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Standing Balance Recovery Strategies of Young Adults in a Densely Populated Environment Following External Perturbations

Thomas Chatagnon^a, Sina Feldmann^b, Juliane Adrian^b, Anne-Helene Olivier^a, Charles Pontonnier^a, Ludovic Hoyet^a, Julien Pettre^a

^aUniv Rennes Inria CNRS IRISA M2S France

^bInstitute for Advanced Simulation 7: Civil Safety Research Forschungszentrum Juelich Juelich Germany

Abstract

The recovery strategies used by young adults to maintain standing balance following external force-controlled perturbations in densely populated group formations was investigated in this work. In particular, the moment of step initiation as well and the characteristics of the first recovery steps and hand-raising were studied here. The experimental data considered in this work are part of a larger dataset relying on a new experimental paradigm inspired by Feldmann and Adrian (2023). In this experiment, 20 participants (8 females, 12 males, 24.8 ± 3.7 yo) equipped with motion capture suits were asked to stand in tightly packed formation before receiving a force-controlled perturbation. In total, four group configurations and two interpersonal distancing conditions have been investigated here. The standing balance recovery strategies observed in this *dense groups experiment* were then compared with the observed behaviour of single individuals following external perturbations (Chatagnon et al., 2023). Results suggest that the moment of initiation for recovery steps was affected by the initial interpersonal distancing conditions. The first recovery steps within the studied dense groups were observed to be slower, smaller and more dispersed than those of single individuals for comparable level of perturbation intensity. However, the relationship between the average speed of first recovery steps and the length of these steps remained similar to the one of single individuals. This suggests that the first recovery step duration remained almost constant during both the *dense groups experiment* and the experiment with single individuals. Finally, we observed a significant occurrence of participants raising their hands, as physical interactions played an important role in this *dense groups experiment*. This behaviour was mainly observed to be initiated before recovery steps.

Keywords: Standing Balance, Recovery Strategies, Dense Crowds, External Perturbations

1. Introduction

Mass events are home of extraordinary dense crowds which sporadically turned into deadly disasters (Rahman et al., 2017; Sieben and Seyfried, 2023). Such situations can cause people in the crowd to lose their balance and fall on top of each other (Zhou et al., 2017). Standing balance in dense crowds is a key element to understand such risks. We propose here an experimental study of balance recovery in the context of dense crowds. In particular, we investigated the stepping recovery strategies, the step characteristics and hand raising initiation of individuals following external force-controlled perturbations in a context of dense crowds.

We define dense crowds in this study as tightly packed formations of individuals in which the motion of a considered individual is limited and likely to result in physical interactions with other individuals. As dense crowds yield potentially deadly situations, modelling of such phenomenon remains a hot topic for safety science. However, such environment may be quite challenging for people in crowds, with many external perturbations arising from different directions and limited available ground to perform stepping recovery strategies. For these reasons even state of the art dense crowd simulations (van Toll et al., 2021; Wang et al., 2023; Li et al., 2023) do not take into account balance recovery, or use simplistic rules to cover the complexity of standing balance in such environment (Kim et al., 2015).

The lack of consideration of balance recovery in dense crowds is associated with a lack of experimental data to use as ground truth for these models. To our knowledge, most experimental studies of such crowds have focused on the static load (Wang and Weng, 2018; Wang et al., 2020) and external forces (Li et al., 2020) experienced by individuals in dense formations. These studies were carried out as asphyxia and fainting due to chest compression appeared to be one of the main causes of death in dense crowds (DeAngelo et al., 1998; Kroll et al., 2017; Sieben and Seyfried, 2023).

Therefore, the risks of falling in dense crowds and balance recovery strategies in dense crowds remain unclear. One can highlight the recent suggestion of a "human domino" model (Wang et al., 2019) as a first approach to introduce standing balance for crowd modelling. However, this model remains limited as the stepping strategies are highly simplified and it cannot be used for crowds with a staggered organisation of individuals. Recently, the development of commercially available IMMU-based ¹ motion capture solutions has made it possible to capture the full body motion of individuals in group formation (Feldmann and Adrian, 2023). Such a technology was used in the present study to investigate standing balance and stepping strategies in dense group formations.

