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Foot placement variables of pedestrians in community setting during curve walking

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A R T I C L E I N F O

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A B S T R A C T

Background: There is no precise description of changes of gait during curve walking. Research in curve walking is exclusively performed in clinical settings.

Research question: Is there a difference in foot placement variables between the inner- and the outer leg during curve walking in a natural environment? And are these differences correlated with time or the curvature of the path?

Method: During this observational study, camera footage was shot on a crossing where pedestrians were not aware of being filmed. Participants ($n = 21$, male, 18–40 yrs) were selected from this video footage. Using the software package "Movieprocessing", the kinematic variables (time, curvature, stride length, step length, step width and relative foot angle (RFA)) were extracted from the collected data. A MANOVA and Pearson correlation test were performed to explore the data.

Results: MANOVA showed no significant differences in stride length and step length between inner- and outer leg. In contrast, a significant difference between the inner ($M = 0.06$, $SD = 0.05$) and outer leg ($M = 0.10$, $SD = 0.06$, $F(20,256) = 3.577$, $p < .001$) for the step width, and the inner ($M = 11.72$, $SD = 7.99$) and outer leg ($M = 11.30$, $SD = 8.07$, $F(20,256) = 4.542$, $p < .001$) for RFA was found. Pearson correlation was significant for curvature and step width for both legs pooled ($r = .28$, $p < .01$) and the outer leg ($r = .64$, $p < .01$), as well for time and RFA in the inner ($r = -.25$, $p < .01$) and outer leg ($r = .213$, $p < .01$).

Significance: This research funds further research in curve walking in natural conditions, since curve walking is found to be performed non-symmetrically and not determined by geometrics but by choice. Foot placement variables change gradually and differently for both legs during walking a curve.

1. Introduction

Traditionally, gait analysis focuses on gait over a straight path. However, about 35–45 % of our gait in daily life is along curves [1]. Although curve walking becomes more common in gait analyses and knowledge on this is needed for rehabilitation purposes like limiting falls and physical assistant robots, research into walking a curve is still rare [2,3]. Moreover, there is no clear description of it in community settings yet. This urges the need to investigate variables derived from placement of the feet in the horizontal plane, in this paper referred to as foot placement variables, during curve walking in an ecologically valid environment.

Hase and Stein [4] were the first to differentiate stepping strategies during curve walking. Sidestep turning includes the inner foot to step into the curve, to start curve walking. The pivot-turn was defined as swinging the outer leg in front of the inner leg [4,5]. The study by Glaister et al. [1] did not find this pivot turn in the natural environment but found that the step turn can be used in two strategies; the cross over turn and the side step turn. Other studies focused on whole body movement during curve walking [6–10]. Courtine et al. [9] found a whole-body tilt into the curve, and differences in the stride length of the inner and outer legs during curve walking. The research by Courtine et al. [8] showed that the stride length of the inner leg decreases and adds a change in foot placement with body rotation by rotating into the curve. Xu et al. [10] found a change in gait parameters before anticipation of the turn by backward and sideward leaning of the center of mass (CoM). Additionally, Orendurff et al. [11] found a change in mediolateral impulse of the ground reaction force in the outer leg and

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inner leg during curve walking. An increase in mediolateral impulse can be associated with an acceleration of the CoM in the direction of the curve. A significant difference in stride length was found, in which the stride length of the outer leg is larger than the stride length of the inner leg. A study by Akyami et al. [6] confirmed these findings while investigating gait parameters in a more natural walking condition. They found that with a steeper curving motion, step length, cadence, and speed decreased more. They identified five different curving strategies based on pelvis inclination, joint angles, and peak GRFs. In most trials outer rotation of both legs was found. However, an inward rotation of the outer foot was also used. Additionally, research focusing on head and torso movement during curve walking found a rotation of these parts of the body into the curve before turning [6,8,7–10,14].

Even though these findings suggest that curve walking is an asymmetrical process [6–10], recent research questions this asymmetry [7]. Akyami et al. [7] found that step distance was not significantly different between the inner and outer leg during curve walking when compared to straight gait. Moreover, heel strike timing did not change, which also suggested symmetry of gait timing in curve walking, linking curve walking in a natural environment more to straight walking than to rotation walking. Overall, previous studies show diverging results when it comes to curve walking. This suggests a difference between findings in lab-studies and more natural studies and shows more research is needed on curve walking, especially in an ecologically valid environment.

