Classification and analysis of the natural corner curving motion of humans based on gait motion

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Abstract

The curving motion of the human body is more complex than gait motion for straight walking. In particular, when human can freely curve corners, the gait motion varies among and even within individuals. However, is it not possible to classify natural curving motion using a statistical method? This study investigates the natural curving motion, encompassing various walking paths selected by subjects, as opposed to previous studies that focused on specific stepping strategies or curving motion under precisely controlled conditions. As a result, the natural curving motions are statistically classified into five distinct groups based on certain motion indices. Each group represents a curving strategy and is mainly characterized by the inner inclination of the pelvis, outer rotation of hip joints at the time of heel contact of the inner leg, and inner and/or outer rotation of hip joints at the time of heel contact of the outer leg. Such strategies are speculated as typical motions within the large variation in natural curving motion. Another finding is that, unlike the joint pattern of lower limb joints in the sagittal plane, hip rotation and the abduction/adduction angle drastically change when curving. In particular, the large inner rotation and abduction angles of the hip joint of both legs, which reached approximately 30° and 10°, respectively, become important when considering the curving gait of a physical

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assistant robot. Our analysis and findings help specify the joint motion required for physical assistant robots.

Keywords: Corner turn, Gait motion, Cluster analysis

1. Introduction

Physical assistant robots have recently attracted considerable attention. In addition to being utilized in hospitals, they are also used to aid humans, who do not have serious disorders but are aged or frail, in performing various daily activities [1, 2]. A physical assistant robot for daily use is sometimes required to be capable of assisting humans in performing various kinds of movements, which are not required for rehabilitation purposes [3, 4]. Turning a corner is one such motion [5], wherein the gait pattern differs from a straight gait.

While the motion of a straight gait mainly occurs in the sagittal plane [6], three-dimensional joint motion, which includes hip rotation, hip abduction/adduction, and body inclination, becomes important for performing a curving motion. However, certain robots do not have sufficient degree of freedom or range of motion (ROM) of the joints [7], which suggests that such robots possibly increase the risk of falling [8, 9]. Furthermore, while several robots allow the human to move along an out-of-sagittal plane [10, 11], they do not intentionally assist in curve motion.

Such curving motion has formed the focus of several studies. Previously, the change of heading direction during curving was the major focus [12, 13, 14, 15]. Xu reported a backward leaning of the subject's body before curving [16], while Orendurff measured the inside shift of the center of mass (CoM) during curving around a circle [17]. Stepping strategies when turning a square corner have also been analyzed, where classified corner turns were studied from the perspective of the stepping position, direction, and the side of the leg [18, 19, 20]. In addition, it should be noted that many of these studies commonly reported that the gait speed decreased when turning. However, these studies did not cover curving motion under natural conditions, wherein the start-from and end-to straight gait and the curving trajectory could be freely selected by the subject, because these studies only focused on a specific phase of motion or the shape of the curve. Nevertheless, there is a question as to whether the curving strategies used for natural curving motion are the same as those observed in these particular conditions.

Further inspection of the gait motion during natural curving motion will help physical assistant robots to assist humans during natural curving motion. In this study, we identified and analyzed several curving strategies and their features by recording gait motion such as joint and body angles, walking path, and ground reaction force (GRF) as a basic research to understand the natural curving motion of humans.

2. Method

Our experiments were performed with the permission of the institutional review board of the Nagoya University.

Apparatus. Experimental trials were conducted as part of a series of gait measurement experiments. A straight path and a round corner were utilized for observing the natural curving motions. The round corner was marked on the floor by means of a tape, and the path consisted of a straight line and quarter circle with radii of 0.5 m (small) and 1.0 m (large). The positions of the ground markers and the typical walking paths are shown in Fig. 1. A 1-m radius is common for a round corner [17, 21], and a smaller radius is utilized to evaluate the effect of curving radii [22].