The standing balance of individuals in a controlled laboratory environment has been studied in detail. In this study we focused on the *Limit of Standing Balance* (LoSB) i.e. the limit beyond which balance cannot be maintained without a *change-in-support* (Maki and McIlroy, 1997), i.e. changing the support surface area, either by stepping or grasping the environment with upper limb movements. This limit was first estimated to be the moment when the ground projection of an individual's *Center of Mass* (CoM) reaches the boundary of the Base of Support (BoS) (Shumway-Cook and Woollacott, 1995; Winter, 1995). The BoS is defined as the enclosed area containing every contact points of an individual with the ground. For a single standing individual, the BoS is the enclosed surface containing both feet.

This first estimation of the LoSB was then improved by taking into account the velocity of the CoM (Hof et al., 2005; Schulz et al., 2006). This allowed a better estimation of the LoSB especially for dynamic situations such as following an external perturbation. In the present study the notion of *Time to boundary* has been used to study the LoSB following the methodology developed in Chatagnon et al. (2023).

Regarding step characteristics, several studies focus on the step length and duration of single individuals following external perturbations (Vallee et al., 2015; Zhang and Fu, 2018; Li et al., 2021). To the best of our knowledge, such studies are based on experiments involving only one or two participants at a time. Therefore, step characteristics of individuals in dense crowds remain unexplored. This knowledge gap may, again, be due to the lack of available technologies to study such quantities in dense crowds.

This study reports the results of experiments conducted with young adults in dense group formations. Dense group here refers to groups of 20 to 36 individuals in tightly packed formations designed to replicate dense crowd situations.

In particular, we investigate in this context the *Limit of Standing Balance* (LoSB) and the recovery strategies including the characteristics of the first recovery steps and the initiation of hand raising following sudden external perturbations. Recovery strategies used in this context of dense groups are studied in relation to the interpersonal distancing observed for different group formations.

All results are compared with those obtained using data from the single person experiment presented in Chatagnon et al. (2023). In this study, these results are subsequently referred to as stemming from the *experiment with single individuals*.

2. Materials and Methods

2.1. Data Collection

The data used in this study are part of a larger experimental dataset created by recording the full body motion and tracking the head trajectory of 80 people throughout a variety of push-recovery activities in dense group formations. These experiments received ethical approval from the University of Wuppertal in April 2022 (Reference: *MS/AE 220330*) and all participants signed an informed consent form relative to the

¹Technology based on *Inertial and Magnetic Measurement Units*.

processing of their data. These experiments have been directed by the Institute for Advanced Simulation, IAS-7: Civil Safety Research of the Forschungszentrum Jülich. The work presented here results from a collaboration which took place in the frame of the CrowdDNA H2020 European research project. The complete dataset and full description of the experiment can be found in Feldmann et al. (2024)

Many parameters were varied during the experiment, including the number of participants, the spatial configurations of the groups, the level of awareness of the upcoming perturbation, and the interpersonal distances between participants. In this study, a trial refers to a single push-recovery cycle of an entire group of participants. Out of the 27 group configurations tested during the experiment we selected here trials from four different group configurations. Specifically, we selected a line configuration (4A11) and three packed configurations with different relative position of neighbours (4B55, 4C55, 4D-) as illustrated in Fig. 1. The selected trials were composed of the same participants, only the spatial configuration changed between the conditions. The interpersonal distance between participants was either null (i.e. direct physical contact between participants) or set to one *Elbow Distance*.