Even though previous research reports on natural walking patterns, all research is conducted in clinical or laboratory settings. Walking precisely on force plates or walking on shoes with ground reaction force sensors built in, will most likely not result in a natural walking pattern. Even doing research on natural gait where a track is taped on the floor will affect the freedom of movement of the subjects and therefore cannot be labelled as fully natural. This study investigates foot placement variables in the most natural way of curve walking, that is, in a community setting where participants are not aware of being observed. This type of research will conduct more robust observations and thereby tries to fill the gaps in existing research when it comes to curve walking in a community setting. It aims to determine whether there is a difference between the inner and outer leg in foot placement variables during curve walking. The foot placement variables that will be compared between the inner- and the outer leg are step length (SL), step width (SW), stride length (StL) and relative foot angle (RFA), explained in more detail in the methods and attachment. Furthermore, this research will try to find correlations between these variables and the curvature of and time spent on the walked path. Based on previous research, increasing differences in foot placement variables with the increase of curvature are hypothesized. Differences in stride lengths are expected.

2. Methods

To create the most natural situation, this research made use of naturalistic observations in a public place. Subjects were chosen randomly from 120 min of footage of pedestrians. A camera was placed at a busy crossing in a shopping district. A surface that covered at least four steps before and after a 90° turn was captured. The corners of a 1 m by 1-meter square were marked with chalk to enable perspective correction of footage afterwards. Pedestrians were not aware of being filmed. Recordings are treated in a way that could not cause personal identification. This is in line with the Ethical Principles of World Medical Association Declaration of Helsinki and is allowed by ‘freedom of information’ by the Dutch law [12,13].

2.1. Subjects

21 men with an estimated age between 18 and 40 were included. They were not carrying loads in a way that affected their gait, did not have visible musculoskeletal limitations and were not using their phone. Participants that made steps that were not clearly visible in the footage or were influenced in their path by others or obstacles, were excluded. Their walking speed had to be between 3.0 km/h and 6.0 km/h at all times.

2.2. Apparatus

A Casio EX-F1 camera with 1080p format was used at 30fps. During filming the camera was not moved and was not zoomed in, in order to get high quality footage and to be sure the analysis could be performed within the same perspective correction. The footage was analyzed using a Matlab-based software package named MovieProcessing. A screenshot of the image plane of the package is shown in Fig. 1. With use of this software package, the heel and toe of every step of all pedestrians were manually marked by two researchers. An Intra Class correlation test showed a non-significant difference between these researchers ($R = 0.996$, $p < 0.01$). After marking the heels and toes, a perspective correction was performed. The software made it possible to, with use of the 1 by 1-meter chalked square, transform the footage in such a way that the route of the pedestrians was displayed as viewed from above (Figs. 2 and 3). Because the validity of this software package is not confirmed yet, the outcomes were compared to outcomes found in other studies to increase reliability.

2.3. Data processing

The footage and x- and y-coordinates of the heel and toe of all the marked feet were used to calculate six variables derived from placement of the feet in the horizontal plane, referred to as foot placement variables, needed for analyzing the data. This included two independent variables; time and curvature, and four dependent variables; step length, stride length, relative foot angle and step width. Frame numbers of the footage (filmed at 30 fps), were used to calculate the variable ‘time’ (t in seconds). Higher values of the time in seconds correspond to further progression in the curve. ‘Curvature’ was extracted from the walked path (CURV in 1/m), defined as CURV = 1/radius. For this variable, the radius of the walked path was calculated as: radius = arch-length/angle in which arch-length was the travelled distance of three steps (the previous step, the current step and the next step) and the angle was the travelled angle of these three steps. The extraction of the four dependent variables is graphically represented in Fig. 2. ‘Step length’ is defined as the distance between the heels of the inner and the outer leg. ‘Stride length’ is the distance between the heels of two steps of the same leg. ‘Relative foot angle’ represents the angle the foot makes towards the absolute stride angle of the opposite foot. ‘Step width’ is the distance between the heels of the inner and outer leg, perpendicular to the step. For the full calculations of all variables, see Attachment 1 in Supplementary material. All steps were labelled as being an inner leg step when the step was made by the leg at the side that was in the direction of the curve. The remaining steps were labelled as outer leg steps.

