Human collision avoidance behavior against autonomous mobile robot

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Highlights

- Human avoidance strategies against a robot approaching head-on were examined.
- The avoidance direction was not simply determined by the participants' attributes.
- Humans used different avoidance strategies when facing other humans and objects.
- The human waist provides an indicator to predict the avoidance direction.

Abstract

Background: As urban development toward smart cities continues in earnest, pedestrians' chances of encountering autonomous mobile robots (AMRs) on the street increase. Although recent studies have discussed how humans avoid collisions with others when passing them, it is still unclear how they would avoid AMRs, which could be common on the streets soon.

Research question: We investigated humans' avoidance strategy against an AMR approaching head-on through an experiment that included recording human-body motions while walking.

Method: The AMR approached from various starting points, including directly from the participants. The participants were asked to circumvent it by moving rightward or leftward while their walking trajectories were tracked.

Result: We found no significant bias on either side, suggesting that the avoidance direction is not simply determined by the participants' attributes, such as the traffic rules followed in their area of living. The probability of rightward avoidance when the AMR approached head-on indicated that the humans had different avoidance strategy when facing other humans and objects. Moreover, the participants' motion analysis revealed that their waists unconsciously twisted in the direction of avoidance before they circumvented.

Significance: The results suggest that the human-waist provides an indicator to predict the avoidance direction. Our findings could be adopted in AMRs' development to fit them more naturally into our lives.

Keywords: Collision avoidance; autonomous mobile robot; avoidance behavior; human walking

Introduction

Humans employ suitable approaches to circumvent a static obstacle, such as a barrier [1,2] or two poles [3,4]. Other people, i.e., a type of obstacle, frequently walk into our surroundings and form a dynamic environment [5]. Many studies have discussed how humans avoid such dynamic obstacles approaching from an orthogonal direction [6,7] and passing each other [8,9]. However, there are few studies on collision avoidance against autonomous mobile robots (AMRs), which may potentially become common dynamic obstacles in the coming years.

Nowadays, the frequency of meeting AMRs, used for logistics, has increased on the streets because governments and companies are actively promoting urban development toward smart cities [10–12]. The AMRs run along a planned delivery route to be quick. However, they must also be safe for pedestrians, even in complex situations [13]. Thus, several studies in robotics engineering utilized human-like behavior to develop robots that are safer and friendlier to use [14–17]. For example, Kamezaki verified control methods in which a robot guided or gave way to humans depending on the situation, based on the estimation of a positional relationship between the human and robot [16]. The study reported that humans preferred to avoid a robot with a mutual concession, rather than either one entirely giving way. These findings suggest the importance of such human-like control in the robots, which positively influences the humans' impressions.

As a result, recent studies have focused on understanding human behavior during walking with an AMR, from the perspective of cognitive science. For example, Vassallo et al. reported that humans gave way to the AMR even though they had a chance to go first [18]. In addition, their avoidance strategies varied depending on the target (human or AMR). Following this, the same group revealed that the human behavior for the AMR was similar to that for other humans when the AMR replicated human avoidance strategy [19]. These findings provided insight into the benefits of the studies involving human walking and AMR. However, these studies only tested the situation of crossing in the orthogonal direction. Thus, it is still unclear how humans avoid the AMR while passing each other when forced to choose an avoidance direction for safety.

Therefore, this study aims to understand the avoidance strategy used by humans against AMRs approaching head-on; specifically, we examine whether humans prefer to lean on a specific side (right or left). In this respect, Souza Silva et al. tested how humans avoid another human and a cylindrical object approaching head-on in the virtual environment [8]. The findings revealed that humans predominantly avoided other humans by moving rightward (right: 75% vs. left: 25%), but there was no bias in the case of the cylindrical object (55% vs. 45%). This suggests that humans changed their avoidance strategy depending on the target. Based on this, we verified whether humans' avoidance strategies for AMRs resembled those for other humans or objects.

Moreover, we tested how the humans' avoidance direction was determined in such a situation. A previous study suggested that humans' tendency to avoid collisions by moving rightward occurred due to a cognitive bias derived from traffic rules associated with right-side driving [8]. If so, people who lived under the other-sided traffic rules would behave differently. We assumed that it would be hard to decide the avoidance direction quickly in an unusual experience, such as when an uncommon object is approaching. Thus, we conceived how humans dealt with AMRs by computing the avoidance probability when an AMR approached as an obstacle. We hypothesized that humans predominantly avoided collisions by moving to a specific side when they considered the AMR as a human, or otherwise, a non-biological object.