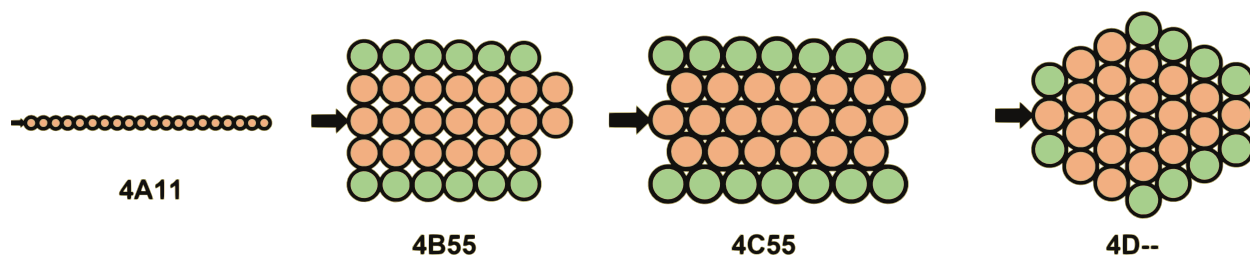


Figure 1: Representation of the selected group configurations. Participants wearing motion capture suits are represented by orange discs. Additional participants at the boundaries (without motion capture suits) are represented by green discs. The external perturbation location and direction is represented by the black arrow.

All participants were facing the same direction at the beginning of each trial. Participants had no prior indication about the upcoming perturbations, and they were asked, before each trial, to recite the alphabet backwards in a quiet voice. The perturbation could happen at any time during this period. Perturbations were manually delivered using a hanging punching bag in the anteroposterior direction at shoulder height on the back of rearmost participant (see Fig. 2).

For each trial, the motions of twenty participants (8 females, 12 males) were recorded using Xsens MVN Link suites (IMU based motion capture, 240 Hz). The average age, mass and height of the participants were 24.8 ± 3.7 yo, 75.8 ± 14.9 kg and 1.79 ± 0.08 m respectively. All demographic information are available in Table 1. Twelve additional participants were added at the boundaries during the packed configuration trials (see Fig. 1). The trials were also recorded using a top-view video camera (GoPro 9, 25Hz). All participants wore a coloured hat with an attached ArUco code linked to demographic information such as body height and mass.

2.2. Data Processing

2.2.1. Video Recordings

The top-down view recordings of the experiment allowed a clear vision of participants' head trajectories during the experiment. These trajectories were extracted from the video recordings using the PeTrack software from Boltes and Seyfried (2013); Boltes et al. (2021). This software automatically detects the participant's coloured hat and ArUco code and calculates the participant's actual trajectories based on the pixel trajectories of the video recordings (see Fig. 3). To do so the software requires an intrinsic calibration (i.e. correction of the camera lens distortion) and an extrinsic calibration based on measurement of the experimental environment. We were then able to reconstruct the relative head positions of participants during the experiment. We could then compute an approximate local density and interpersonal distance of each participant to their up-front neighbour. Both variables were computed for the initial position, using the first frame of the recordings, before the perturbation occurred.



Figure 2: Picture of the experiment for a group formation close to the 4B55 configuration. In this picture, the group is only composed of participants wearing motion capture suites. For the 4B55 configuration, additional participants without motion capture suites were placed on the side boundaries of the group formation.

Table 1: Demographic details of the considered participants of the dense groups experiment wearing motion capture suits.

Gender	Mass (kg)	Height(m)	Gender	Mass (kg)	Height(m)
Female	81	1.77	Male	67	1.81
Female	56	1.75	Male	75	1.84
Female	56	1.69	Male	120	1.87
Female	77	1.74	Male	87	1.84
Female	65	1.73	Male	84	1.9
Female	60	1.64	Male	87	1.88
Female	65	1.64	Male	75	1.82
Female	87	1.84	Male	69	1.78
Male	69	1.77	Male	89	1.89
Male	64	1.85	Male	82	1.82

The distance to the up-front neighbour was computed relative to the head distance between a considered participant and the closer neighbour up-front. For staggered configuration, by definition, the neighbours up-front were not aligned with the considered participant. In order to be able to compare all trials together, only the distance in the direction of participants' sight was considered. This distance can also be seen as the distance to the up-front row, as illustrated in Fig. 4.