2.4. Data analysis

The data analysis was conducted with SPSS. Outliers originating from marking errors due to impeded complete vision on a step, were removed from the data. Additionally, every first and last step of the analyzed videos were removed from data analysis but were used for calculating the variable outcomes for consecutive steps. For the remaining steps, two separate analyses were performed. Because the variables in the subgroups were normally distributed, parametric tests were conducted. For comparing the inner and outer leg and to prevent alfa inflation, a MANOVA, with the Pillai’s Trace for multivariate testing, was performed. The between-subjects factors that are included in the analysis are leg, with the categories inner and outer leg, and subject, with the subject numbers as categories. Pearson correlations for time and curvature were checked for the four foot placement variables. By this, the relationship between the foot placement variables and the

Fig. 1. Image plane of the MovieProcessing package. The marked footprints show the walked trajectory of participant four. The purple square shows the perspective correction. The red footprints correspond to the right foot and the green footprints to the left foot (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

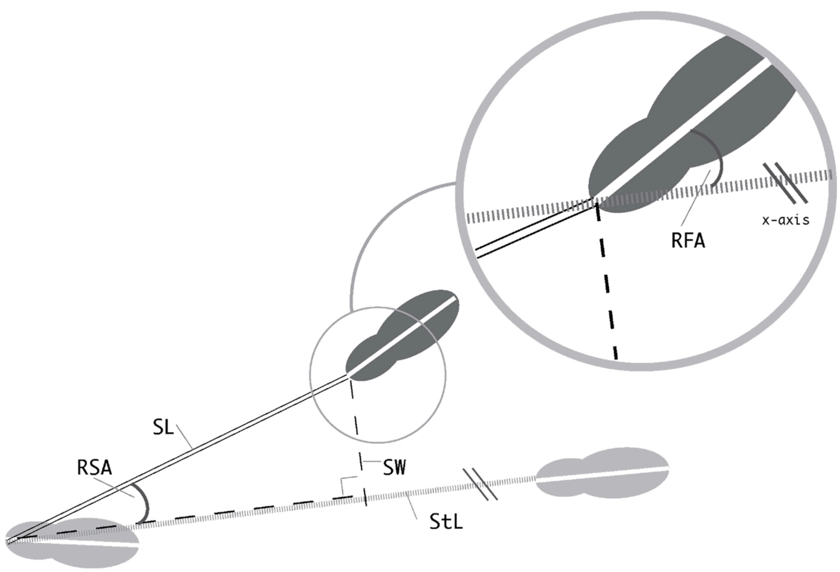

Fig. 2. Representation of the marked feet. The axis represents the distance in meters.
The figure includes a graphical explanation of the extraction of the parameters.
Step length (SL), stride length (StL), step width (SW), relative foot angle (RFA) and relative step angle (RSA).

independent continuous variables time and curvature was investigated.

3. Results

A MANOVA was used to compare the inner and outer leg for the different gait parameters. The full results of the MANOVA are reported in Table 1.

The multivariate test shows a significance for the main effect subject (Pillai's Trace = 1.295, $F(80, 1024) = 6.126$, $p < .001$), for the main effect leg (Pillai's Trace = .192, $F(4, 253) = 15.031$, $p < .001$), and for the interaction leg*subject (Pillai's Trace = .643, $F(80, 1024) = 2.454$, $p < .001$). Out of the four variables that were looked into, two variables, i.e. step length and stride length, did not show significance for the univariate tests of the interaction leg*subject. Based on the interaction leg*subject, the step width of the inner leg ($M = 0.06$, $SD = 0.05$) was significantly different from the step width of the outer leg ($M = 0.10$, $SD = 0.06$, $F(20, 256) = 3.577$, $p < .001$) and the RFA of the inner leg ($M = 11.72$, $SD = 7.92$) was significantly different from the RFA of the outer leg ($M = 11.30$, $SD = 8.07$, $F(20, 256) = 4.542$, $p < .001$). The four variables differ all significantly between subjects.

An overview of the Pearson correlation test results is reported in Table 2. Pearson correlations show a small positive linear, but significant correlation between the step width and curvature ($r = 0.28$, $p < 0.01$) for both legs pooled. A high positive linear and significant correlation was found between curvature and step width for the outer leg ($r = 0.64$, $p < 0.01$). Additionally, a Pearson correlation showed a small correlation between the relative foot angle and time for the inner leg ($r = -.25$, $p < .01$) and the outer leg ($r = 0.21$, $p < 0.01$). A small, but significant correlation was found between curvature and stride length ($r=-.13$, $p = 0.025$) for both legs pooled.