We used a real AMR as the obstacle and recruited human participants living in an area under the left-sided traffic rule. We expected that using a physical AMR would realistically elicit human behavior similar to the actual situation without limiting the field of view often associated with virtual reality [3,8,9,20,21]. Specifically, we ran an experiment to verify how humans avoid the AMR approaching from five directions, including head-on. Simultaneously, a motion tracker system estimated their walking trajectories. Furthermore, we verified whether any indexes could be derived from the human body movement to predict the avoidance direction.

Materials and Methods

Participants

Sixteen students (one woman; average age of 22.9 ± 0.7) at Toyohashi University of Technology participated in this experiment. All participants declared right-handedness themselves; the average hand preference was 9.1±1.9 as assessed by the Flinders Handedness Survey (FLANDERS) questionnaire [22,23]. All experimental protocols were approved by the institutional review board of Toyohashi University of Technology for involving human participants in the experiments following the Declaration of Helsinki. Written informed consent was obtained from all participants for the publication of their details.

Apparatus

Control system for AMR: We used a custom-made wheeled platform (Mega Rover Ver 2.1, Vstone) as an AMR (see **Figure 1A**). The outside measurement of the AMR was 460 mm in length, 320 mm in width, and 800 mm in height. A computer located on the AMR controlled two motors connected to its wheels. Another computer set up in the experiment room received signals from a tracking system (mentioned below) and sent them to the computer on the AMR via Wi-Fi. The Robot Operating System (ROS) Melodic with Ubuntu 18.04 LTS controlled both computers.

Tracking system: To measure the participants' motions, they were asked to wear five motion trackers (VIVE Tracker 3.0, HTC) on their waists, wrists, and ankles. The AMR had one tracker at the top of its front (see **Figures 1A and 1B**). A computer tracking system (Windows 10) communicated with those trackers controlled by Unity (2020.3.20f1), Steam VR (1.20.4), and Steam VR Unity Plugin (v2.7.3; SDK 1.14.15). The tracking system detected the positions and rotations of each body part with a 90 Hz sampling frequency in a play area defined by four base stations (Steam VR Base Station 2.0) in the experiment room.

Environment: Figure 1B shows an experimental environment in this study. A goal position was 5 m straight away from the start position from which the participants began to walk. A theoretical point of collision (TPC) with the AMR was set at 3 m away from the starting point of the participants. The initial positions of the AMR were 1.5 m away from the TPC with five different angles (-40,-20, 0, 20, and 40 degrees).