To compute the local density of participants two different methods were used depending on the group configuration. For the single row configuration (4A11), a 1D definition of the density was used. Local density in this condition was computed as the multiplicative inverse of the half interpersonal distances between the considered participant and the direct neighbours (Cao et al., 2016). The definition of density can then be

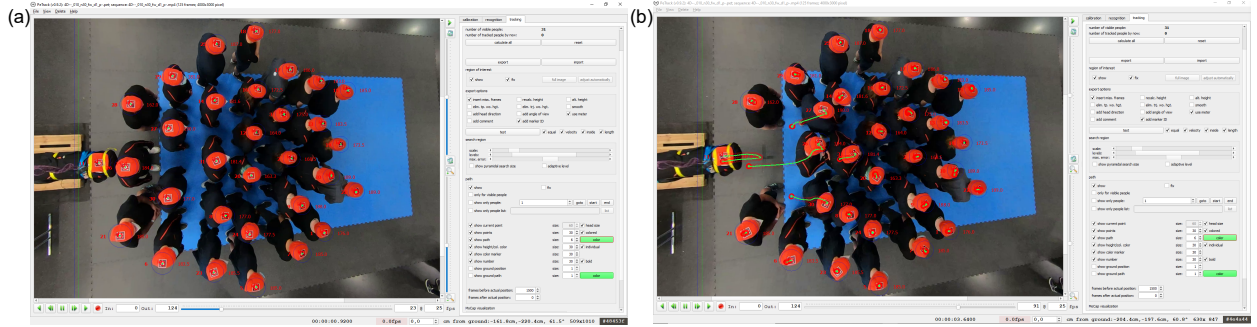


Figure 3: Screenshots of the PeTrack software (Boltes and Seyfried, 2013; Boltes et al., 2021) while processing one of the trial with the 4D- configuration. (a) The head tracking is visible before the external perturbation happened. (b) The head tracking is visible after the perturbation. The green lines represent the tracked head trajectories.

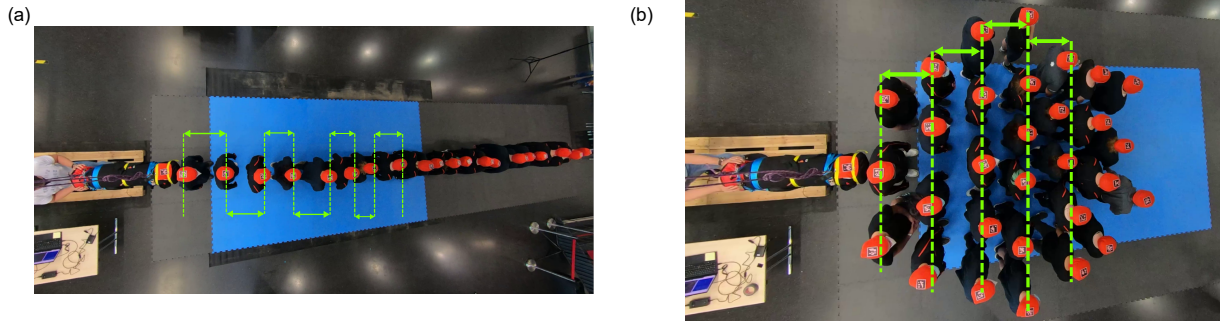


Figure 4: Representation of the interpersonal distance (green arrows) for two representative examples: (a) 4A11, line formation, (b) 4D-, staggered group formation.

expressed as :

$$\rho_i = \max \left\{ \left(\frac{\|X_i - X_{i-1}\|}{2} + \frac{\|X_{i+1} - X_i\|}{2} \right)^{-1}, 1 \right\}, \quad (1)$$

with ρ_i being the local density of the considered participant indexed i and X_i, X_{i+1}, X_{i-1} being the position of the considered participant and the immediate neighbours up-front and behind respectively. For group configurations (4B55, 4C55, 4D-), local density was computed using a method based on Voronoi diagrams called Voronoi density, as in Steffen and Seyfried (2010). These diagrams are created using seeds and composed with cells around the seeds created so that every point within the cell is closer to its seed than to any other seeds (see Fig. 5). To compute the Voronoi density, a diagram is computed using the head positions of participants as seeds. Density is then defined as the multiplicative inverse of the intersecting area of the Voronoi cell and a circle centered on the participant with a $1m^2$ area. This intersection prevents the Voronoi density from falling below one person per square meter for unbounded cells at the edge of the group.

