To appear in *Advanced Robotics*
Vol. 00, No. 00, January 2013, 1–14

FULL PAPER

Gait motion for naturally curving variously shaped corners

Yasuhiro Akiyama[a]*, Shogo Okamoto[a], Hitoshi Toda[b], Takao Ogura[b], and Yoji Yamada[a]

[a] *Department of Mechanical Science and Engineering, Nagoya University, Nagoya, Aichi, Japan*;
[b] *Mie Prefectural Police, Tsu, Mie, Japan*;

(*v1.0 released January 2013*)

Modeling the curving motion of humans in actual environment is rarely done because of the complexity and variability of the turning motion. In this study, various gait motions, including straight, round corner, and circular walks, were recorded and analyzed using factor analysis. As a result, we successfully extracted several factors that represent turning motions, such as long stride motion, turning motion led by the inner leg, and turning motion led by the outer leg. In particular, we found that the natural curving motion, which is a motion that results when turning around a round corner, is widely and continuously distributed on the factor space. Although several typical stepping strategies were reported by related studies, we found that the stepping motion changes between straight and turning gaits in the factor space during natural curving motions. Thus, the classification of curving motion into several typical distinct stepping patterns is probably insufficient to understand the natural curving motion. Furthermore, natural curving motions that comprise circular curving motions that were believed to represent typical curving motions was not validated. On the other hand, this result also suggests the possibility of generating curving motions for a physical assistant robot by combining straight gait and circler curving motion.

Keywords: Turning; Gait motion; Factor analysis; Stepping strategy; Physical assistant robot

1. Introduction

The use of physical assistant robots has started spreading in society because such robots can be used not only for the rehabilitation on the treadmill [1] but also for gait assistance of the elderly in daily living [2, 3]. Thus, the out-of-sagittal motion, which is required in daily activities such as turning, should be considered. However, many physical assistant robots have no or limited number of actuators or joint mechanisms for out-of-sagittal plane motions [4–6], and only few exoskeletons have sufficient degree of freedom and range of motion for such motions [7], although fall is sometimes caused by failure in turning [8–11].

Because of the complexity of human curving motion, previous studies focused on a limited part of curving motions. Several groups have measured a 180° turn [12, 13], and the difference between straight gait and on-site 180° turn has been analyzed [14]. Furthermore, some studies reported that several stepping strategies are available for humans to turn around a square corner [15–17]. For example, Taylor et al. [16] indicated the existence of three types of curving strategies: pivot turning of the inner foot, placing the outer foot in front of the contralateral foot, and directing the inner foot to the curving direction. Xu et al. [17] separated turning motion around a square and a 45° corner to two strategies: step and spin. In addition, the first step when the walking direction is

*Corresponding author. Email: akiyama-yasuhiro@mech.nagoya-u.ac.jp

altered, which is probably the transitional motion between a straight gait and turning motion, was investigated by Patla et al. [18]. However, in an actual environment, humans rarely perform such a steep walking path. Furthermore, in these experiments, the subjects could not freely select their walking path and gait timing because the walking path was strictly controlled by directions and markers on the floor. Thus, we anticipated that stepping motions when naturally turning around corners would be different from those observed in earlier studies and show more variations.

In contrast, continuous turning around a circler path whose radius probably resembled an actual curving path was also analyzed by other groups [19, 20]. These studies clarified the eye and head direction, ground reaction force, and lower limb flexion angles when rounding a circler path. However, the transitional motion between straight gait and circler walk, which appears in the natural curving motion, was not considered in these studies.

On the other hand, curving motions under more natural conditions were studied by several groups. Olivier and Cretual reported the relationship between the curving radius and speed at a corner section [21]. Reed-Jones reported the gait motion when turning a blind corner [22]. Okamoto and Yamada studied the stepping strategy when a pedestrian avoids another oncoming pedestrian at a corner [23]. In these studies, the subjects walked naturally. However, these studies were not intended to measure various types of curves, and the observed physical parameters were limited.

Owing to the large degree of freedom or variability, the motion when turning a corner without any constraints in the walking path and the speed can possibly vary among different corner radii, trials, and subjects. However, such observations and analyses were rarely done previously although such observation could determine varieties of human curving strategies. Thus, we need to experimentally observe various curving motions such as turning motion around an arc with multiple radii and the transitional phase between turning and straight walk. Understanding the factors that represent the various curving motions and how the natural walk is composed of these factors can possibly enable the design of curving motions of exoskeletal walking assistant devices by combining such factors and will be helpful in analyzing its applicability to a variety of natural curving motions. Furthermore, such information will be helpful in determining the specification of the joint coordination and experimental protocol of the safety and performance test.

2. Method

The experiment was performed with the permission of the institutional review board of Nagoya University.

2.1 *Apparatus*

A series of experiments was conducted in an approximately 4 m $\times$ 5 m of recording area in which motion was recorded using 10 cameras with 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 some additional markers were attached (Figure 1(a)). The ground reaction force was recorded using mobile six-axis force plates (M3D, Tech Gihan Co., Ltd., Japan) fixed under the sole (Figure 1(b)). Three types of walking paths, namely, straight, round corner, and circle, were marked with tape on the floor in the recording area (Figure 2). The total experimental area, which included the acceleration and deceleration areas, was approximately 5 m $\times$ 8 m. The radii of the corner sections were 0.5 m (small) and 1.0 m (large). A 1-m radius is common for a round corner [19, 20], and a smaller radius, which was closer to a square corner, was also used in another study [21].