4. Discussion

This study investigated foot placement variables in a natural environment during walking a curve. Foot placement variables in the inner and outer leg were compared. As suggested in the majority of previous

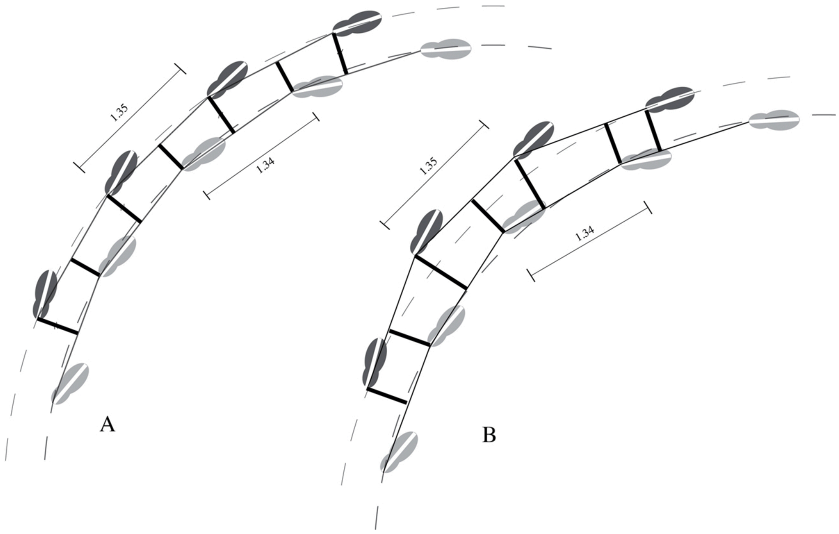

Fig. 3. A. Geometrical approach of curve walking, while remaining the average step width of the inner leg and the outer leg constant. The stride length of the outer leg needs to be larger than the stride length of the inner leg to perform curve walking. B. Schematic view of curve walking as found in the current study. Step width changes over time and increases with increasing curvature, mainly for the outer leg.

Table 1
Mean and SD of the gait parameters for all steps, steps of the inner leg and steps of the outer leg, and the results of the MANOVA (N = 326).

	Both legs			Inner leg			Outer leg		
Step length (in m)	317	0.68	0.11	168	0.67	0.11	149	0.68	0.10
Stride length (in m)	301	1.34	0.20	160	1.34	0.20	141	1.35	0.20
Step width (in m)[a]	313	0.08	0.06	166	0.06**	0.05	147	0.10**	0.06
RFA (in degrees)[a,b]	323	11.51	7.99	173	11.72**	7.92	150	11.30**	8.07

[a] The results from the MANOVA show a significant result for the main effect subject (Pillai's Trace = 1.295, $F(80, 1024) = 6.126$, $p < .001$), for the main effect leg (Pillai's Trace = .192, $F(4, 253) = 15.031$, $p < .001$) and a significant result for the interaction leg*subject (Pillai's Trace = .643, $F(80, 1024) = 2.454$, $p < .001$). A significant difference was found for the interaction leg*subject for step width ($F(20, 256) = 3.577$ $p < .001$), and relative foot angle ($F(20, 256) = 4.542$, $p < .001$), tested with a MANOVA (two-tailed, $\alpha = .05$).
[b] RFA = relative foot angle.
** $p < 0.001$.

Table 2
Pearson correlation coefficients (r) between time and curvature, and the gait parameters extracted from curve walking data for both legs, the inner leg and the outer leg (N = 326).

	Both legs			Inner leg			Outer leg		
	N	Time	Curvature	N	Time	Curvature	N	Time	Curvature
Step length (in m)	317	0.011	−0.063	168	0.029	−0.064	149	−0.015	−0.073
Stride length (in m)	301	−0.005	−.130*	160	−0.026	−0.114	141	0.019	−0.153
Step width (in m)	313	0.076	.276**	166	0.113	−0.099	147	0.031	.636**
RFA (in degrees)[a]	323	−0.045	−0.044	173	−.254**	−0.075	150	.213**	0.004

[a] RFA = relative foot angle.
* $p < 0.05$.
** $p < 0.01$.

research, significant differences in for example step length between the inner and outer leg could be expected [1–5]. However, the MANOVA showed no significant differences in stride length and step length of the inner and outer leg. In contrast, a significant difference between the inner and outer leg was found for the step width. Additionally, a significant difference between the inner and outer leg was found for the relative foot angle. Pearson correlation shows a correlation between the curvature and step width for both legs pooled and the outer leg, as well as a relation between time and RFA in the inner leg and outer leg.