2.2.2. Motion Capture recordings

The classical optical motion capture technique used in Chatagnon et al. (2023) could not be used in a context of dense group due to its high sensitivity to visual occlusion. To solve this matter a method based on *Inertial Measurement Units* (IMUs) was used. This technology does not require any optical information and can thus be used in dense crowds situation. IMUs can measure linear acceleration and angular velocity (using accelerometers and gyroscopes). During the experiment, a commercial solution from Xsens company was used (MVN Link). This solution uses *Inertial and Magnetic Measurement Units* (IMMUs) which improve the accuracy of body segment position estimation (Fang et al., 2018). However, one should keep in mind that systems using these motion capture methods require to be calibrated in order to derive the positions of

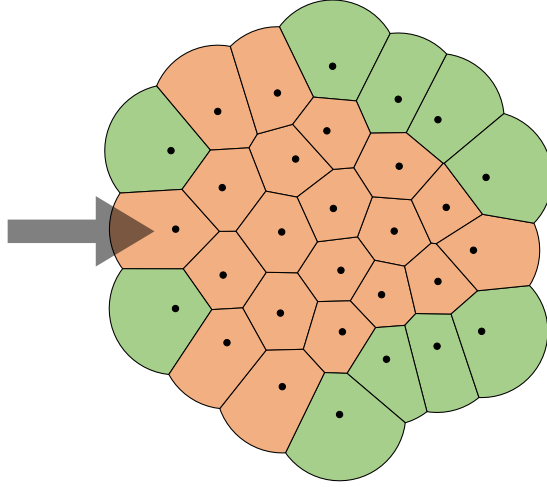


Figure 5: Representation of the Voronoi diagram for using participants initial head positions as seeds (black dots). This example has been created using a trial with the 4D- group formation (also visible in Fig. 3). For participants wearing motion capture suits the Voronoi cells are orange. Cells of additional participants at the boundaries (without motion capture suits) are colored in green. The external perturbation location and direction is represented by the black arrow.

the limbs from the information of the sensors. Thus, only *estimation* of the limbs positions are reconstructed using this technique and reconstruction method relies greatly on the quality of the calibration. This can be problematic if a sensor position on a participant’s body moves during the experiment leading to a drifting of the reconstructed limb position in the recorded data. Here, two calibration protocols were performed before and after the experiments. The ‘N-pose’ protocol described in Schepers et al. (2018) was used for calibration of the motion capture suits. The first calibration recording was used to reconstruct the data and the second recording was kept as a backup and could be used to estimate sensor drift during the experiments.

All biomechanical quantities used in this study are computed following the same method exposed in Chatagnon et al. (2023). We especially use here the *Center of Mass* (CoM), which is the average position of the body mass distribution in space. As in Chatagnon et al. (2023), the CoM was estimated by using inverse kinematics of an osteoarticular model fitted to the filtered reconstructed motion capture data. This computation was performed using the CusToM library (Muller et al., 2019).

The *Base of Support* (BoS) was also used in this study. The BoS is approximated to the enclosed polygon linking all external reconstructed feet markers (see Fig. 6).

