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Minimal predicted distance: A common metric for collision avoidance during pairwise interactions between walkers

Anne-Hélène Olivier [a,b,*], Antoine Marin [a], Armel Crétual [a], Julien Pettré [b]

[a] Laboratoire Mouvement Sport Santé (M2S), UFRAPS, Université Rennes 2-ENS Cachan, Avenue Charles Tillon, CS24414, 35044 Rennes, France
[b] INRIA, Centre de Rennes Bretagne Atlantique, Campus Universitaire de Beaulieu, 263 avenue du Général Leclerc, 35042 Rennes, France

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ABSTRACT

This study investigated collision avoidance between two walkers by focusing on the conditions that lead to avoidance manoeuvres in locomotor trajectories. Following the hypothesis of a reciprocal interaction, we suggested a mutual variable as a continuous function of the two walkers' states, denoted minimum predicted distance (*MPD*). This function predicts the risk of collision, and its evolution over time captures the motion adaptations performed by the walkers. By groups of two, 30 walkers were assigned locomotion tasks which lead to potential collisions. Results showed that walkers adapted their motions only when required, i.e., when *MPD* is too low (<1 m). We concluded that walkers are able (i) to accurately estimate their reciprocal distance at the time the crossing will occur, and (ii) to mutually adapt this distance. Furthermore, the study of *MPD* evolution showed three successive phases in the avoidance interaction: observation where $MPD(t)$ is constant, reaction where $MPD(t)$ increases to acceptable values by adapting locomotion and regulation where $MPD(t)$ reaches a plateau and slightly decreases. This final phase demonstrates that collision avoidance is actually performed with anticipation. Future work would consist in inspecting individual motion adaptations and relating them with the variations of *MPD*.

1. Introduction

When two humans walk in the same proximity, each can be considered as a moving obstacle for the other one. Such a situation occurs during everyday life activities such as walking in the streets. There is a fundamental difference between the avoidance of a non-human moving obstacle and the avoidance of human moving obstacles. The situation, in essence, is reciprocal: each walker is avoiding the other one while being avoided at the same time.

Previous studies have focused on the locomotion trajectory of a walker confronted with static or passive moving obstacles. Studies have mainly described the adaptation made to step over [1–3] or to circumvent [4] static obstacles. The extension to passive moving obstacles in a few studies has shown that walkers adapt their trajectories along both the anteroposterior and mediolateral axes to avoid a mannequin with a predefined trajectory [5–7]. The observed clearance area, also known as personal space, was modelled as an ellipse which dimensions depend on the level of attention required by the task [5]. In another study, Fajen and Warren [8] proposed to model interactions between a walker and the environment as a pair of coupled dynamic systems. Authors proposed to adapt heading according to the distance and the angle between the walker and stationary goals and obstacles. This model was extended to the avoidance of moving obstacles [9–11]. Following a vector–field interaction model in which goals represent attractors and obstacles represent repellors, the path of the walker was computed at each instant as the resultant of all forces applied to him/her. To the best of our knowledge, no study has considered the avoidance behavior between two human walkers. Two-human interactions have however been investigated by considering interpersonal coordination [12–14]. Ducourant et al. [12] focused on two participants (a leader and a follower) placed face to face and moving forwards and backwards. Results showed the presence of coordination mechanisms that depend on leadership and distance between people. This study provides an understanding of the interaction mechanisms during walking. However, trajectories were highly constrained and the nature of interactions between walkers was very specific. Compared to previous studies, our objective was to investigate collision avoidance between two human walkers. The main question was to identify the conditions that lead to avoidance manoeuvres in locomotor trajectories: what are the relations between the respective positions and velocities which yield motion adaptations? Based on the assumption of a reciprocal interaction, we

* Corresponding author at: INRIA, Centre de Rennes Bretagne Atlantique, Campus Universitaire de Beaulieu, 263 avenue du Général Leclerc, 35042 Rennes, France. Tel.: +33 2 99 84 71 38.
E-mail addresses: anne-helene.olivier@inria.fr (A.-H. Olivier), antoine.marin@univ-rennes2.fr (A. Marin), armel.cretual@univ-rennes2.fr (A. Crétual), julien.pettre@inria.fr (J. Pettré).

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suggested a mutual variable, common to both walkers, the minimum predicted distance (*MPD*), which (i) predicts potential collisions and (ii) describes the mechanism of collision avoidance over time in three successive phases.