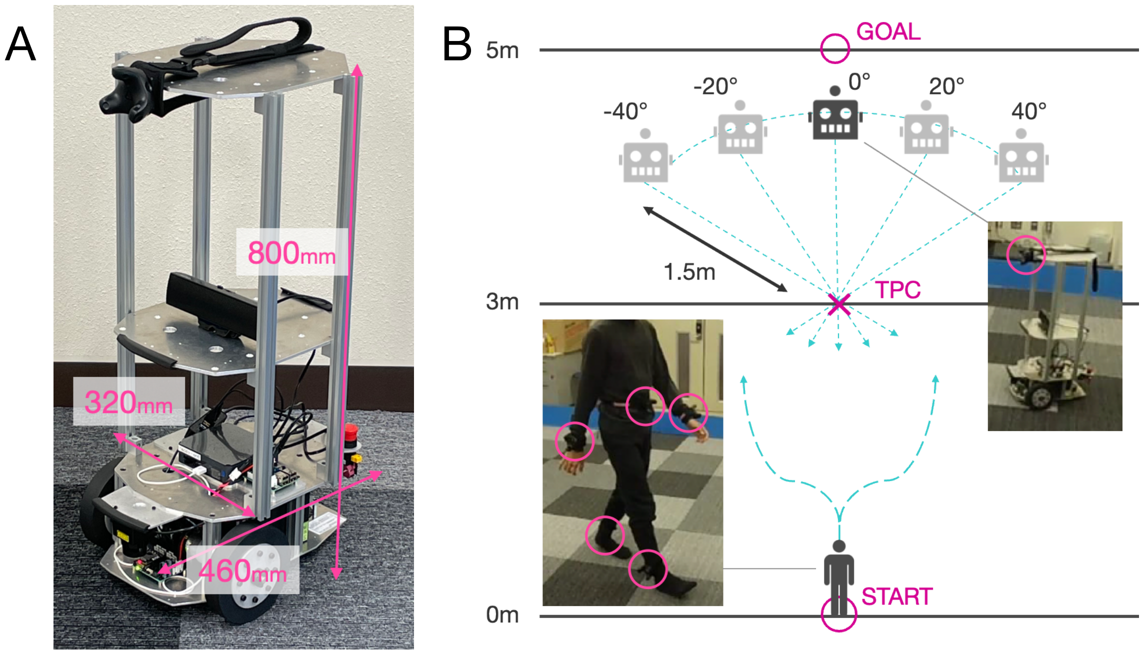

Figure 1. Experimental setup (A) The AMR in the experiment. (B) Illustration of the environment. The participants moved from the start towards the goal. Note that the ratio of distances used in this panel differed from the actual ratio used in the study.

Procedure and task

First, the AMR randomly traveled to one of the five initial positions. Then, the AMR beeped from its speaker as a cue to start a trial. Subsequently, the participant began to walk from the start to the goal at a comfortable speed. When the participant took a step, the AMR moved straight toward the TPC at a constant speed of 0.5 m/s. One trial finished when the AMR went until 3 m from the start position, and the participant and AMR returned to their initial positions.

The participants were asked to circumvent right or left during walking to avoid a collision with the AMR. Regarding how to avoid collisions, they were instructed that 1) they should not circumvent extremely to result in an inefficient route toward the goal, 2) they should not rapidly change the walking direction as a feint, and 3) they should circumvent as they would do usually with a comfortable speed. Before the experiment, we informed the participants about 1) the possibility of the AMR approaching from any of its initial points, 2) the sequence of one trial, and 3) the number of trials in the experiment. No other instructions were given that could affect their behavior. We ran 50 trials (ten trials × five angles) in a random order for each participant.

Data analysis

For the analysis, we defined an interval's beginning as the time when the AMR beeped and its ending as the time when the participant completed walking straight for 5 m or rotated more than 90 degrees on either side, whichever was earlier. We excluded trials exceeding 20 s as artifacts (corresponding to 1.5% of all trials) and two trials in which the trackers provided exceptional values due to a hardware issue. The average trial time for the participants was 14.14 ± 0.40 s. Then, we normalized the trial time from second to percentage (0–100%).

In each trial, we estimated a walking trajectory using the 3D coordinates of the participants' heads in space provided by the tracker from the waist of the participants. Then, we computed the probability of rightward avoidance. The criterion was which direction had a larger change in the mediolateral (ML) displacement at the TPC (i.e., the position where the participants reached after walking straight for 3 m). The average walking speed was estimated by the distance and time of the interval in which the participants walked between 1 m and 3 m in an anteroposterior (AP) direction to exclude an acceleration period [8].

Using the Palamedes toolbox, a psychometric function was fitted for the probabilities of rightward avoidance in five angles with threshold and slope as free parameters [24,25]. When those probabilities formed a step function, we fitted them with threshold as the only free parameter (corresponding to four participants). We had to exclude one participant from the analysis because we could not fit the psychometric function properly, and the data of fifteen participants were used for further analysis. To quantitatively estimate the participants' bias for an ML direction, we computed the point of subjective equality (PSE) in each case, as an index of their bias for circumventing right or left.

Results

Human avoidance behavior

Figure 2A shows the average walking trajectory in each avoidance direction. Participants in all trials succeeded in avoiding collision with the AMR, circumvented symmetrically, and kept away from the TPC. The participants' average walking speed was 0.51 ± 0.04 m/s, and the minimum distance to the AMR was 0.66 ± 0.18 m.