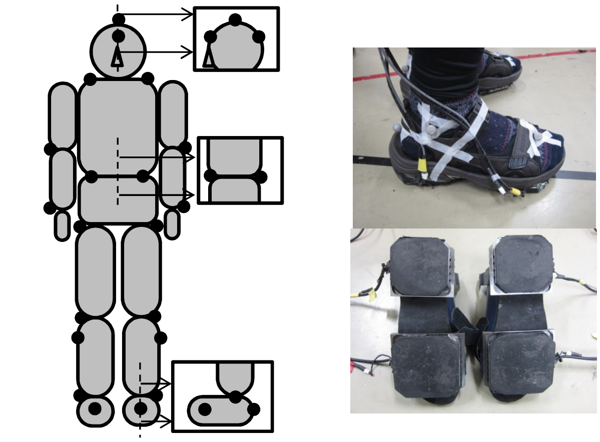

Figure 1. Motion capture markers and force sensing shoes worn by the subject

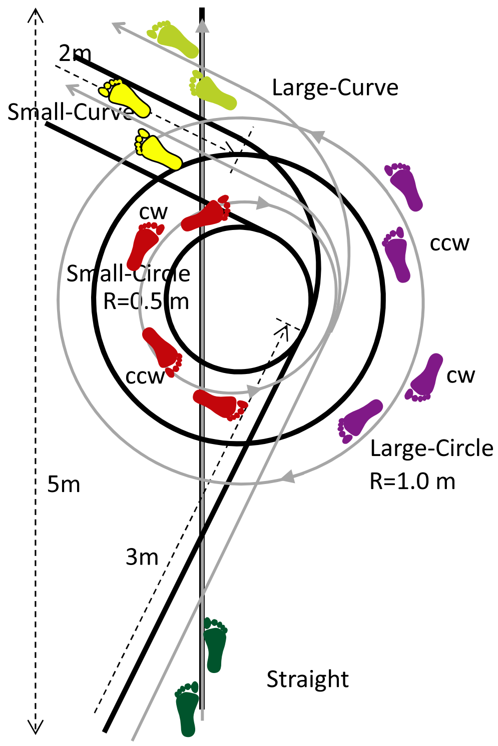

Figure 2. Ground mark and walking pathways (black solid lines: ground mark, foot stamp and gray lines: walking pathways and directions, dashed lines: scale, cw: clock wise, ccw: counter clock wise)

2.2 *Subject*

Twelve healthy male subjects participated in the experiment. The average age was 21.2 years old, and the standard deviation (SD) was 1.7. None of the subjects reported any disabilities that could affect their gait or balance. Their mean height and weight were 172.4 cm (± 3.6 SD), and 61.3 kg (± 6.9 SD), respectively. Their average body mass index was 20.6 and ranged from 17.5 to 24.5.

2.3 *Protocol*

The subjects wore well-fitted sportswear with reflective markers for the motion capture system. During the experiment, each participant walked in self-selected speed along a straight line, a round corner, and a circle in a randomized order.

The straight-walks were repeated 10 times for each subject. The subject was instructed to cross a ground line in a standing posture. Then, he walked straight to the target, which was placed at the extension of the walking lane.

The corner walks included two circles with different radii. To observe the various curving motions, the starting legs were switched during the trials. A total of 40 trials were conducted, which consisted of four different condition combinations (two radii by two starting legs), and recorded. The order of the trials was also randomized. During the trials, the subjects could freely select their gait speed and walking trajectory except for stepping inside the drawn curves.

The circular walks consisted of two radii and two directions. The subject was instructed to walk on each circle with four laps and then turn and cover the same circle for another four times in the opposite direction to prevent dizziness caused by continuous turn. In addition, a sufficient interval was introduced between each trial. The radius of the circle and the starting direction were also randomized. A total of eight trials, which consisted of four different condition combinations (two radii by two starting directions) were recorded. The subjects were also able to freely select their gait speed and walking trajectory except for stepping inside the ground mark.

2.4 *Data Processing*

Gait motions were recorded at 120 Hz using the motion capture and force plates. To remove the effect of acceleration and deceleration, the first and last 2 m of the straight and corner trials and the first and last half-cycles of each circle trial were trimmed. Then, the data from the motion capture were smoothed using a 6-Hz Butterworth filter. The timing of the heel contacts and toe offs were determined on the basis of the ground reaction forces with a threshold of 10 N. Trials in which the tracking markers were critically hidden were not used in the analysis. Thus, in this study, three trials were unused for the statistics.

The position of the footprint was calculated as the center of the toe and heel markers. The direction of the footprint was defined as the line that connected the toe and heel markers. The orientation and position of the pelvis origin were determined as the center position between two anterior superior iliac spines. The position of the center of mass (CoM) of the whole body was calculated using Zatsiorsky's method [24]. The position and inclination of body links were calculated by fitting the motion of markers to the human model of SIMM by using the least-squares method.

In the curving trials, rotation radius of the subject was calculated separately from corner radius to evaluate the actual curving radius of the subject. The rotation radius was determined as the radius of the circle that fit the path of CoM in the corner section, which consisted of a quarter of a circular area in the horizontal plane. Fitting was done using the least-squares method.

Cadence was calculated as the inverse of the time difference between successive heel contacts (HC). Double support phase was calculated as the ratio of the sum of time distance between HC and toe off (TO) of both legs against gait time. Pelvis velocity, which was the parameter to evaluate speed during turning phase, was calculated by dividing the length of path of the center of pelvis, which was determined as the center position between sacral and center of both anterior superior iliac spines, by gait time. HC timing of opposite leg was defined as the ratio of the time distance between HC of leading leg and HC of another leg against the gait time of the leading leg. When evaluating mean values of gait parameters, all trials were used.

The parameters used in the later analysis are shown in Figure 3. The following parameters represent the basic gait parameters.

- *Step distance* is the distance between the center position of both legs, which was calculated

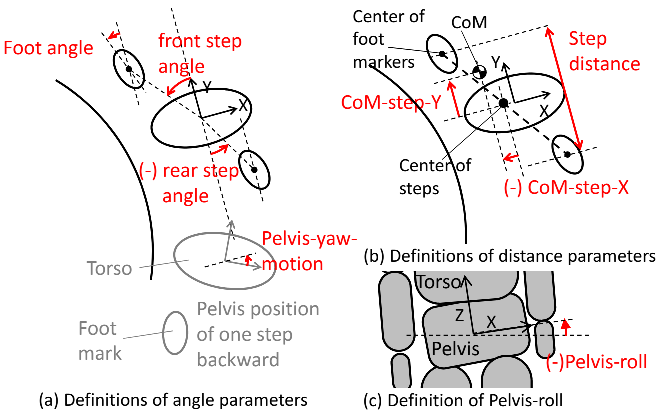

Figure 3. Coordinate system and parameters used (Minus was inserted for parameters whose direction was inversed in the figure.)

as the center of toe and heel markers, along the anteroposterior direction of the pelvis. This definition allowed us to compare the step length even when the direction of motion is altered.

- *Step time* is the duration between the current and previous heel contacts.

The following parameters indicate the orientation of the body, which are used to evaluate the strength of the curving motion [25]. These parameters were calculated at the timing when both heel and toe contacted to the ground to obtain accurate footmark position.