2. Methods

2.1. Participants

Thirty participants (11 women and 19 men) volunteered for this experiment. They had no known vestibular or neurological pathology which would affect their locomotion. Participants gave written and informed consent before their inclusion and the study conformed to the Declaration of Helsinki. They were 26.1 years old ($\pm$6.9) (mean $\pm$ S.D.) and 1.74 m tall ($\pm$0.09).

2.2. Experimental protocol and apparatus

A 15 m edge square was used for the experiments. In pairs of two, starting from corners not sharing the same diagonal, participants were instructed to reach the opposite corner without restriction on gait or path. Interaction was mainly based on visual information: participants were not allowed to speak during the experiment and they walked barefoot or with socks on a carpet to avoid anticipation through auditory clues.

Participants waited for a start signal displayed on a computer screen placed on their right at each corner of the area. By synchronizing the two start signals, we provoked situations of potential collisions on orthogonal trajectories. The variability in natural speeds and reaction times actually changed the exact kinematic conditions of interactions, thereby allowing us to study their influence. The presence of occluding walls (2 m high by 3 m long) between corners (Fig. 1A and B) prevented participants from seeing each other before reaching their natural speeds. More precisely, there were six participants in a session located at the four corners of the area, but only two of them were actually given a start signal. This prevented walkers from anticipating who they would interact with and from which side he/she would come. 420 trials were performed.

2.3. Analysis

3D kinematic data were recorded using 12 Vicon MX-40 cameras (Oxford Metrics®) at a sampling rate of 120 Hz. Reconstruction and labeling were performed using Vicon IQ software and computations using Matlab (Mathworks®). We approximated participant's motions by using the middle point between their shoulders (two reflective markers were attached to participants acromions). The present study focused on the overall duration of the interaction between two walkers which lasted in average 4.1 s ($\pm$0.5). The higher frequency stepping oscillations were averaged out by applying a butterworth low-pass filter (dual-pass, third order, 0.5 Hz cut-off frequency) on mid-shoulder positions. Velocity was computed as the discrete time derivative of the mid-shoulder position in the horizontal plane.

2.3.1. Temporal segmentation

Experimental conditions prevented participants from seeing each other before they reached their natural speeds. By analyzing the geometry of occluding walls and the position of participants, we derived the time at which participants first saw each other (denoted '*tsee*'). They had orthogonal and convergent trajectories: they reached a minimum distance between them (clearance distance denoted '*dmin*') and we measured the time '*tcross*' at which *dmin* occurred (Fig. 1C). Crossing was considered as a relative concept in space (*dmin*) and time (*tcross*) between participants. We then focused on the analysis of the portion of data between *tsee* and *tcross*, given that interaction would occur during this period. We performed a temporal normalization of all trials between *tsee* (0%) and *tcross* (100%) to enable comparison.

2.3.2. Minimal predicted distance

We introduced and based our analysis on the minimal predicted distance (*MPD*): at each instant *t*, $MPD(t)$ represents the distance at which participants would meet if they did not perform motion adaptation after this instant *t*. Distance, being a mutual variable, appears relevant to describe reciprocal interactions. This distance was strictly positive since measured between the middle of the shoulders of each walker. When assuming that no motion adaption was performed, we can model future trajectories of walkers as linear extrapolations of their current states. For example, the trajectory of participant #1 was predicted by $P_{\text{pred},1}(t, u)$ as follows:

$$P_{\text{pred},1}(t,u) = P_1(t) + (u - t)V_1(t) \qquad (1)$$

where u is a time parameter, $P_1(t)$ the current position and $V_1(t)$ the current velocity vector of participant #1.

MPD is thus formulated by computing the minimum distance between predicted positions $P_{\text{pred},1}$ and $P_{\text{pred},2}$ (Fig. 2A) reached by participants #1 and #2:

$$MPD(t) = \underset{u}{\operatorname{argmin}} \| P_{\text{pred},2}(t,u) - P_{\text{pred},1}(t,u) \| \qquad (2)$$

Eq. (2) can be solved as the argument of the minimum of a second degree polynomial. If a positive solution is found ($u > 0$), trajectories are converging; if a