Both the CoM and the BoS were then used to study the limit of standing balance using the *Time to Boundary* (Ttb). The Ttb is the time required by the projection of the CoM on the ground to reach the BoS boundary given the current CoM velocity. Ttb is computed as:

$$Ttb = \frac{Dtb}{\|\dot{\mathbf{x}}_{CoM}\|}, \quad (2)$$

$$Dtb = (\mathbf{u}_{max} - \mathbf{x}_{CoM}) \cdot \frac{\dot{\mathbf{x}}_{CoM}}{\|\dot{\mathbf{x}}_{CoM}\|} \quad (3)$$

with the *Distance to boundary* (Dtb) being the oriented distance between the CoM and \mathbf{u}_{max} , the closest point on the BoS boundary in the direction of the CoM velocity. This concept was proposed by Schulz et al. (2006) and appear to be a good criterion to estimate standing balance of a given individual (Emmens et al., 2020; Chatagnon et al., 2023).

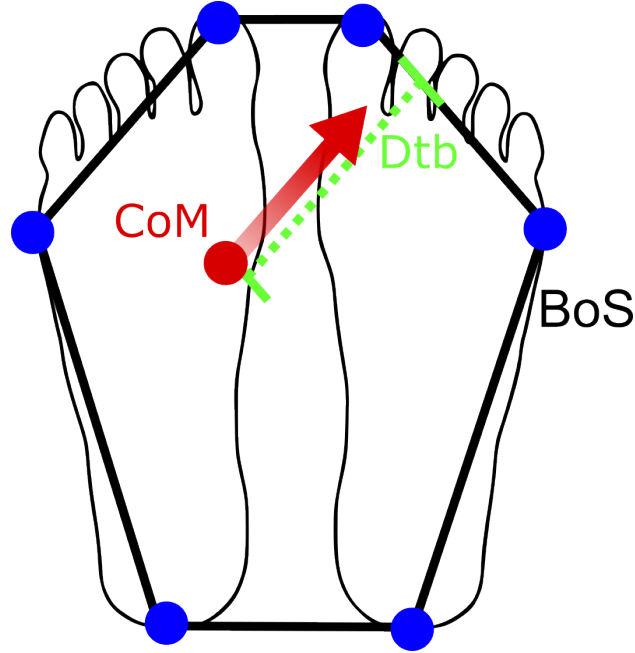


Figure 6: Representation of the *Base of Support* (BoS), defined as the enclosed polygon linking all external feet markers, here in black. Blue dots represent reconstructed markers positions. The ground projection of the *Center of Mass* (CoM) CoM and *Distance to boundary* (Dtb) are also respectively represented by the red dot and the green dashed line. The red arrow represent the CoM velocity.

Classically, balance recovery and step characteristics were usually studied with regard to the applied perturbation (Vallee et al., 2015; Robert et al., 2018; Li et al., 2020; Batcir et al., 2022). Here we consider the CoM momentum as a relevant quantification of the intensity of the perturbation. The CoM momentum is defined as the mass of the participant multiplied by the speed of the participants' CoM at a given moment.

For each trial, a few participants were not affected by the external perturbation. This was usually the case for participants in the front rows who could benefit from the energy dissipation of the perturbation by previous participants (Feldmann and Adrian, 2023). Without perturbation, their CoM remained static or with a very low velocity throughout the entire recorded trial. This causes issues with the numerical computation of the *Time to boundaries* (Ttb) which is by definition infinite for a static CoM. To prevent any numerical artefacts we removed the recording of all participants whose CoM speed did not exceed 0.05 m/s . This threshold was chosen to ensure no computational error and remains below the lowest maximum CoM speed value observed after perturbations during the previous experiment with single individuals (Chatagnon et al., 2023).

2.2.3. Step and Hand Raising Detection

The step detection method used in this study is the same as the one exposed in Chatagnon et al. (2023). In this study, characteristics of the first recovery steps were investigated. In particular, three main aspects were monitored, the length, the average speed and the angular deviation. The step length corresponds to the norm of the step vector. The step vector being defined as the vector from the position of the Toe marker at t_{begin} and its position at t_{end} , with t_{begin} and t_{end} being the initial and final stepping time as defined in Chatagnon et al. (2023). The step average speed is the step length divided by the step duration between t_{begin} and t_{end} . The step angle deviation is the oriented angle between the step vector and the direction of the CoM velocity at the moment of minimal Ttb (see Fig. 7). We have used here the CoM velocity at the moment of minimal Ttb as an estimated value of the actual perturbation angle. Step characteristics of the dense groups experiment are here compared with step characteristics of single individuals following

perturbation in the anteroposterior direction. These comparison data were obtained using experimental recordings presented in Chatagnon et al. (2023).