- *CoM-step* is the relative position of the CoM of the subject from the center of both footprints in both X (lateral) and Y (anteroposterior) axes. The axes are directed to the front and outer side of the corner.
- *Pelvis-roll* is the rotation angle of the pelvis in the frontal plane. The motion that elevates the inner side of the pelvis is indicated by a positive sign.
- *Front step angle* is the angle of the line that connects the front footprint and pelvis against the anteroposterior direction of the pelvis. Similarly, *rear step angle* is defined by the rear footprint and pelvis. The rotation toward the inner side of the corner is indicated by a positive sign.

The following parameters indicate the characteristics of the stepping strategy when turning curves [16].

- *Foot angle* is the direction of the footprint along the anteroposterior direction of the pelvis in which the direction is the same as the step angle.
- *Pelvis-yaw-motion* is the change in the pelvis-yaw angle between the current and last heel contacts in the global coordinate in which the rotation toward the inner side of the corner is indicated by a positive sign.

Step distance and *CoM step* were normalized by the height of each subject. The orientation and position values such as step angle, foot angle, pelvis orientation, and others at the timing of each heel contacts were used in the analysis after determining the *z*-score. These values such as the step angle, foot angle, and CoM position were defined in the local coordinate system that located on the pelvis of each subject.

Because of the gait asymmetry between the inner and outer steps due to the turning motion, single stride, which started at the heel contact of the outer leg and ended at the next heel contact of the same leg, was used as a single sample. Because of the difference in the walking paths, the number of recorded strides differed among conditions. The range of the number of strides under each condition and subject was from 15 to 168. Only one or two valid strides were observed from a single trial of straight motion. In the curving cases, two to four strides, two or three of which overlapped with the curve section, were recorded in each trial. Thus, the same numbers of strides, namely, 15, were randomly extracted from each of the straight, small-corner, large-

Table 1. Correlation matrix of parameters

		Outer step									Inner step								
		S-dis	Cs-X	Cs-Y	Rsa	Fsa	Fta	Pr	Py	S-time	S-dis	Cs-X	Cs-Y	Rsa	Fsa	Fta	Pr	Py	S-time
Outer step	S-dis		0.32	-0.83	0.34	0.55	-0.33	0.32	-0.54	-0.36	0.87	0.35	-0.84	0.53	0.15	-0.54	-0.07	-0.49	-0.29
	Cs-X			-0.62	0.55	0.66	-0.60	0.58	-0.89	-0.16	0.16	0.69	-0.52	0.34	0.49	-0.36	0.23	-0.61	-0.14
	Cs-Y				-0.56	-0.65	0.57	-0.51	0.79	0.25	-0.73	-0.56	0.92	-0.47	-0.40	0.52	-0.04	0.68	0.21
	Rsa					0.09	-0.78	0.58	-0.68	-0.31	0.33	0.63	-0.55	0.49	0.44	-0.48	0.38	-0.78	-0.28
	Fsa						-0.32	0.32	-0.58	0.07	0.35	0.51	-0.64	0.34	0.42	-0.31	-0.02	-0.41	0.15
	Fta							-0.54	0.68	0.21	-0.28	-0.76	0.63	-0.47	-0.55	0.45	-0.35	0.87	0.31
	Pr								-0.60	-0.25	0.25	0.47	-0.46	0.29	0.33	-0.38	0.48	-0.52	-0.09
	Py									0.33	-0.43	-0.62	0.70	-0.52	-0.38	0.52	-0.15	0.70	0.28
	S-time										-0.41	-0.16	0.33	-0.23	-0.01	0.42	-0.10	0.30	0.62
Inner step	S-dis											0.29	-0.80	0.58	0.16	-0.59	0.01	-0.44	-0.29
	Cs-X												-0.67	0.32	0.84	-0.51	0.50	-0.92	-0.23
	Cs-Y													-0.54	-0.51	0.64	-0.15	0.80	0.23
	Rsa														0.04	-0.59	0.12	-0.46	-0.14
	Fsa															-0.37	0.52	-0.70	0.03
	Fta																-0.45	0.62	0.36
	Pr																	-0.44	-0.05
	Py																		0.34
	S-time																		

S-dis: Step distance, Cs-X: CoM step-X, Cs-Y: CoM step-Y, Rsa: Rear step angle, Fsa: Front step angle, Fta: Foot angle, Pr: Pelvis-roll, Py: Pelvis-yaw-motion, S-time: Step time

corner, small-circle, and large-circle conditions for each subject. Hence, a total of 900 strides (five conditions × 12 subjects × 15 strides) were used in the analysis.

Table 1 shows the correlation matrix of the above mentioned gait-related parameters. Because several parameters showed some extent of correlations, we used factor analysis to extract fundamentally correlated parameter groups. After each parameter was z-scored, and a factor analysis provided by the MatLab "factoran" function was applied. This function uses the maximum likelihood estimation and Bartlett method for factor loading and scoring, respectively. After calculating the factor scores, major factors were rotated using varimax method, which is a general procedure to facilitate the interpretation of the major factors [26].

3. Results

For the circle condition, the gait parameters, gait timings, and stepping geometries were symmetric between the clockwise and counterclockwise walking directions. Thus, both directions of rotation were equally treated. Furthermore, for the straight-walk trials, because no asymmetry was observed, the gait cycles starting from the left and right legs were considered in the same manner.

The typical walking pathways of the straight, corner, and circle walk conditions are shown in Figure 4, which shows the trace of the footprints, position and orientation of the pelvis, trace of the CoM of the whole body, and center of consecutive footprints.

3.1 *Gait parameters*

The gait parameters among the conditions were compared and are listed in Table 2. The speed and step length, which were typically used in related studies, could not evaluate the curving gait in a correct manner because these parameters were defined using travel direction, which was difficult to be determined in the turning gait. Thus, the pelvis velocity and step distance were defined and used in this study. In the straight condition, the speed (1.38 ± 0.13 m/s) and step length (72.8 ± 6.2 cm) were consistent with newly defined parameters.

The rotation radius is shown in Figure 5. One outlier trial, whose rotation radius exceeded 10 m, was out of range. In all cases, the rotation radius was larger than the corner radius. Compared to the circle cases, the distribution of the curve cases was skewed because the subject sometimes deviated from the mark at the start and end points of the corner section.