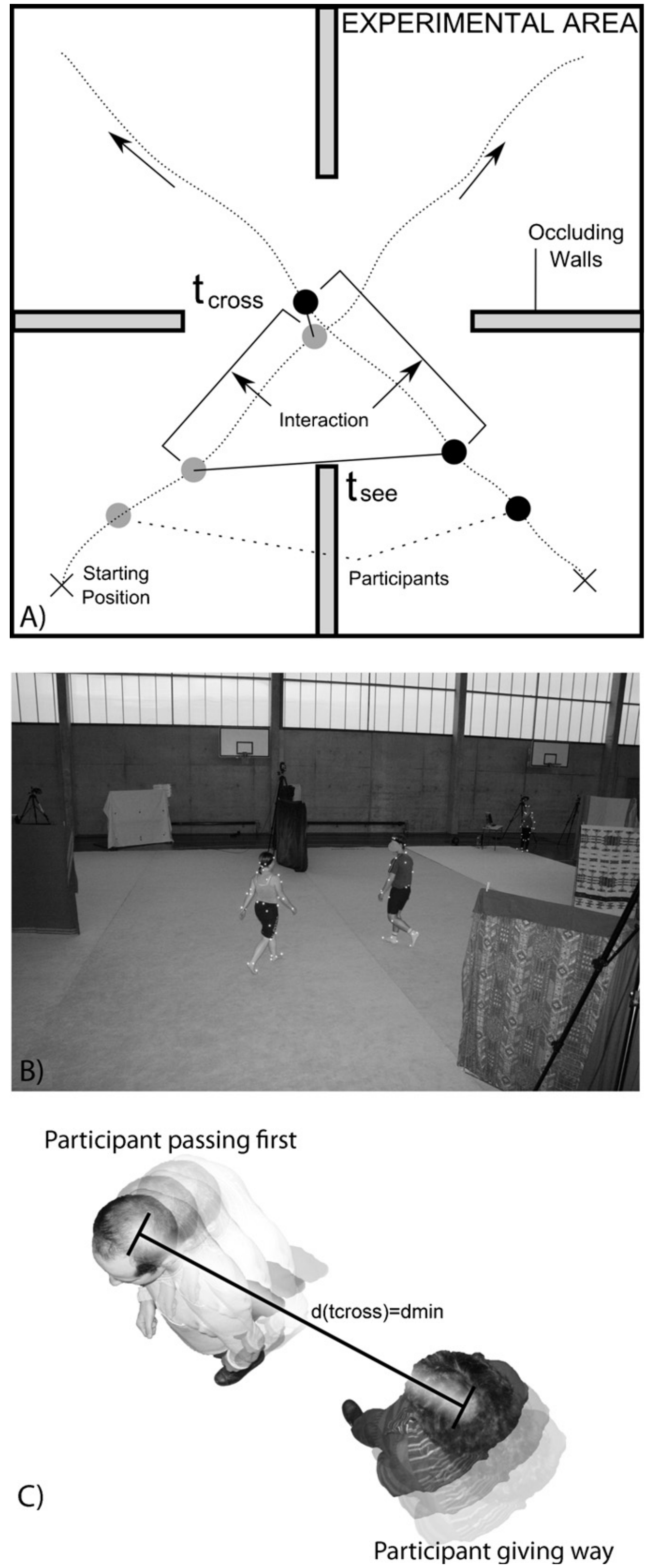

Fig. 1. (A) Experimental setup. Area is 15 m $\times$ 15 m. Two participants stand at the corners of the area and are synchronously given a start signal. Their task is to walk to the opposite corner. They implicitly start an interaction to avoid any collision. (B) Picture taken during experiment. (C) *tcross* is the time when the distance between walkers is minimal.

negative solution is found ($u < 0$), they are diverging; finally, if a null solution is found ($u = 0$), trajectories have actually reached their point of minimal distance. Indeed:

$$MPD(tcross) = d\min \quad (3)$$

dmin cannot be lower than a threshold distance considered to be admissible by participants and which needs to be precisely investigated. Nevertheless, we hypothesized its definition as a combination of contact distance (i.e., no collision between body envelopes) and social distance as suggested by previous studies on personal space preservation [5,15].

MPD is a prediction of *dmin* given current position and velocity of walkers. *MPD* varies if and only if motion adaptations are performed (Fig. 2B). We hypothesized that motion adaptations are linked to the admissibility of future clearance distance.

2.3.3. Statistics

Statistics were performed using Statistica (StatSoft®). The data were presented with mean and standard deviations. All effects were reported at $p < 0.05$. Wilcoxon signed-rank tests were used to determine differences between values of *MPD* at various instants.