The gait motion was recorded at 120 Hz by a three-dimensional motion capture system (MAC 3D system, Motion Analysis Corporation, U.S.). A total of 22 markers, which consisted of a set of critical markers of the SIMM Motion Module (SIMM, MusculoGraphics, Inc., U.S.) [23], were attached. The GRF was recorded with mobile six-axis force plates (M3D, Tec Gihan Co., Ltd., Japan) affixed under the sole. Four force plates were separately attached at the toe and heel of each foot.

Subject. Twelve healthy male subjects participated in the study. The average age was 21.2 years, and the standard deviation (SD) was 1.7. Their mean height and weight were 172.4 ± 3.6 cm and 61.3 ± 6.9 kg, respectively. The body mass index of the subjects ranged between 17.5 and 24.5.

Protocol. The subjects wore well-fitting sportswear with reflective markers. Then, each participant walked along the straight line, around the corner, and other walking lanes in a randomized order at a self-selected speed.

Each subject repeated the walk along the straight-line direction a total of 10 times. Each subject was instructed to cross a line from a standstill position. Subsequently, the subject walked straight to the target, which was placed at the end of the walking lane.

Turning a corner involved walking along two circles of different radii. To observe the various curving motions, the leg used to start the walk was switched during the trials because the timing when changing the walking direction was affected by the stepping timing [24]. We conducted and recorded a total of 40 trials, which consisted of four different condition combinations (two radii $\times$ two starting legs). The order of the trials was also randomized. During the trials, the subjects were instructed to turn the corner freely, but not to step inside the corner made by the tape marked on the floor.

Data Processing. The walking path and stepping positions varied widely among subjects and trials because the subjects could freely select them. Thus, only the motion in the corner section, which consisted of a quarter-circular area, was extracted from the corner trial and used for cluster analysis. The typical walking paths of the natural curving trial are shown in Fig. 1. Although the curving area did not include all of the curving motion, it covered the sharpest part of the curving path, which probably represents the gait pattern of natural curving motion.

The data from the motion capture system were smoothed with the use of a 6-Hz Butterworth filter. The timing of the heel contacts (HC) and toe offs (TO) were determined based on the GRF with a threshold of 10 N.

The cadence was calculated as the inverse of the time difference between successive HCs. The double support ratio was calculated as the ratio of the time when both legs are in the stance phase with gait time. The pelvis velocity, which was utilized as the parameter to evaluate speed during the turning phase, was calculated by dividing the length of the path of the pelvis center by gait time. When evaluating the mean values of the gait parameters, we considered all the trials.

To calculate body inclination and joint angles, especially the hip rotation and abduction/adduction, the human SIMM model was scaled and fitted to the motion of the markers by means of the least-squares method. It should be noted that the human model could not be fitted perfectly owing to the deformation of skin and clothes. This model was scaled for each subject. The positive direction of the hip rotation angle was defined as the inner direction. The posterior and outer inclination of the body segment was defined as the positive direction of the pitch and roll angle. The lumbar yaw angle was considered as positive when the torso rotated along the counterclockwise direction on the pelvis segment. The GRF of each leg was calculated as the sum of the forces recorded by both the toe and heel plates. Subsequently, this GRF was normalized by body mass. The coordinate system of the GRF was fixed at the bottom of each foot, and the X-axis was directed to the left side (inner side of the curve) of the short axis. The Y-axis was directed backward along the longitudinal axis.

The rotation radius, which probably affected curving motion [22], was defined separately from the corner radius as the radius of the circle that fit the trajectory of the CoM in the corner section in the horizontal plane. Although the curvature of the CoM trajectory changed gradually when curving, the shape grew closer to the circle in the corner section. Fitting was performed with the use of the least-squares method. The maximum and minimum values of body inclination, joint angles, and GRFs in the corner section were calculated as the indices of the curving trials.

To evaluate the characteristics of the curving strategy, corner trials were classified into five groups by using the three types of parameters corresponding to pelvis posture. They included the maximum angles of the pelvis anterior inclination, pelvis inner inclination, and lumbar yaw rotation in a direction towards the curving direction, which meant the left side for each trial. These body inclination parameters possibly reflect the pelvis posture at the sharpest part of the curving path of the subject, whereas the joint angles are related to the timing of specific gait events. Next, cluster analysis, which is based on Ward's method [25], was applied for classification.