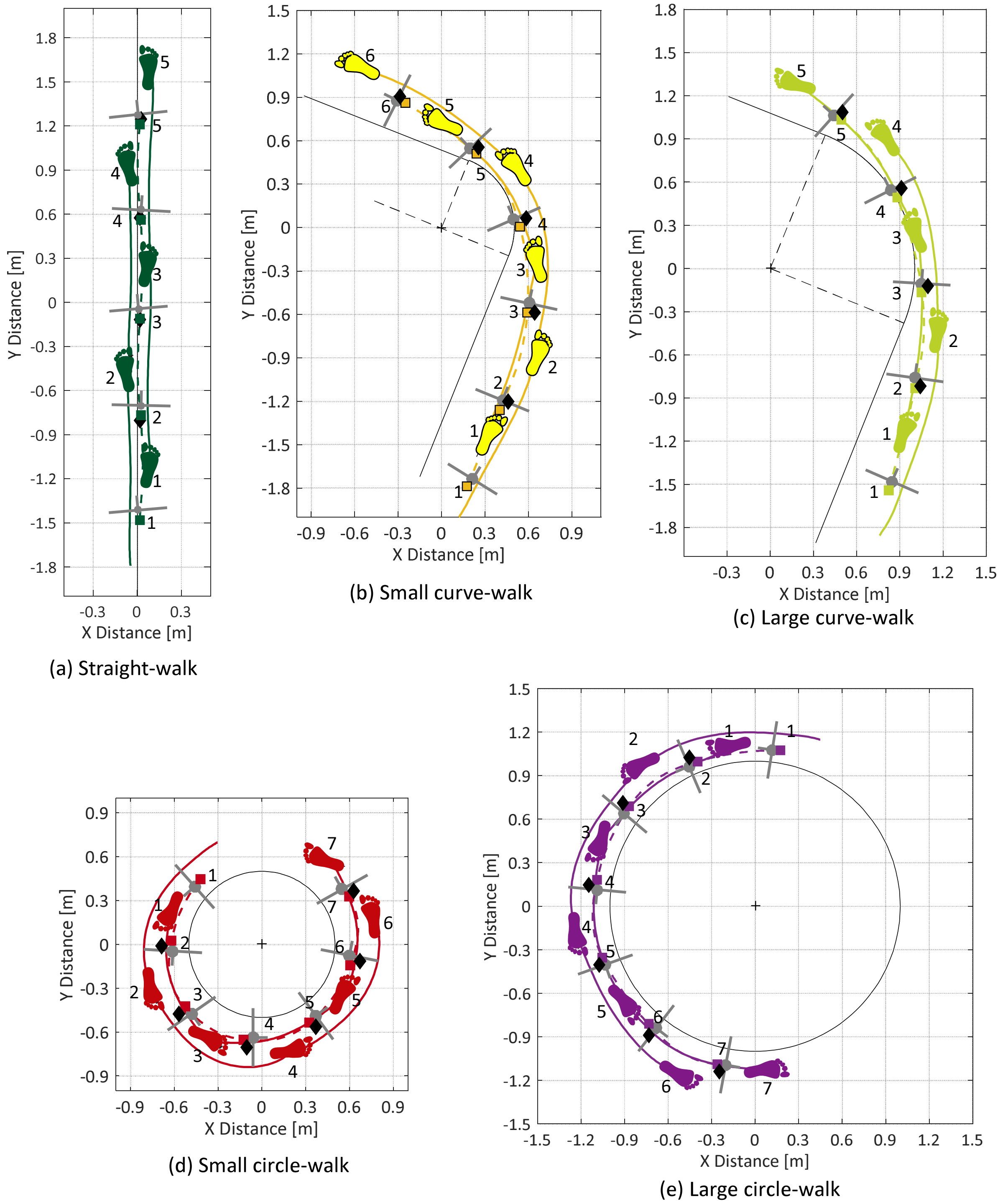

Figure 4. Walking pathways (solid line: trace of foot, dashed lines: trace of CoM, square mark: CoM position at each foot contact, diamond mark: center of consecutive foot marks at each foot contact, gray cross lines: pelvis position and direction)

3.2 *Results of factor analysis*

The first to third factors collectively explained the 64.8% of the variances of the samples, and that of the fourth factor was merely 5.4%. Thus, the three major factors were extracted. After varimax rotation, the contributions of these factors were 24.6, 22.8, and 17.4%. The factor loadings of each factor are shown in Figure 6 after being scaled by the contribution ratios. In the case of the straight gait, the first step was treated as the outer step. The original values of these parameters are listed in Table 3 for comparison among different motions.

Table 2. Mean and standard deviation of gait parameters of various curving motions

	unit	Straight	Large curve	Small curve	Large circle	Small circle
Pelvis velocity	m/s	1.36 ± 0.13	1.23 ± 0.14	1.17 ± 0.14	1.00 ± 0.12	0.79 ± 0.08
Cadence	step/min	112.1 ± 3.9	108.8 ± 6.0	107.9 ± 6.1	105.9 ± 5.8	104.1 ± 7.9
Step distance (left)	cm	71.8 ± 5.6	68.4 ± 6.3	66.4 ± 7.2	59.3 ± 8.6	51.7 ± 7.1
Step distance (right)	cm	72.1 ± 6.7	68.3 ± 6.8	66.4 ± 7.4	60.3 ± 7.7	52.2 ± 6.9
Double support ratio	%	23.4 ± 2.5	25.3 ± 3.5	25.9 ± 3.7	27.5 ± 4.4	28.7 ± 4.4
HC timing of opposite leg	%	50.3 ± 1.3	50.3 ± 1.7	50.2 ± 1.7	49.5 ± 1.5	49.5 ± 1.7