3. Results

No collision occurred during the experiment and *dmin* was never below 0.41 m. Occluding walls fulfilled their role since participants reached a stable speed at *tsee*, i.e., before interaction. Fig. 3 illustrates a representative 90° crossing (A), the associated instantaneous velocity before *tsee* (B), and *MPD*(t) evolution during interaction (C). In this situation, the initial *MPD* (*MPD*(*tsee*)) is approximately 0.2 m (i.e., a future collision will occur if no adaptation is performed) and increases along the trial to reach 0.8 m at *tcross*.

Throughout all trials, the mean walking speed of participants was 1.57 m s^{-1} (±0.24) during the interaction phase and the mean clearance distance *dmin* was 1.09 m (±0.47) ranging from 0.41 to 3.48 m. *MPD*(*tsee*) ranged from 0 to 3.81 m (Fig. 4A). To consider the wide variety of *MPD*(*tsee*) values across our experiment, we subdivided the dataset in 10 groups of 42 trials according to

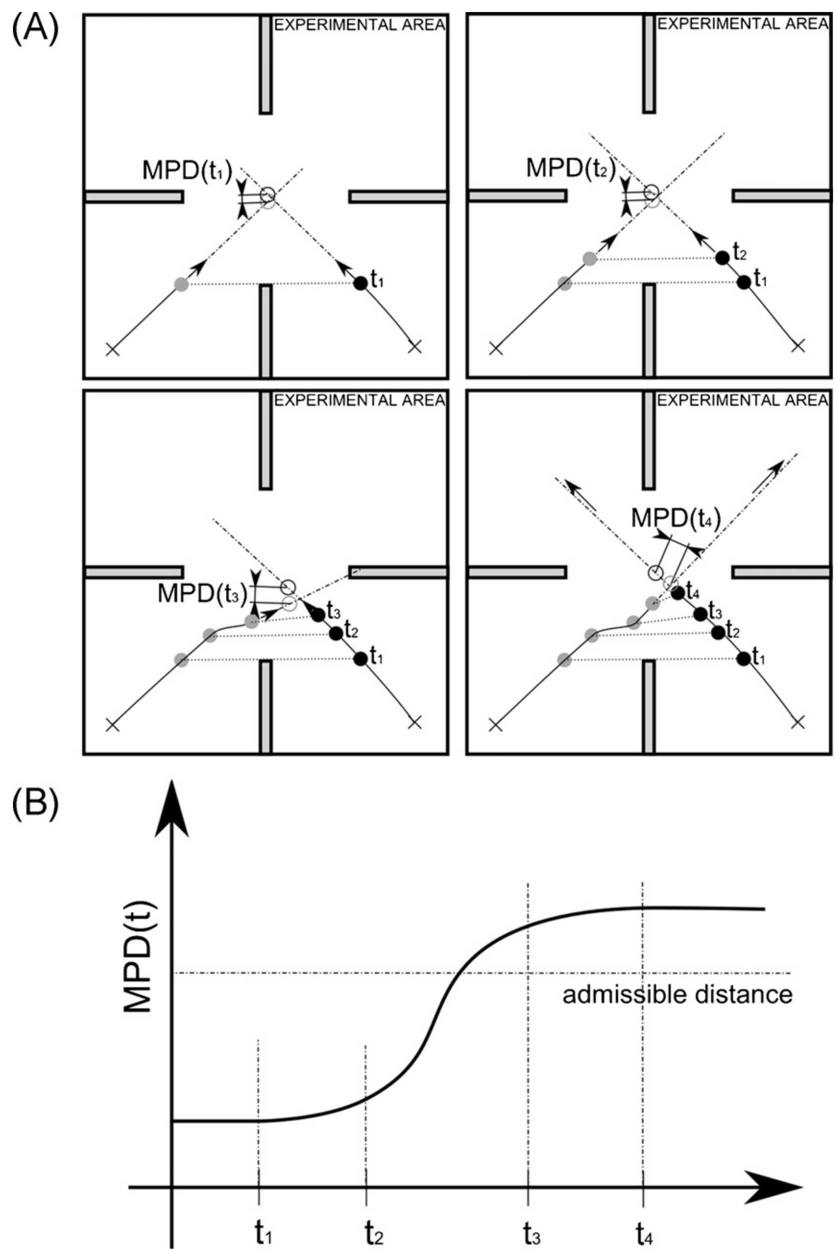

Fig. 2. (A) Schematic illustration of the minimum predicted distance (*MPD*) computed at four different times. A motion adaptation occurs between times $t2$ and $t3$. (B) *MPD*(t) evolution in time. *MPD* values change between $t2$ and $t3$: the increase of *MPD* indicates that motion adaptations were performed. In that case *MPD* was above an admissible distance at crossing.