After classification, the indices of each group were compared with the use of the Steel-Dwass test [26] because it was presumed that this clustering illustrated the difference in curving strategies among groups, with respect to joint pattern, GRF, and posture.

3. Result

The means and SDs of the gait parameters during the straight-walk trials were as follows: pelvis velocity, 1.36 $\pm$ 0.13 m/s; cadence, 112.1 $\pm$ 3.9 step/min; step distance, 72.1 $\pm$ 6.7 cm (right) and 71.8 $\pm$ 5.6 cm (left); and double support ratio, 23.4 $\pm$ 2.5%. Here, we mention that although the pelvis velocity and step distance do not exactly correspond to the speed and step length, the values of these parameters are similar and consistent with those of previous studies [27, 28]. Next, we obtained the abovementioned parameters for the curving trials with the large radius as follows: pelvis velocity, 1.23 $\pm$ 0.14 m/s; cadence, 108.8 $\pm$ 6.0 step/min; step distance, 68.3 $\pm$ 6.8 cm (right) and 68.4 $\pm$ 6.3 cm (left); and double support ratio, 25.3 $\pm$ 3.5%. In addition, for the small-radius case, we obtained the following values: pelvis velocity, 1.17 $\pm$ 0.14 m/s; cadence, 107.9 $\pm$ 6.1 step/min; step distance, 66.4 $\pm$ 7.4 cm (right) and 66.4 $\pm$ 7.2 cm (left); and double support ratio, 25.9 $\pm$ 3.7%.

The results of the cluster analysis for the corner trials are shown in Fig. 2. According to Fig. 2-B, the first (blue) and second (red) groups lie close to each other, and their sizes are larger than those of the other groups, particularly the fourth (cyan) and fifth (magenta) groups. The representative pattern of posture parameters used for clustering is shown in Fig. 2-C. Even in the dendrogram shown in Fig. 2-A, the first and second groups lie close. It should be noted that almost all trials classified under the fourth and fifth groups corresponded mostly to one subject respectively, as can be inferred from Fig. 2-D.

The means and SDs of each motion index and the p-value of each coupling as calculated by the Steel-Dwass test are indicated in Table 1. We note from the table that as a common trend, the pelvis inclined towards the inner side and the lumbar was also directed towards the inner side along the horizontal plane. Although the rotation radius was not effective as a clustering parameter, the radius differed among strategies and could be separated into two groups. Speed showed a similar trend and it corresponded to the rotation radius. In contrast, the effect of the difference in the corner radius appears negligible because the difference of the curving strategy within the subject is not the same among subjects, as listed in Fig. 2-D.

4. Discussion

4.1. Common trends in natural curving motion

A change in gait timing was commonly observed during curving corner motion. The steeper the curving motion, the more step length, cadence, and speed decreased, as suggested previously [12, 13, 14, 29].

The common motion observed when curving is demonstrated in Table 1, in addition to the difference in curving motion strategy among groups. The most representative characteristics of curving are the inside inclination of the pelvis and the torso, appearing as large negative values of the minimum roll angle. This inclination matches the inside movement of the CoM, as reported previously [17]. At the same time, the subject directs his head and torso towards the rotation direction before turning [12, 13, 14, 30], which was observed as a large maximum lumbar yaw angle in our study. Across all groups, the GRF in the lateral direction (Fx), which indicates the centripetal force, is larger on the outer (right) leg, as suggested by Orendurff et al. [17]. A similar trend is observed regarding the deceleration force (maximum Fy) and normal force (Fz). This result indicates that the thrust force to turn around the corner mainly comes from the outer leg.

Although the joint motion becomes asymmetrical between legs, it is difficult to find significant difference in the joint flexion between them. In addition, our finding that the gait parameters retain symmetry even during curving trials also suggests symmetry of the gait motion in the sagittal plane. Thus, the contribution of the joint flexion to the curving motion should be small. Instead, the large outer rotation of the hip, followed by its inner rotation and abduction, were commonly observed as reported previously [29]. This out-of-sagittal-plane motion, particularly foot rotation, is necessary to alter the pelvis direction.

