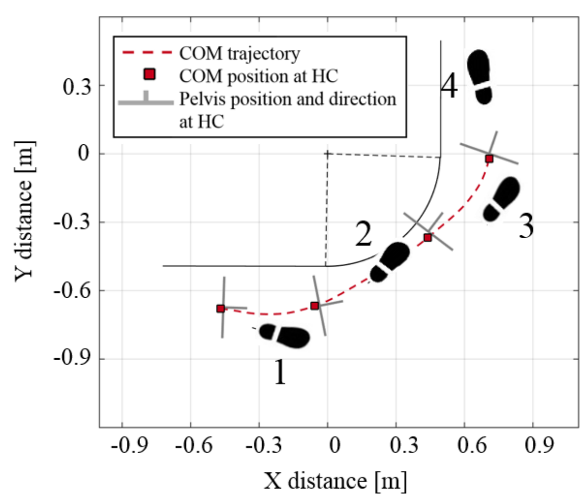

Fig. 7. The motion trajectory of an outer swing trial in the non-restricted condition

TABLE II
MAXIMUM ADDUCTION/ABDUCTION ANGLE OF HIP JOINT OF OUTER FOOT STEPS

Subject	direction	side	restricted	non-restricted
A	Adduction	Left	0.0± 0.6	5.9± 1.2
	Abduction	Right	1.4± 1.3	7.9± 1.3
B	Adduction	Left	3.3± 1.0	4.0± 0.9
	Abduction	Right	2.4± 1.5	4.5± 1.6

note : Value is mean ± SD.

meant that the range of motion decreased.

Fig. 8 shows the rotation angle of the hip joint of Subject A, in non-restricted and restricted cases, including the inner swing. The horizontal axis represents the gait cycle, which corresponded to the range between the second and fourth steps shown in Figs. 4 and 5, respectively. The vertical axis represents the joint angle. The red line represents the mean and SD of the rotation angle of the hip, while the blue line represents the mean and SD of the rotation angle of the left hip. The continuous line represents the non-restricted condition and the discontinuous line represents the restricted cases. The motion between 10% to 50% in Fig. 8 corresponds to the inner swing. The rotation angle of the peak values for the left and right hip were located at approximately 60%, as shown in Fig. 8. The restricted value was lower than the non-restricted value, which was possibly due to the effect of restriction.

On the other hand, Fig. 9 shows the rotation angle during the gait cycle, which corresponded to the range between the second and fourth step, as shown in Figs. 6 and 7. The motion between 10% and 50% corresponds to the outer swing. The peak values for the rotational angle of the left and right hip, in the restricted cases, were also lower than those in the non-

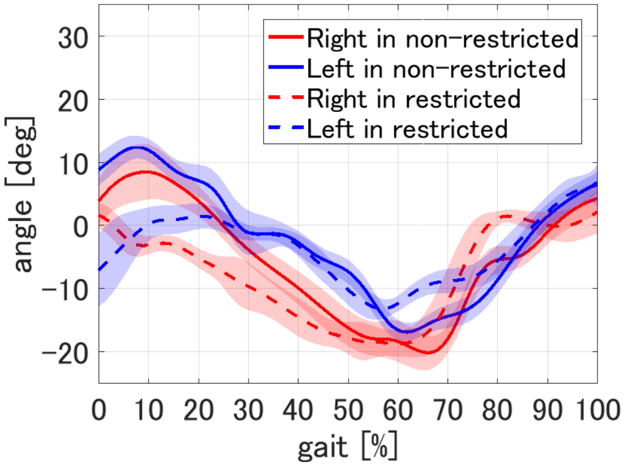

Fig. 8. Hip rotation angle in non-restricted and restricted cases including inner swing