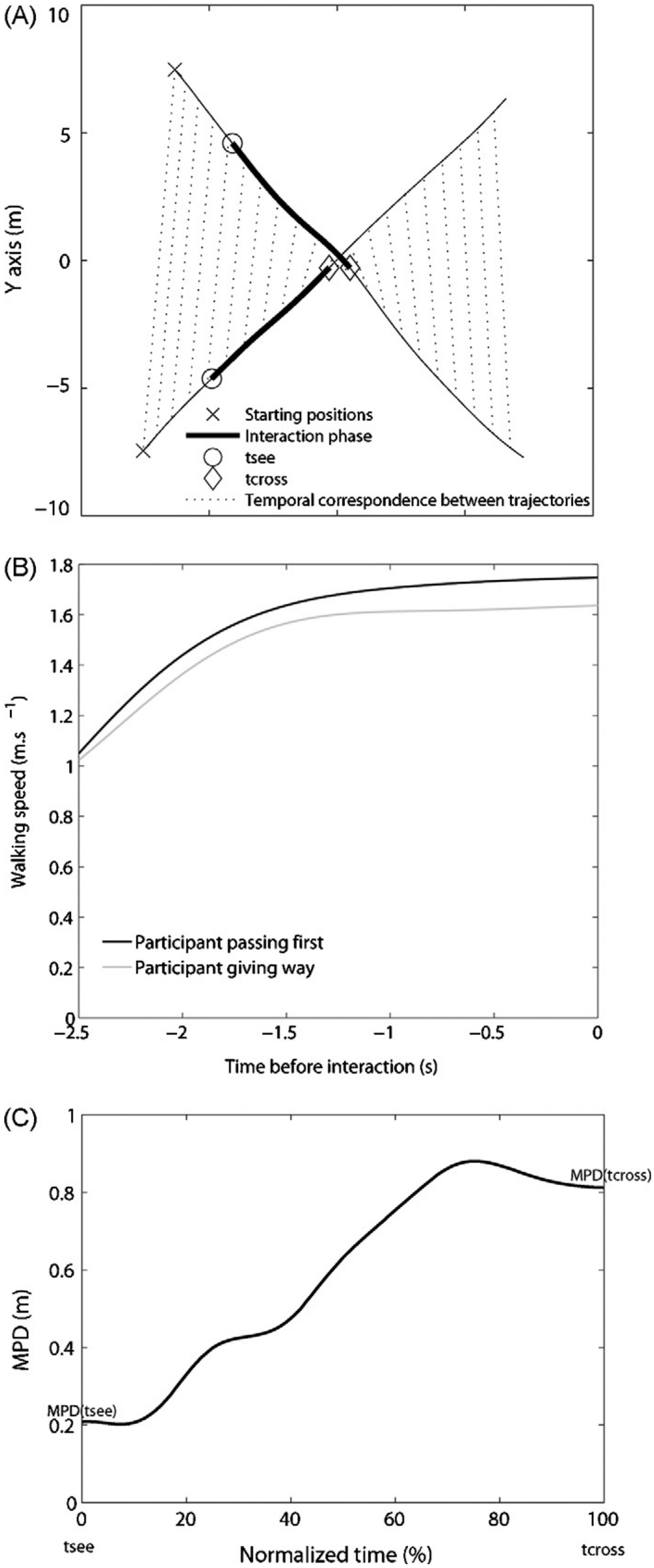

Fig. 3. (A) Participants' trajectories for one 90° crossing. Interaction phase is in bold line. (B) Instantaneous walking speed for both participants before *tsee*: they reach a stable speed before interaction. (C) *MPD*(t) evolution during the interaction phase.