Figure 2B shows the distribution of the PSEs, indicating the directions in which the participants circumvented with fitted individual curves. The average PSE was -3.47±14.43 degrees (vertical red line in **Figure 2B**), and there was no significant difference from zero ($t(14) = -0.93$, p = 0.37, CI = [-11.46, 4.52]). Specifically, the nine left-avoided people had smaller absolute values of the PSE and variances compared to the six right-avoided persons. Thus, these findings suggest that the participants did not have any biases in the ML direction. In other words, each avoidance direction was different depending on the participants.

A similar "no-bias" trend appeared when the AMR approached head-on (0 degrees; see green circle in **Figure 2C**), showing that the average probability of rightward avoidance was 0.43 ± 0.28. However, this was composed of avoidance directions with a considerable variance depending on the participants (**Figure 2D**). This suggests precise predictions of avoidance directions are difficult to make with only the position data when humans and the AMR pass each other.

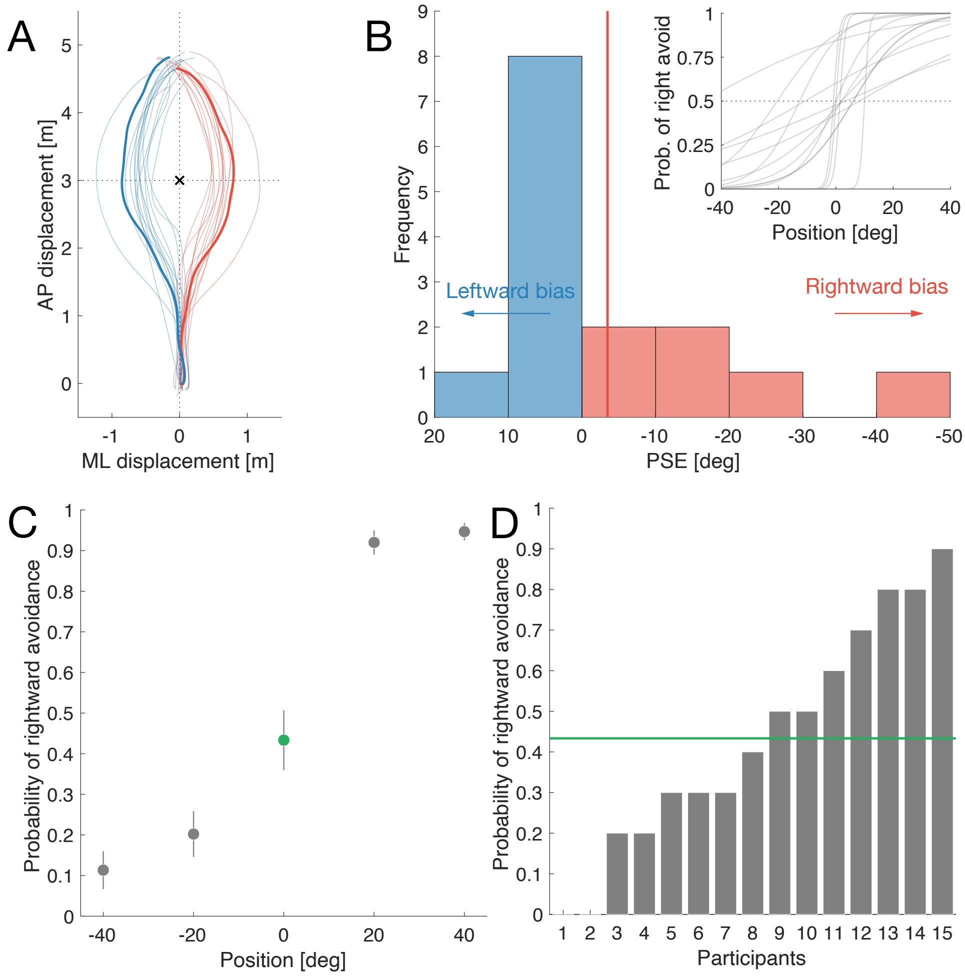

Figure 2. Human avoidance behavior (A) Walking trajectory. The horizontal and vertical axes indicate ML and AP displacements, respectively. The lines represent the walking trajectories (red: rightward avoidance, blue: leftward avoidance) on average (thick) and for each participant (thin). The black cross shows the location of the TPC. (B) Histogram of the PSEs among the participants. The horizontal axis indicates PSEs; negative values indicate rightward avoidance. The number of participants with rightward and leftward avoidance was six (red) and nine (blue), respectively. The red vertical line represents the average PSE (-3.47 degrees). The image in the top right corner illustrates fitted individual curves to estimate the PSEs. (C) Average probability of rightward avoidance (the vertical axis) at the AMR's initial positions (the horizontal axis). Error bars represent the standard error of the mean. (D) Probabilities of rightward avoidance for each participant (the horizontal axis) in the head-on direction. The vertical axis is the same as in C. The green horizontal line represents the average (the same as zero degrees in C).