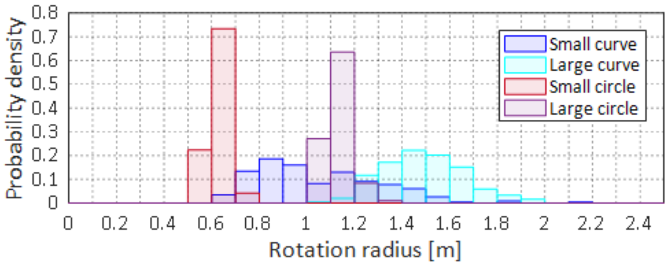

Figure 5. Probability density of rotation radius

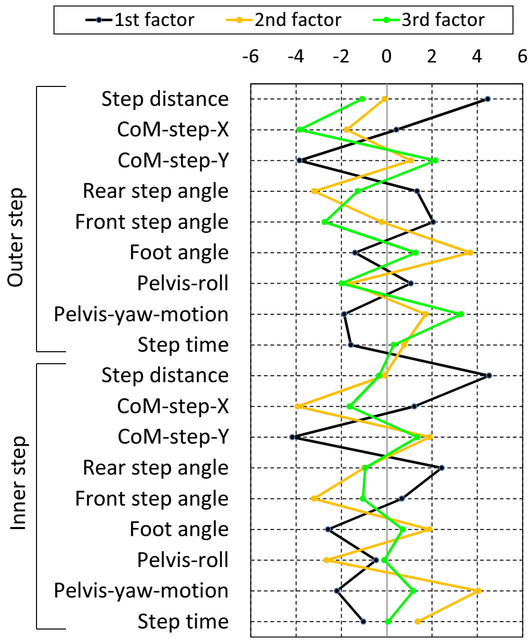

Figure 6. Factor loading vectors (upper half: outer step, lower half: inner step)

3.2.1 *First factor (long stride factor)*

The first factor could be considered as a long stride factor, which affected the orientation and motion of the body in the sagittal plane. The large positive *step distance* of this factor indicats long strides. The negative *CoM-step-Y* indicats that the CoM position in relation to the footprint was positioned backward. These trends were mainly observed during the straight gait, as listed in Table 3. Furthermore, this factor was symmetric between both legs, which suggested that the first factor did not pertain to the turning motion.

In addition, in the first factor, the *pelvis-yaw-motion*, which represents the strength of the turning motion, was smaller than that in the second and third factors. The positive *step angles* should be understood by considering the relative motion of the stepping leg and the pelvis orientation. As shown in Figure 4, the step of the straight gait was located relatively outside the pelvis because the pelvis rotated to the opposite direction at the time of the heel contact, in contrast to the

Table 3. Mean and standard deviation of gait parameters used on the factor analysis (upper half: outer step, lower half: inner step)

		unit	Straight (N=334)	Large curve (N=462)	Small curve (N=440)	Large circle (N=1344)	Small circle (N=1209)
Outer step	Step distance	m/BH	0.42 (± 0.03)	0.39 (± 0.04)	0.38 (± 0.04)	0.35 (± 0.04)	0.30 (± 0.04)
	CoM-step-X	m/BH	-0.04 (± 0.03)	-0.12 (± 0.05)	-0.13 (± 0.06)	-0.14 (± 0.04)	-0.15 (± 0.04)
	CoM-step-Y	m/BH	-0.44 (± 0.03)	-0.40 (± 0.04)	-0.38 (± 0.05)	-0.34 (± 0.03)	-0.26 (± 0.03)
	Rear step angle	deg	12.06 (± 3.34)	4.54 (± 4.89)	4.10 (± 5.54)	-1.44 (± 4.31)	-2.01 (± 4.83)
	Front step angle	deg	-19.08 (± 4.86)	-24.42 (± 6.84)	-25.53 (± 8.20)	-26.04 (± 6.59)	-32.57 (± 9.11)
	Foot angle	deg	-12.27 (± 5.42)	-3.17 (± 8.13)	-1.01 (± 9.51)	5.02 (± 5.95)	11.67 (± 7.14)
	Pelvis-roll	deg	0.08 (± 1.61)	-2.16 (± 2.14)	-2.35 (± 2.46)	-3.64 (± 2.12)	-3.85 (± 2.10)
	Pelvis-yaw-motion	deg	11.16 (± 5.76)	27.10 (± 11.34)	30.18 (± 13.85)	35.58 (± 6.94)	47.00 (± 7.65)
	Step time	s	0.54 (± 0.03)	0.55 (± 0.04)	0.56 (± 0.04)	0.58 (± 0.04)	0.59 (± 0.05)
Inner step	Step distance	m/BH	0.42 (± 0.03)	0.39 (± 0.04)	0.38 (± 0.04)	0.35 (± 0.05)	0.30 (± 0.04)
	CoM-step-X	m/BH	0.04 (± 0.03)	-0.07 (± 0.04)	-0.08 (± 0.06)	-0.10 (± 0.03)	-0.13 (± 0.03)
	CoM-step-Y	m/BH	-0.44 (± 0.03)	-0.39 (± 0.03)	-0.37 (± 0.04)	-0.33 (± 0.03)	-0.24 (± 0.02)
	Rear step angle	deg	-12.08 (± 3.43)	-15.81 (± 4.60)	-15.40 (± 5.41)	-19.28 (± 4.19)	-21.50 (± 5.81)
	Front step angle	deg	18.85 (± 4.86)	7.95 (± 7.33)	7.73 (± 8.95)	2.86 (± 6.85)	0.34 (± 10.39)
	Foot angle	deg	12.26 (± 5.38)	21.44 (± 6.70)	21.14 (± 9.44)	26.33 (± 6.02)	33.41 (± 6.52)
	Pelvis-roll	deg	-0.15 (± 1.58)	-3.02 (± 2.06)	-2.67 (± 2.52)	-3.21 (± 2.15)	-2.71 (± 2.21)
	Pelvis-yaw-motion	deg	-10.94 (± 5.67)	10.19 (± 8.86)	12.63 (± 12.12)	22.62 (± 5.49)	35.38 (± 7.63)
	Step time	s	0.53 (± 0.02)	0.55 (± 0.03)	0.56 (± 0.04)	0.57 (± 0.04)	0.57 (± 0.05)

turning motion where both the pelvis and leg rotated to the turning directions.

3.2.2 Second factor (inner leg turn factor)

The second factor could be considered as the rotation factor of the inner step. The large positive *pelvis-yaw-motion* directly indicated a turning motion, and the negative *CoM-step-X* and *pelvis-roll* indicated the inside tilt of the body. A positive *foot angle* means that the foot was directed to the curving direction. These tendencies were observed mainly in the parameters of the inner step of the second factor. The *front* and *rear step angle* of the inner step, which were defined by the angular difference between the pelvis and foot step, were not large, which meant that the subjects changed the directions of the pelvis and inner step when altering the walking direction.