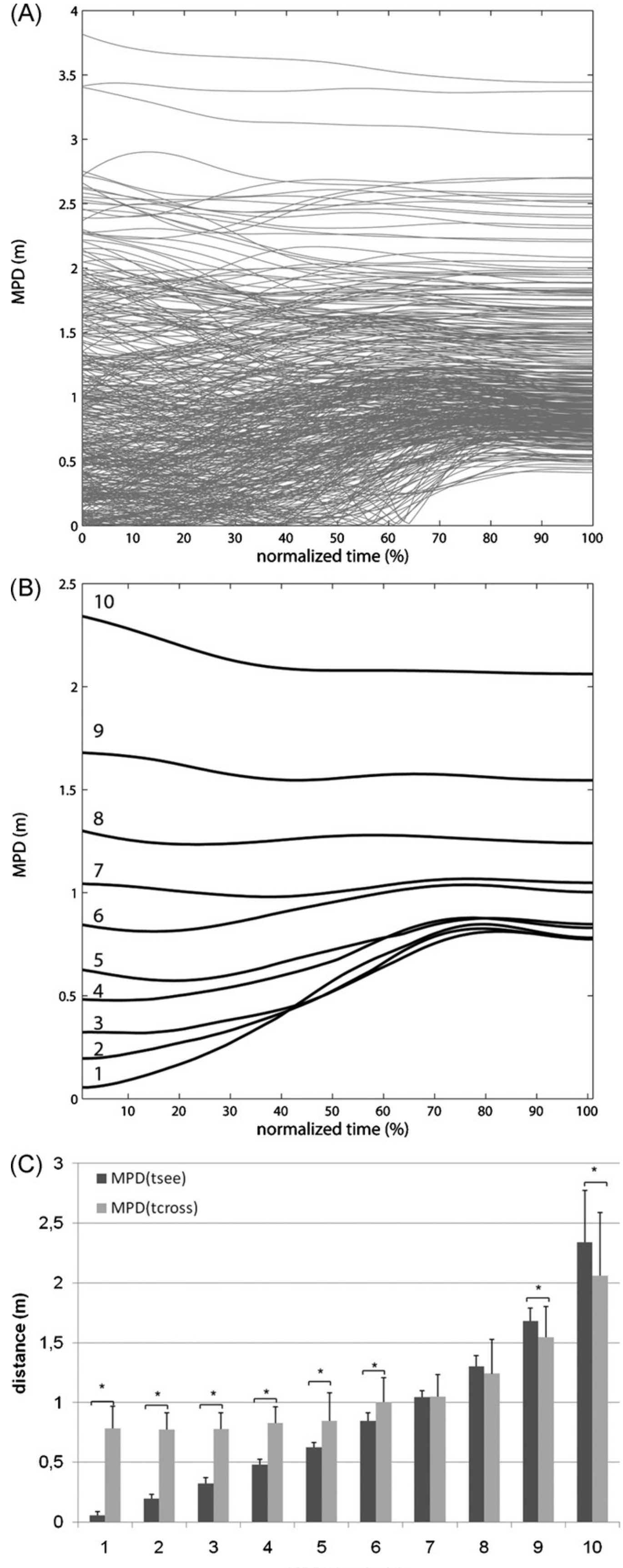

Fig. 4. (A) *MPD*(t) evolution for each of the 420 trials during the interaction phase. (B) Mean $\overline{MPD}(t)$ evolution for 10 groups of ascending *MPD*(*tsee*) values. (C) Mean values of *MPD*(*tsee*) and *MPD*(*tcross*) for each of the 10 groups.

ascending *MPD*(*tsee*) values. For each group, we computed $\overline{MPD}(t)$, the mean *MPD* evolution along the interaction phase (Fig. 4B). When $\overline{MPD}(tsee)$ is lower than 1 m (groups 1–6), the set of *MPD*(*tcross*) values for each group (see Fig. 4C) is significantly higher than *MPD*(*tsee*) (respectively, Wilcoxon signed-rank tests results were $T_1 = 0$, $T_2 = 0$, $T_3 = 0$, $T_4 = 0$, $T_5 = 72$, $T_6 = 125$; $df = 41$, $p < 0.01$). When $\overline{MPD}(tsee)$ ranges from 1 to 1.5 m, there is no significant difference between the sets of *MPD*(*tcross*) and *MPD*(*tsee*) ($p > 0.05$). When $\overline{MPD}(tsee)$ is higher than 1.5 m, *MPD*(*tcross*) is significantly smaller than *MPD*(*tsee*) (respectively, $T_9 = 208$, $T_{10} = 56$; $df = 41$, $p < 0.05$).