Motion analysis

We attempted to find cues to predict the avoidance direction elicited by human behavior. If it could be predicted in advance and if that knowledge was applied to control the AMRs, it would be possible for humans to circumvent it in safer, smoother, and more comfortable ways. Thus, we proposed a method to predict the avoidance direction based on the positions and rotations measured by the trackers. We assumed that humans twisted their waists in the preferred direction before they started circumventing. Therefore, we focused on the waist angle as an apparent cue, which common sensors could measure.

We compared the 1) rotating angle and 2) ML displacement from the waist tracker. First, we computed changes in those two indexes for each avoidance direction through a time course. **Figure 3A** shows that the participants' average rotating angle (top) peaked faster than the ML displacement (bottom). This finding indicates that humans' waists sufficiently twist towards their target direction before their bodies move to circumvent it. Next, we quantitatively compared the onset times of deviating from straight walking to either side. Specifically, the onset times were defined as waist twists over 13.6 degrees [26] and moves exceeding 0.25 m in ML displacement [8,27]. **Figures 3B** and **3C** show that the waists significantly twisted before moving (right: $t(14) = 3.46$, $p < 0.005$, CI = [1.70, 7.24], $d = 0.89$; left: $t(14) = 4.19$, $p < 0.001$, CI = [4.58, 14.21], $d = 1.08$). Thus, these findings suggest that humans twist their waists earlier than the displacement towards the direction of circumventing.

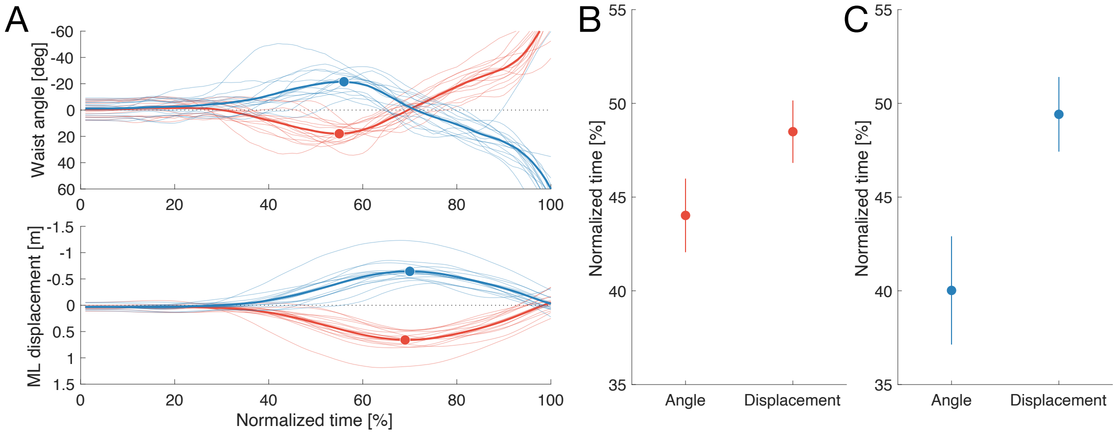

Figure 3. Motion analysis (A) Changes in rotating angle and ML displacement at the waist. The horizontal axis indicates the normalized time between the beginning and end of trials. The vertical axis indicates the waist angle (the top) and the ML displacement (the bottom). The other format is the same as in **Figure 2A**. (B) Comparison of the onset times between rotating angle and ML displacement in the case of rightward avoidance. Error bars represent the standard error of the mean. (C) This panel is the same as B, except for the avoidance direction. Asterisks indicate statistically significant differences in the *t*-test; *** $p < 0.005$, **** $p < 0.001$.