3.2.3 Third factor (outer leg turn factor)

In contrast, the third factor was mainly related to the rotation of the outer step. This factor was very similar to the second factor except that the variables related to the turning motion were largely prominent at the outer step.

3.2.4 Sample distribution in factor space

The factor score of each consecutive step is shown in Figure 7. The stride samples were distributed along with the rotation radius. The strides of the straight walk (dark green with edge) were located in the area with positive first factor and negative second and third factors. In contrast, the small-circle walks (scarlet with edge), for which the rotation radii were smaller than 0.8 m, were located in the area with high negative first factor and small negative or positive second and third factors. The large-circle walks (purple with edge in most cases), for which the rotation radii were 0.8 to 1.2 m, were located between the straight and small-circle trials. The general observations in the present study are consistent with those in the earlier studies. The distribution of the small and large circle trials matched the phenomenon observed by Orendurff et al. [19], where the CoM moved inside when turning, and this inside shift in the CoM increased as the turn became sharp. The inside shift of the CoM corresponded to large second and third factor scores. Positive front foot angles, which means the inward direction of the front foot, in the positive second and third factors matched the stepping strategy, i.e., putting the pivot foot toward the curving direction, when the walking direction is altered [16].

The corner walks (yellow with black edging for the small radius and chartreuse for the large radius) were widely distributed between the circle and straight trials and were especially spread on the second and third factor planes. The order of distribution, namely, small-circle, large-circle, corner, and straight walks, which is clearly shown in Figure 7(a), suggested that the three factors indicated the strength of the turning motion, which is related to the corner radius.

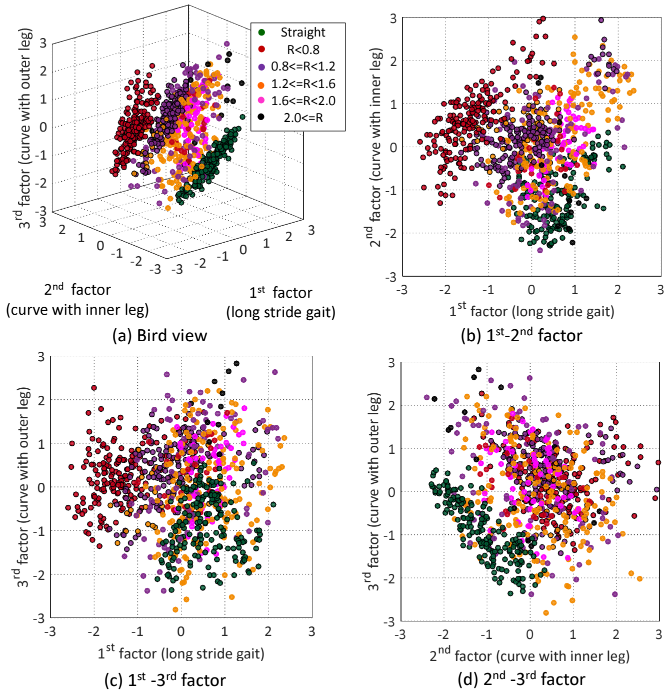

Figure 7. Factor score vectors (dark green: straight; scarlet: rotation radius of less than 0.8 m; purple: rotation radius is between 0.8 and 1.2; orange: rotation radius is between 1.2 and 1.6; pink: rotation radius is between 1.2 and 2.0; black: rotation radius is larger than 2.0; and edged marks: straight and circle cases)

4. Discussion

4.1 *Validity of gait motion*

The gait parameters for the straight walk shown in Table 2 were compared with those reported in previous studies [27, 28] because the types of gait parameters for the corner and circle walks were not unified across previous studies. Speed, cadence, and step length were not critically differed from that of the present studies. The double support ratio also matched that of the previous study [29]. Previous study [29] also reported that the value of the foot angle of the straight walk was approximately 6.3° from the travel direction. We note that the definitions of the foot angles are different between the two studies. Our result were close to these values when considering the several degrees of pelvis-yaw angle, which affected the foot angle in our analysis. The pelvis-roll angle at the right heel contact was approximately 0.1 ± 0.7°, and that at the left heel contact was -0.1 ± 0.9°. The values were smaller than 1° as previously reported in previous study [30], and motion symmetry was retained. Although the soles of the shoes used in the present study was thicker than general soles, their effect was minor at least on the gait parameters.

According to Table 2, the gait parameters of the curving cases are located in between the straight and circle cases. However, it is unclear that which parameters are causal and dependent. In addition, although the curve trials included transitional motion between the straight gait and turning motion, the standard deviation of the gait parameters of the curve trials were not larger than that of the other trials, which suggested that the gait parameters did not change during the corner turning motion.

The change in the pelvis velocity can probably describe the change in the gait parameters among the conditions. Previous studies, which compared the gait timing among straight gaits with different speeds, reported that the cadence and step distances decreased, and the double support ratio increased when the pelvis velocity decreased [29, 31]. The small deviation of the gait parameters of the natural curving cases probably be considered that the deceleration and acceleration phase around the corner was not observed because of the limitation of the length of

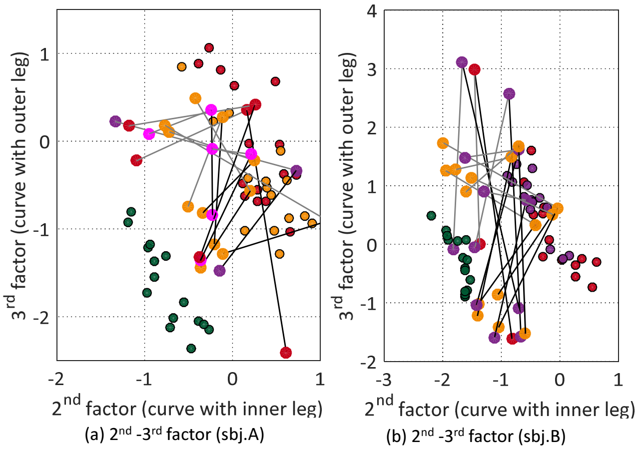

Figure 8. Factor score vectors of the curve trials (dark green: straight; scarlet: rotation radius of less than 0.8 m; purple: rotation radius is between 0.8 and 1.2; orange: rotation radius is between 1.2 and 1.6; pink: rotation radius is between 1.6 and 2.0; black: rotation radius is larger than 2.0; edged marks: straight and circle cases; black line: connection between the first and second steps; and gray line: connection between the second and third steps)

the walking lane.