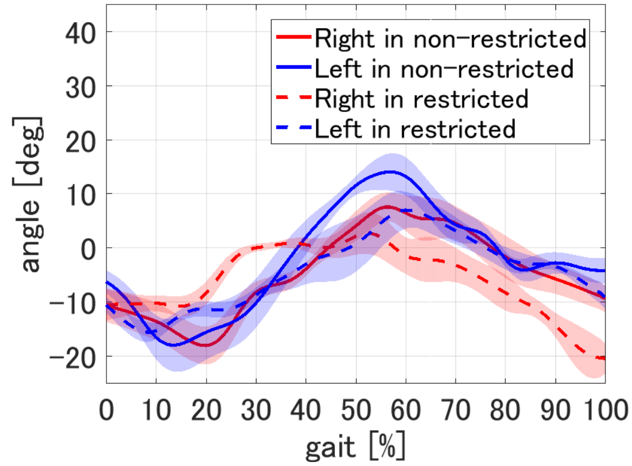

Fig. 9. Hip rotation angle in non-restricted and restricted cases including outer swing

restricted cases.

IV. Discussion

Winter and Eng [20] analyzed the inner torque of hip abduction during straight walking. They found that the hip abduction torque was generated to control the upper body motion in the direction of the lateral side. However, the hip adduction torque became almost zero during walking. In our experiment, the wearer had to exert torque to adduct/abduct the hip joint, owing to the restriction, as shown in Fig. 3. Thus, the range of adduction/abduction angle decreased as shown in Tables I and II. In addition, change of COM trajectory, step length were observed as shown in Figs. 4 through 7. Furthermore, Figs. 8 and 9 suggested the decrease of hip rotation. It seemed that they were not only related to the restriction but also related each other. Further experiment with increased numbers of subjects will discover their walking habit more clearly.

Among these changes caused by the restriction, the COM trajectory was focused on in this study because it probably stood for the risk of fall caused by the restriction. In the case of straight walking, the COM moved close to the support leg during the swing phase [21]. However, the COM did not move close to the stance leg (Second footprint) during the inner swing under both restricted and non-restricted conditions when curving as shown in Figs. 4 and 5. On the other hand, the COM moved close to the stance leg and sometimes exceeded it under the non-restricted condition during the outer step as shown in Fig. 7. Although moving COM closer to the corner is effective to curve the corner, it did not happen under the restricted case.

Owing to the restriction, it seemed that the subjects could not move their COM close enough toward the medial direction of the body. Although the subjects were required to adduct their inner hip to control the COM position, the adduction angle of the left hip, which was restricted by the device, decreased as shown in Table II.

From the viewpoint of safety, disturbance applied during gait increases the risk of fall. Akiyama at el. [22] analyzed a recovery motion when an assist torque was abnormally applied with a physical assistant robot. They found that subjects changed the gait in response to abnormality when they walked straight. Yamaguchi et al. [13] found that fall caused by induced slips during turning probably resulted in the harmful event. In our experiment, the motion restriction changed the COM trajectory because of the compensation motion for the restriction torque. However, especially when the assist torque, which moved the swing leg farther, was applied during the outer step, the assist torque probably interfered with the short outside step, which intended to compensate for the restriction. Such mismatch occurs when the assist robot expected a normal gait motion despite the wearer intended to curve. When the COM position separated from the base of the support substantially, the fall moment increased and the risk of fall increased as well, owing to recovery failure. Thus, it may not be appropriate to work for stepping higher during corner curving.

V. Conclusion

In this study, the effect of the out-of-sagittal plane motion restriction at the hip joint was observed. This restriction, which simulated the restriction of a physical assistant robot, was applied during curving corner, which was the motion frequently required in the daily living environment. In addition to the decrease of the adduction/abduction and rotation of the hip joint, the change of the COM trajectories, which was the compensation motion for the restriction, was observed. In particular, unlike non-restricted condition, the COM did not move close to the support leg nor exceeded it under restricted conditions during the outer swing. This meant that the COM trajectory moved outside of the corner owing to the restriction.

By considering the decrease in the peak adduction/abduction angle during step motion, it was inferred that the restriction of inner leg adduction disturbed the control of the COM position during the outer swing. From the viewpoint of safety, although the restriction did not cause fall by itself, the restriction probably resulted in fall when the compensation motion observed in this study was disturbed. Unfortunately, the assist torque, which was applied by the wearable robot, potentially becomes such interference when the robot expected normal gait motion. Thus, in particular, the assist should be designed not to disturb the stepping motion of outside leg when curving corner.

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