Discussion

This study tested how humans avoided an AMR approaching from several directions by recording their motions. In **Figure 2A**, the participants' walking trajectories represented the same trends as found in the previous studies [8,9]. This finding suggests that humans' avoidance trajectory is robust, regardless of the target attribute. In contrast, the average walking speed was slower (0.51 m/s) than reported in the previous studies, suggesting that the participants would carefully behave with caution to reduce the risk of collision [28]. Moreover, the speeds of humans and the AMR were close, and this similarity indicated that humans' walking would synchronize, using the internal motor control, with the AMR's locomotion perceived through sight [29]. At the same time, the minimum distance to the AMR was shorter (0.66 m). One interpretation is that the participants were simply affected by the interferer's (AMR's) size because it was smaller than them [30]. An alternative perspective is that such movements could lead to approaching closer to the AMR. Thus, we suggest, depending on this disengaging psychological state, to keep a safety distance greater than the larger avoidance distance between real and virtual environments [9].

We found no significant bias on both sides, and it varied for each participant based on the ease of circumvention (**Figure 2B**). Souza Silva et al. suggested that participants' bias for rightward avoidance was influenced by the right-sided traffic rule, which was adapted in the area they lived in [8]. By contrast, our results did not indicate such bias, though participants slightly preferred to avoid leftward (the probability of rightward direction was 43%) affected by the traffic rule. Hence, this implies that various factors, including social rules, may determine our circumvention strategy.

In addition, our findings were similar to those of the study of humans avoiding the cylindrical object in the virtual environment [8]. In other words, comparing different targets (humans and the AMR) indicated that the human avoidance strategy differed between humans and objects as targets [18]. This suggests that humans employ the object avoidance strategy against AMR.

Importantly, our findings showed that predicting the direction of avoidance was hard when the AMR approached head-on.

The participants twisted their waists before the ML displacement (**Figures 3A** and **3B**), suggesting that humans unconsciously twist their waists in a direction they would like to circumvent. This indicator from the human body would work as a factor in determining the avoidance direction. In previous studies, for example, it was found that an involuntary waist rotation by the Hanger Reflex changed the walking direction [31,32]. This means that twisting the waist prior to moving may play an essential role in determining the walking direction without the use of intention or spontaneous action. Thus, we suggest the importance of focusing on the angle of humans' waist.

Similarly, it has been revealed that a signal from the body part, such as gaze, becomes a cue to predict the avoidance direction [33–35]. For example, the gaze direction of the person who approaches head-on affects a moving trajectory [34]. It means that although humans guess the direction of a facing person, they gaze at the facing person as a signal to indicate their directions and vice versa. Similarly, humans' shoulder rotation would become an index to point out the passability of apertures [4], but head rotation is not associated with the walking direction [36]. Taken together, our findings suggest that humans' avoidance direction can be predicted by their body direction before they move.

Although we only focused on waist movement to predict the avoidance direction, it would be possible to predict the avoidance direction more precisely by analyzing other motions, such as the movements of wrists and ankles, because motion and gait features also work as indicators for recognizing disorders [37]. A recent study reported that paying attention to a person's landing foot during walking indicated the predictability of their avoidance direction [15]. Thus, we expect that a difference in the avoidance direction derived from the individuals would be determined by various factors (i.e., each part of the body).

Further studies using additional signals would solve these challenges. It is important to explore how and in what context humans employ the avoidance strategy and move. Based on our findings, we suggest that if the AMR detects the rotating angle of the facing person's waist, the human and the AMR could more smoothly pass each other. Furthermore, the avoidance probability or distance may change when we provide more "human-like" features to the AMR. For example, although this study used a simple wheeled AMR, changing the AMR's appearance to mimic a human would influence human behavior positively. Similarly, in terms of actions, the AMR's bowing when passing an individual would trigger a human-to-human behavior from the individual. Thus, these approaches could fill a gap between humans and AMRs and help to develop the AMR for a more friendly use.

Conclusion

In summary, we clarified the avoidance direction of humans against a passing AMR. There was no significant bias between rightward and leftward avoidance, and we suggest that the employed strategy was to deal with the AMR as an approaching object rather than a human. In addition, our findings revealed that humans twisted their waist in advance to the direction in which they moved. Further studies are required to find other indicators from the human body against the approaching AMR to ensure a safer environment, and those findings would provide support to develop the AMRs for smart cities.

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Conflict of Interests

The authors declare no competing interests.