Results showed that walkers adapted their trajectories to increase *MPD*(t) when *MPD*(*tsee*) was lower than 1 m. For all these trials, we computed the overall mean $\overline{MPD}(t)$ and its time derivative (Fig. 5A and B). We then considered three successive phases in time with respect to the value of the time derivative $\overline{MPD}'(t)$. The first phase, to which we referred to as the observation phase, was between normalized time *t*0% and *t*7%, for which $\overline{MPD}'(t)$ was negative. Note that we still considered $\overline{MPD}(t)$ to be constant during the observation phase with respect to Wilcoxon signed-rank tests ($MPD(t0\%) = 0.44 \pm 0.28$, $MPD(t7\%) = 0.44 \pm 0.28$, $p > 0.05$). The second phase, from *t*7% to *t*79%, was called the reaction phase: $\overline{MPD}'(t)$ was positive and $\overline{MPD}(t)$ significantly increased up to 0.88 ± 0.22 m ($T = 258$, $df = 263$, $p < 0.01$). Finally, the third phase, from *t*79% to *t*100%, was called the regulation phase: $\overline{MPD}'(t)$ was negative again and $\overline{MPD}(t)$ slightly decreased to $dmin = 0.84 \pm 0.19$ m, ranging from 0.41 to 1.48 m ($T = -4648$, $df = 263$, $p < 0.01$). The mean trial duration was 4.1 s (± 0.5). Therefore, these three periods of time respectively lasted about 0.3 s, 3 s and 0.8 s.

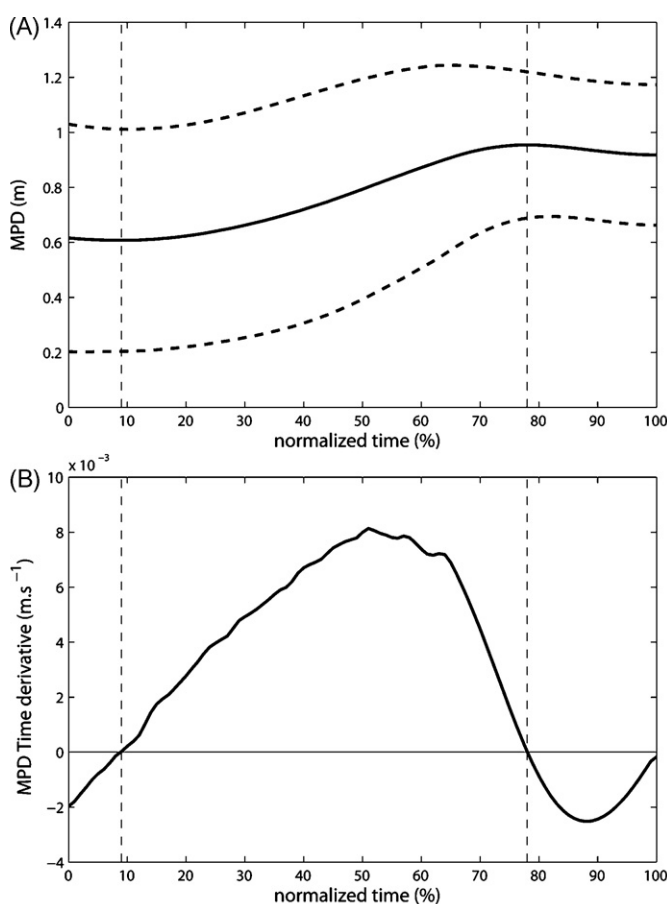

Fig. 5. Mean $\overline{MPD}(t)$ evolution ($\pm$S.D.) (A) and its time derivative (B) for all trials for which *MPD*(*tsee*) is below 1 m. Interaction follows three successive phases: observation, reaction and regulation phases.

4. Discussion

We experimentally examined interactions between two participants avoiding each other. We then considered *MPD* as well as its variations as kinematic clues to represent interaction. Finally, we described collision avoidance as a three-phases process.

MPD(t) is a predictive variable which is defined as the distance walkers would meet if no adaptation to their trajectories was performed. *MPD*(t) varies in time if and only if locomotion is adapted by one or both walkers. An experimental setup allowed us to observe changing initial conditions of *MPD*(*tsee*). By grouping trials according to *MPD*(*tsee*) thresholds, typical behaviors were observed. When *MPD*(*tsee*) is below 1 m, participants avoid a future collision by increasing this distance to reach an admissible value at *tcross*. When *MPD*(*tsee*) is between 1 m and 1.5 m, no adaptation is performed and when *MPD*(*tsee*) is above 1.5 m, participants even take the liberty of decreasing *MPD*(t).