Previous studies [29, 31] reported that when the walking speed decrease to approximately 70%, the cadence drops to approximately 80%, and the step length drops to approximately 85%. At the same time, the double support ratio increases by approximately 57%. However, in the small-circle case, although the pelvis speed decreases to approximately 58% from the straight case, the cadence drops to approximately 93%, and the step distance drops to 72%. Because of the body inclination, the pelvis velocity became smaller than the speed calculated from the step distance and cadence. In addition, the double stance ratio approximately increases by 23%. Thus, it appears that the change of the cadence is small compared to that of the previous studies.

The first factor is related to the walking velocity and the curve motion is not solely explained by this factor. However, because the walking velocity was not controlled in this study to observe the natural motion of the subject, separating the effect of walking velocity and curving condition is impossible. Thus, another study is required to identify the effect of such parameters.

4.2 *Gait parameters do not become asymmetric when curving*

As listed in Table 2, asymmetry in the step distance was not observed even during the natural and circler curving conditions. Although it was unexpected that the step distance of left and right legs were almost the same even when turning-left the curve or circle, these data suggest that the asymmetry foot angle did not affect the stride in the sagittal plane. In addition, the timing of the HC of the opposite leg was nearly 50%, which also suggested the symmetry of the gait timing in the turning motion. These facts suggest that gait parameters are not related to the second and third factors, which are the turn factors of the inner and outer legs.

4.3 *Circle rotation partially simulates the natural turning motion*

Figure 7 shows that the strides could be separated among the straight and different radii of the circle walks in the factor space. However, they were widely distributed, and the strides of the corner walks overlapped with the straight and circle walks. In particular, the distribution became wider in the corner walks than that in the other conditions and was distributed between the straight and circle walks. An explanation for these distribution characteristics is that the data for the corner walks included some walking phases such as straight and circle-curve gaits and their transitional motion that appeared during the natural curving motion.

The strides of some subjects on the factor space where consecutive three gait cycles were observed during the corner walks are shown in Figure 8. In the plane of the second and third factors, the corner walk started near the area of the straight gaits (dark green) and approached the area of the circle walks (scarlet, purple, and orange with edge) as the subject entered the corner section. Then, it moved back toward the straight gait as the subject finished turning.

However, the values of the first factor significantly differed between the corner and circle walks as shown in Figure 7. Figure 6 shows that the low first factor, which means the small step distance and large CoM-step-Y, of the circle walk indicates the gait motion of the short step and forward leaning, which was a trend that did not occur in the straight and corner walks. This difference between the corner and circle walks probably indicate the qualitative difference between them. In the circle walk, the subject continuously turned; hence, their turning motions might have been adjusted to the circle walk. On the other hand, the turning motion is temporal in the corner walk.

When developing an exoskeleton, which covers the curving motion, the curving performance should be tested. As a test method, continuous rotation around a circle is probably more convenient than corner curving due to the small deviation in motion, compact experimental space, and ease in controlling the rotation radius. However, the difference between the natural curving and circle rotation motions should be considered.

Figures. 7 and 8 show that the natural curving motion will probably be considered as the combined motion of straight gait and circle rotation in the plane of the second and third factors. In contrast, the first factor of the circle cases differs from that of the straight and curve cases. According to Table 3 and Figure 6, the difference in the first factor mainly resulted in the difference of the motion in the sagittal plane. Although such difference probably comes from the difference in the walking velocity, the effect is not very clear. Thus, when the circle rotation motion is tested instead of the natural curving motion, we should consider that the natural walking speed changes depending on the walking path, and the gait parameters and posture, such as the *step distance* and *CoM-step-Y*, differ between natural curving and circle rotation motions. From our study, it is also suggested that this difference become smaller when the curve radius become larger.

4.4 *Natural turning motions are highly variable in the space including representative curving strategies*

Figure 8 shows that the distributions of the strides of the corner walk were widely spread even for the same subject, especially in the plane of the second and third factors. The wide and seamless distribution of the second steps is attributed to the difference in the walking course, the side of the leg they used to turn around the corner, the strength of turning of each leg, and the behavior adaptive to these subtle differences in the curving motions. In contrast to the straight and circular walks, the gait motion varied among the subjects and trials in the corner walks because the subjects could select the position, direction, and timing to enter and exit the corner, in contrast to turning around the small circles.

Because of such enormous degree of freedom in the natural curving motion, determining the "typical" curving motions that were reported in earlier studies [16, 17] under limited experimental conditions is difficult. Instead, it appears that the strides of the curving gait seamlessly distributed in the factor space and the natural curving motion can probably be considered as the connection of such strides. In addition, part of such curving motions possibly includes stepping strategies previously reported in related studies [16, 17, 19, 25].

5. Conclusions

To determine the characteristics of a natural curving motion, gait experiments, which included a straight gait and a continuous looping motion, in addition to the natural curving motion, were conducted. As a result of the factor analysis, the curving motions were found to be composed of three major factors: long-stride factor, rotation factor of the inner step, and rotation factor of the outer step. According to the distribution of the factor score vectors, the straight and circle walks could be separated, and the corner walks, which represent the natural curving motions, can be understood as the motion trajectory that moved between the straight and circle turning gaits in the plane of the second and third factors of factor space.

The turning patterns of the strides in the factor space varied and were widespread due to the unconscious selection of the walking course. Such corner-curving motions might not be categorized into a few patterns that were considered in some of the previous studies. Instead, they should be expressed in a continuous space such as the factor space used in this study.

Because of the gradual change in the gait motion when curving a corner, employing several typical curving motions in a physical assistant robot may not be effective. On the other hand, the distribution of the curving motions between straight gaits and circler walks suggests the probability of generating curving motions by combining these motions. In addition, by comparing the motion distribution in the factor space of actual curving and that of the assistant robot, robot applicability can be evaluated.

Acknowledgment

We thank the support by JSPS KAKENHI (# 26750121) and the support of Mr. Tsubasa Goto.