Combining these results suggests a non-symmetrical change of walking parameters when curvature changes. Especially changes in step width stand out in the results of this research. To find an explanation for the outcomes, a theoretical geometrical analysis was conducted. Walking on trajectories with various radii was simulated using Matlab, while keeping foot placement variables constant. This simulation revealed that geometrically speaking, the stride length of the outer leg should be larger than the stride length of the inner leg, if step width is not zero, since the inner and outer leg walk on trajectories with different radii, as shown in Fig. 3A. However, the results found in this research reveal that, in an ecological setting, curve walking does not appear that way (Fig. 3B). Stride lengths of the inner and outer leg did not differ significantly. This may be due to the large radius of the curve the subjects were walking (seven meters), but supports the symmetrical findings of Akiyama et al. [7].

In previous curve walking research, significant differences in step and stride length are often reported without reporting changes in step width [1–3]. Fig. 3A shows that curve walking indeed is geometrically possible when step widths are equal but stride length differs significantly. However, in this study, stride length does not differ significantly, while step width does, suggesting that pedestrians choose to increase their step width during curve walking. A graphical representation of the strategy found in this research is suggested in Fig. 3B. This strategy cannot be explained by geometry but is by choice of the pedestrian. This observation may have a link with balance control which may be slightly compromised by walking a curve [14–16]. Pedestrians might have developed the habit of increasing the base of support during curve walking, anticipating a possible change of angular velocity, regardless of the radius of the curve, but this is speculation.

Findings of changes in variables over time correspond to finding of earlier research [4,5]. The correlation found between time and RFA for the inner leg suggests that the inner foot is turned into the curve at the start of the trajectory and after that gradually comes back to the walking direction. In contrast, the small relative foot angle in the outer leg increases at the start of the curve until it is in line with the new direction (Fig. 3B). These changes in foot angles were mentioned in previous research where side step strategies were found. Moreover, rotation of the legs, together with rotation of the torso and head, have been found to initiate curve walking [10,15]. The inner foot is secured in line with the new direction and maintains this orientation while progressing through the curve. This causes the found large relative foot angle of the inner foot before starting the curve and allows it to slowly be reduced through the curve. Another stepping strategy defined in previous research is the crossover technique [5,7]. Pedestrians using this technique narrow their base of support before the curve by reducing the step width. Swinging the outer leg around the inner leg causes a small relative foot angle of the outer leg. The outcomes of different curve walking strategies could have influenced the total outcomes, causing correlations to be significant and explainable, but low. Nevertheless, pre-positioning parts of the body when initiating curve walking is not a new finding. The head and eyes are anticipating changes in angular direction and stabilize gaze into the curve [10,14,15]. Future research is needed to prove whether different initiation strategies actually exist and depend on curvature.

The present research with its measurements in a community setting has offered some new data on curve walking, opening new questions on the topic. However, measurements are less accurate and it limits the number of variables that can be measured. An advantage of the methods is its low-cost and by its nature is easy to implement anywhere in a natural environment without interfering with the behaviour of the subjects, and therefore capture the 'real' natural gait of pedestrians for analysis. A major finding in this way of investigating is that in an ecological environment, foot placement variables change in every step, for several steps during curve walking, showing that walking curves is gradual and not imposed.

5. Conclusion

Research with video-analysis based software has given new insights in changes of foot placement variables during curve walking. Foot placement variables, like the relative foot angle and step width, change gradually during curve walking. It is concluded that curve walking in a natural condition shows a gradual change of outcomes in several steps, while it is not symmetrical with respect to the inner and outer leg. These changes are not physically needed for curve walking, therefore this might suggest the possibility of choice. Subsequently, direction related changes in foot angles were found. The inventive way of data collection formed a base for future research in pedestrian walking in natural conditions. Further research is needed to extend the knowledge on curve walking, which has several applications in human movement research.

Declaration of Competing Interest

The authors report no declarations of interest.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.gaitpost.2021.03.017.

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