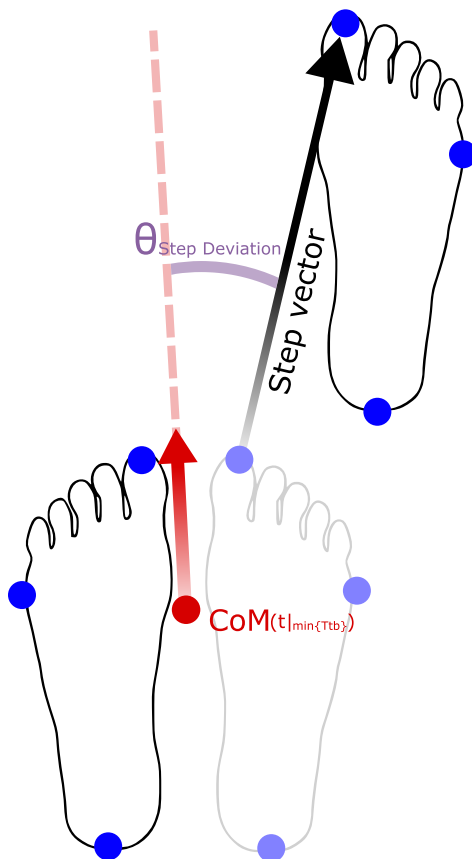


Figure 7: Representation of the step vector (black arrow) and deviation angle (purple line). Step vector is defined as the displacement of the reconstructed stepping toe marker between the begin and the final time of the first recovery step. Deviation angle is defined as the angle between the step vector and the direction of the CoM velocity at the moment of minimal Ttb.

The detection of the hands raising used in this study is similar in many ways to the detection of step proposed in Chatagnon et al. (2023). This method relies on the analysis of the position and velocity of the reconstructed hands motion recorded during the experiment.

The following three stage method was applied to each hand to detect hand raising.

1. The upward motion of the hand during a trial was checked to be higher than a distance threshold $d_t = 20cm$ (i.e. larger than an average human hand length Aboul-Hagag et al. (2011); Guerra et al. (2014)),
2. The first positive peak of the vertical speed of the hand was located and assumed to correspond to motion induced by hand raising,
3. The first inflexion points of the hand's vertical speed before the peak and under 10% of the global maximal speed was then located (ensuring not to fall into local minimums).

This method returned the first inflexion point (before the first hand's vertical speed peak). This moment was considered to be the initial time of hand raising (see Fig. 8).

If the participant's hands were already raised at the beginning of the trial, or if the participant made physical contact without raising their hands, no information about the preparation to physical interactions can be retrieved with this method.