4.2. Characteristics of the curving motion of each group

As shown in Fig. 2-B, the main parameter that separates the various groups is the maximum lumbar yaw angle. Furthermore, the fourth and fifth groups can be mainly identified by the minimum pelvis roll and pitch angles, which become positive when the pelvis inclines in the posterior and outer direction.

Based on a further comparison of the peak rotation angles of the outer and inner hips, we depict the curving strategy of each group in Fig. 3. In the case of straight walking, the hip rotation is close to zero at the time of HC and is maximum in the early stance phase [6]. In contrast, during the curving motions, a large hip rotation occurs in the early stance phase. The manner of this hip rotation determines the curving strategy. However, the validity of the fourth- and fifth-groups should be certified by testing additional subjects because of the limited number of samples. The curving motion of the first and second groups is characterized by a large outer rotation of the hip joints. A large outer rotation of both legs at the timing of HC of the inner foot alters the walking direction to execute the curve. In contrast, the third group displayed a large inner rotation of the outer leg in the stance phase. The fourth group exhibited the same characteristics, but for the inner leg. The fifth group displayed a relatively large inner rotation in both legs. These trends indicate that the fifth-group uses the inner rotation of both legs, whereas those third- and fourth-group use only one leg to turn. As previously discussed, the curve motion of all groups can be mostly characterized by the hip rotation.

Although many parameters of the first and second groups are similar, there are several parameters that also define their differences. In the first group, the pelvis inclined to the inner side of the curve during the swing phase of the inner leg via a combination of certain features, such as the large maximum pelvis inclination towards the inner side, which comes from a large abduction angle of the inner leg, and asymmetrically large hip and knee maximum flexion angles of the inner leg. In other words, the subjects' upper body leaned towards the curving direction. However, those in the second group did not show such rolling motion of the pelvis and upper body.

4.3. Practical implications of curve motion classification

In brief, the strategies shown in Fig. 3 can be separated as curving with the inner step and curving with the outer step. In this experiment, the "spin" motion was not observed to be the same as in the study, which recorded the curving motion in a simulated daily living environment [5]. Furthermore, the stepping motions were separated more precisely than in previous studies [18] and connected to the joint motions. The existence of groups with large numbers of trials, such as the first, second, and third groups, suggest that there are several strategies commonly used by the subjects. However, it should be noted that the existence of unique strategies is also suggested from the result.

In this study, although further analysis is required to characterize the motion of each stride during curving, it appears probable that the gait cycle, whose curve angle is steepest, can be extracted from this analysis. In addition, the extracted curving strategies determine the ROM required for a natural curving motion, which also should be equipped in a physical assist device as shown in Table 1 and Fig. 3-C. Furthermore, the analysis of specific curving strategies can aid in determining the assist pattern of each joint.

The change in speed accompanied by the curving motion also possibly cause the motion mismatch, because some physical assistant robots require several gait cycles to fit the change in gait timing. Thus, it is also important to control the gait timing along with the progression of curving motion.

5. Conclusion

In this study, the natural curving motion, which is the motion obtained when freely turning around corners, was recorded, and several curving strategies were identified using cluster analysis. The five identified curving strategies were characterized by motion indices such as the inclination of the pelvis, maximum and minimum joint angles, and peak GRFs. The curving strategy can be largely summarized by the peak inner and outer rotation angles of the hip joints. In most trials, subjects used the outer rotation of both legs when stepping on the inner foot; however, the inner rotation of the outer foot was also used in some trials. Although these strategies suggest a large variation in the curving motion within and among subjects, it is possible to categorize such motions into one of the five representative strategies. Such identification of motion characteristics can aid in analyzing the natural curving motion of humans, which has not thus far been sufficiently understood. Furthermore, it can also help physical assistant robots to match natural curving motion in daily living environments.

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7. Conflict of interest statement

The authors declare no conflict of interest.

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