References

[1] Hidler J, Nichols D, Pelliccio M, Brady K, Campbell DD, Kahn JH, Hornby TG. Multicenter randomized clinical trial evaluating the effectiveness of the lokomat in subacute stroke. Neurorehabil Neural Repair. 2009;23(1):5–13.
[2] Suzuki K, Mito G, Kawamoto H, Hasegawa Y, Sankai Y. Intention-based walking support for paraplegia patients with robot suit HAL. Advanced Robotics. 2007;21:1441–1469.
[3] Yasuhara K, Shimada K, Koyama T, Ido T, Kikuchi K, Endo Y. Walking assist devices with stride management system. Honda R&D Technical Review. 2009;21(2):54–62.
[4] Raj AK, Neuhaus PD, Moucheboeuf AM, Noorden JH, Lecoutre DV. Mina: A sensorimotor robotic orthosis for mobility assistance. Journal of Robotics. 2011;2011(284352):1–8.
[5] Akiyama Y, Higo I, Yamada Y, Okamoto S. An analysis of recovering motion of human to prevent fall in responce to abnormality with a physical assistant robot. In: IEEE international conference on robotics and biomimetics. 2014. p. 1493–1498.
[6] Veneman JF, Kruidhof R, Hekman EE, Ekkelenkamp R, Van Asseldonk EH, Van Der Kooij H. Design and evaluation of the lopes exoskeleton robot for interactive gait rehabilitation. IEEE Transactions on Neural Systems and Rehabilitation Engineering. 2007;15(3):379–386.
[7] Wang S, Wang L, Meijneke C, van Asseldonk E, Hoellinger T, Cheron G, Ivanenko Y, Scaleia VL, Sylos-Labini F, Molinari M, Tamburella F, Pisotta I, Thorsteinsson F, Ilzkovitz M, Gancet J, Nevatia Y, Hauffe R, Zanow F, van der Kooij H. Design and control of the MINDWALKER exoskeleton. IEEE Transactions on Neural Systems and Rehabilitation Engineering. 2015;23(2):277–286.
[8] Robinovitch SN, Feldman F, Yang Y, Schonnop R, Leung PM, Sarraf T, Sims-Gould J, Loughin M. Video capture of the circumstances of falls in elderly people residing in long-term care: an observational study. The Lancet. 2013;381:47–54.
[9] Morris ME, Huxham F, McGinley J, Dodd K, Iansek R. The biomechanics and motor control of gait in Parkinson disease. Clinical Biomechanics. 2001;16:459–470.
[10] Cumming RG, Klineberg RJ. Fall frequency and characteristics and the risk of hip fractures. Journal of American Geriatric Society. 1994;42(7):774–778.
[11] Connell BR, Wolf SL. Environmental and behavioral circumstances associated with falls at home among healthy elderly individuals. Archives of Physical Medicine and Rehabilitation. 1997;78:179–186.
[12] Lin JC, Kuo FC, Hong CZ, Liau BY. Kinematic variability of the head, lumbar spine and knee during the ”walk and turn to sit down” task in older and young adults. Gait & Posture. 2014;39:272–277.

[13] Hase K, Stein RB. Turning strategies during human walking. Journal of Neurophysiology. 1999;(81):2914–2922.

[14] Chong RK. Factor analysis of the functional limitations test in healthy individuals. Gait & Posture. 2008;28:144–149.

[15] Crenna P, Carpinella I, Rabuffetti M, Calabrese E, Mazzoleni P, Nemni R, Ferrarin M. The association between impaired turning and normal straight walking in Parkinson's disease. Gait & Posture. 2007;26:172–178.

[16] Taylor M, Dabnichki P, Strike S. A three-dimensional biomechanical comparison between turning strategies during the stance phase of walking. Human Movement Science. 2005;(24):558–573.

[17] Xu D, Chow JW, Wang YT. Effects of turn angle and pivot foot on lower extremity kinetics during walk and turn actions. Journal of applied biomechanics. 2006;22(1):74.

[18] Patla AE, Prentice SD, Robinson C, Neufeld J. Visual control of locomotion: Strategies for changing direction and for going over obstacles. Journal of Experimental Psychology. 1991;17(3):603–634.

[19] Orendurff MS, Segal AD, Berge JS, Flick KC, Spanier D, Klute GK. The kinematics and kinetics of turning: limb asymmetries associated with walking a circular path. Gait & Posture. 2006;23:106–111.

[20] Segal AD, Orendurff MS, Czerniecki JM, Shofer JB, Klute GK. Local dynamic stability in turning and straight-line gait. Journal of Biomechanics. 2008;41:1486–1493.

[21] Olivier AH, Cretual A. Velocity/curvature relations along a single turn in human locomotion. Neuroscience Letters. 2007;(412):148–153.

[22] Reed-Jones RJ, Hollands MA, Reed-Jones JG, Vallis LA. Visually evoked whole-body turning responses during stepping in place in a virtual environment. Gait & Posture. 2009;30:317–321.

[23] Okamoto T, Yamada Y. Decision model for determining the behavior of pedestrians approaching from both sides of a blind corner by considering tactics and information uncertainty. In: Proceedings of the 2012 IEEE international conference on robotics and biomimetics. 2012 Dec. p. 1494–1501.

[24] De Leva P. Adjustments to zatsiorsky-seluyanov's segment inertia parameters. Journal of Biomechanics. 1996;29(9):1223–1230.

[25] Xu D, Carlton LG, Rosengren KS. Anticipatory postural adjustments for altering direction during walking. Journal of Motor behavior. 2004;36(3):316–326.

[26] Lord S, Galna B, Verghese J, Coleman S, Burn D, Rochester L. Independent domains of gait in older adults and associated motor and nonmotor attributes: validation of a factor analysis approach. The Journals of Gerontology Series A: Biological Sciences and Medical Sciences. 2013;68(7):820–827.

[27] Finley F, Cody K. Locomotive characteristics of urban pedestrians. Archives of Physical Medicine and Rehabilitation. 1970;51(7):423.

[28] Blanke DJ, Hageman PA. Comparison of gait of young men and elderly men. Physical Therapy. 1989;69(2):144–148.

[29] Murray MP, Kory RC, Clarkson BH, Sepic S. Comparison of free and fast speed walking patterns of normal men. American Journal of Physical Medicine & Rehabilitation. 1966;45(1):8–24.

[30] Ounpuu S, Gage J, Davis R. Three-dimensional lower extremity joint kinetics in normal pediatric gait. Journal of Pediatric Orthopaedics. 1991;11(3):341–349.

[31] Öberg T, Karsznia A, Öberg K. Basic gait parameters: reference data for normal subjects, 10-79 years of age. Journal of rehabilitation research and development. 1993;30:210–210.