Based on the analysis of initial and final values of *MPD*, our general conclusion is that this variable is adapted only when required. Walkers are able to accurately estimate future crossing distance and to mutually adapt this distance. This result can be linked to the notion of personal space during collision avoidance between a walker and a mannequin mounted on an overhanging rail [5]. In our situation, the need to adapt trajectories is then revealed by *MPD*(*tsee*). This mutual metric reveals the presence of motion adaptations, but does not relate individual collision avoidance strategies. Indeed, it was previously shown that walkers adapt their heading [8] or their heading and walking speed [5–7] to avoid a moving obstacle. Future work is then required to determine the nature of individual trajectory adaptations. Moreover, the locomotor path generated by the behavioral dynamic model [8] depended on the angle and the distance between the walker and the goals and obstacles. It would then be interesting to investigate the influence of these parameters on collision avoidance.

MPD(t) also revealed the temporal structure of interactions. In the situation where the interaction requires motion adaptations (*MPD*(*tsee*) < 1 m), we identified three successive phases: observation, reaction, and regulation. Respectively, these phases correspond to periods of time when, first, *MPD*(t) is constant, second, increases to acceptable values by motion adaptation and, third, reaches a plateau and slightly decreases. The observation phase is short. Information about future collision is quickly available. A similar observation was made by Gérin-Lajoie et al. [5] who observed an initial deviation of the trajectory one step after seeing a moving mannequin on a colliding path. The use of eye-trackers in future experiments would be a solution to study more carefully the characteristics of the observation phase as well as its duration in time. Gaze direction would additionally provide a more accurate description of the interaction by detailing visual information taken during the combined goal-directed and avoidance locomotion tasks.

The reaction phase is the longest part of the interaction. Participants adapt their trajectories to increase the future crossing distance and consequently to avoid a collision. There is no hesitation to the way interaction is mutually solved since *MPD*(t) is increasing on average during this period of time. The value reached at the end of this phase is relatively constant (0.88 ± 0.21 m). These two observations show that participants accurately perceive the kinematics of the interaction and adapt their motion with positive effect on the interaction. Adaptation is quite optimal since *MPD*(t) is not exaggeratedly increased at the end of this phase. This reaction phase can be linked to the anticipatory locomotor phase as described by Gérin-Lajoie et al. [5] during avoidance of dynamic obstacles.

Whereas this study analyzed individual adaptations, we focused on *MPD*(t) to illustrate that interactions are mutually solved. This variable does not indicate individual strategies but the effect of their joint combination.

The regulation phase, which starts approximately 0.8 s before crossing, demonstrates anticipation: the collision is solved, and the future crossing distance is maintained. It is even slightly decreased (4 cm). This anticipating behavior is not consistent with Fajen and Warren's model [8] but corroborates the results of other studies [5,16]. Moreover, contrasting with Gérin-Lajoie et al. [5], we did not observe a readjustment phase which increases the mediolateral distance from the obstacle before crossing. In their study, the mannequin was passive (i.e., with a linear trajectory), and therefore, the walker was not expecting any reaction. In our study, we considered interactions between two humans: they could expect a sharing of the effort to adapt trajectories, but with uncertainty about the other's attitude. This can explain that collision avoidance is solved 0.8 s in advance, close to the duration of a stride. This period may be associated with the one-stride interval related by Patla [17], which is sufficient to successfully implement adaptive strategies.

In conclusion, this study proposed a new metric, *MPD*(t), to investigate collision avoidance between two walkers. *MPD*(t) was defined as the prediction at each instant of the future crossing distance. Results showed that walkers adapt their motion only when required (when *MPD* is too low) with anticipation (existence of the regulation phase). Future work will investigate the nature and the quantity of individual adaptations necessary to solve interactions. The crossing order would be an important parameter since at the crossing point, the participant giving way views the other participant in front of him/her, and the participant passing first has the second one to his/her side or back. This asymmetric configuration emphasizes on asymmetric strategies for collision avoidance. Indeed, personal space may have an elliptic shape [5]. Therefore, collision risk should be perceived as being higher when the walker to avoid is in front compared to the side (see Fig. 1C). *MPD* is a relevant parameter to conduct such an analysis. First, *MPD* reveals the effect of individual reactions on the interaction, and second, the partial derivative of *MPD* with respect to each walkers speed and heading reveals the contribution of each participant manoeuvre to the evolution of *MPD*.

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Conflict of interest statement

None.

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