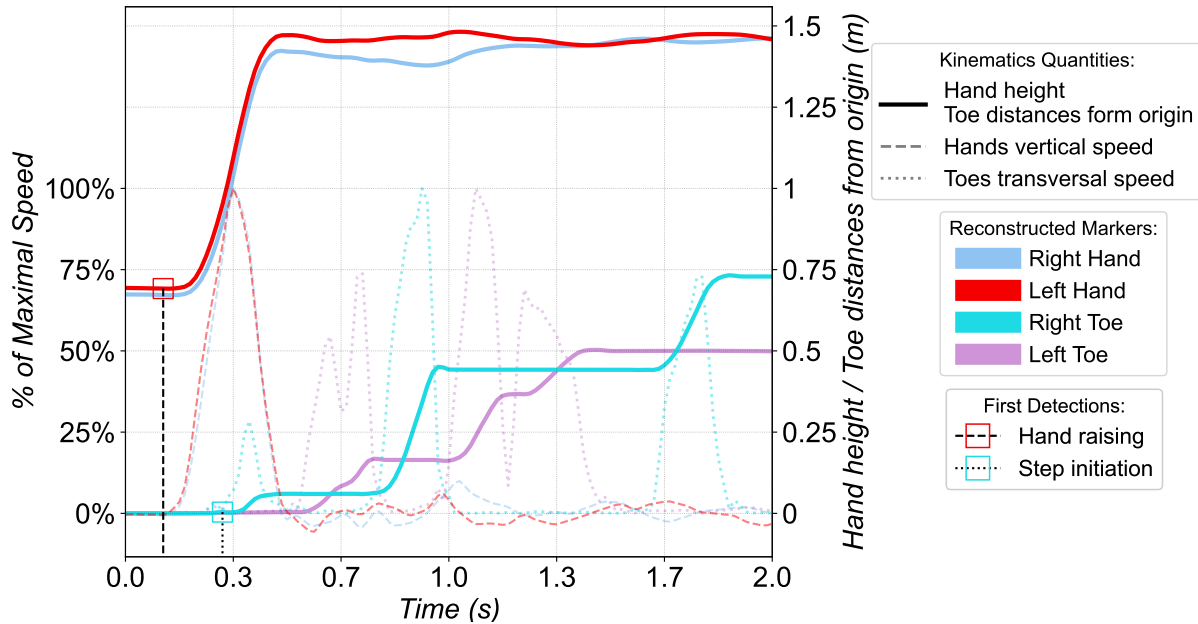


Figure 8: Representation of the reconstructed hands’ height and toes’ transversal distance from origin, i.e. the initial position at the beginning of the recording, for a participant during the dense groups experiment. Vertical and transversal speed are represented in dashed or dotted lines for the reconstructed hands and toes respectively. The moments of hand raising and step initiation are considered to be the first inflexion points before speed peaks. The detection time of these moments is indicated by square markers.

2.2.4. Statistical Analysis

We worked here with logistic regressions to study the LoSB, i.e. the limit after which participants were more likely to initiate a stepping recovery strategy following the perturbations (Kleinbaum et al., 2002). These regressions were created using the minimal values T_{tb} before step initiation for each trial. If a participant did not initiate a step to recover from the perturbation, the overall minimal value of T_{tb} during the trial was considered. The logistic regressions were then used to create separation models between stepping and non-stepping recovery strategies. If a logistic regression value is above 0.5 the model indicates that a stepping strategy is more likely to be used, under 0.5 a strategy not involving step is more likely to be used. The threshold value for which the regression is equal to 0.5 is referred as the *Decision Boundary* (DB).

In particular, we monitored the accuracy, sensitivity and specificity of the models. Accuracy corresponds to the number of correct estimations of the model divided by the total number of trials. Sensitivity is the number of step trials correctly detected divided by the total number of trials with steps, i.e. a high sensitivity is linked to a high efficiency of the model at detecting step trials. Specificity is the number of *Non-Step* (NS) trials correctly estimated divided by the total number of NS trials, i.e. a high specificity is linked to a high efficiency at detecting NS situations.

To assess the effect of the experimental interpersonal distancing conditions on step initiation, we built *Logistic Mixed Models* (LMMs) upon the dataset. This model is a general logistic model assessing the probability for participants of taking a step for a given minimal value of T_{tb} , and considering the experimental interpersonal distancing conditions as factors. The different participants were considered in the models as a random effect due to specific reaction each participant might have. The LMMs and all related analyses were created and performed using the Jamovi software suite (Jamovi, 2022).

Linear models were created to study the relationship between the step length and average speed and the CoM momentum at step initiation. In addition, the distancing condition was associated to a binary factor for the linear model created on data of the dense groups experiment. The variable associate with the distancing condition is null for *No Distance* trials and equal to one for *Elbow Distance* trials. This can be

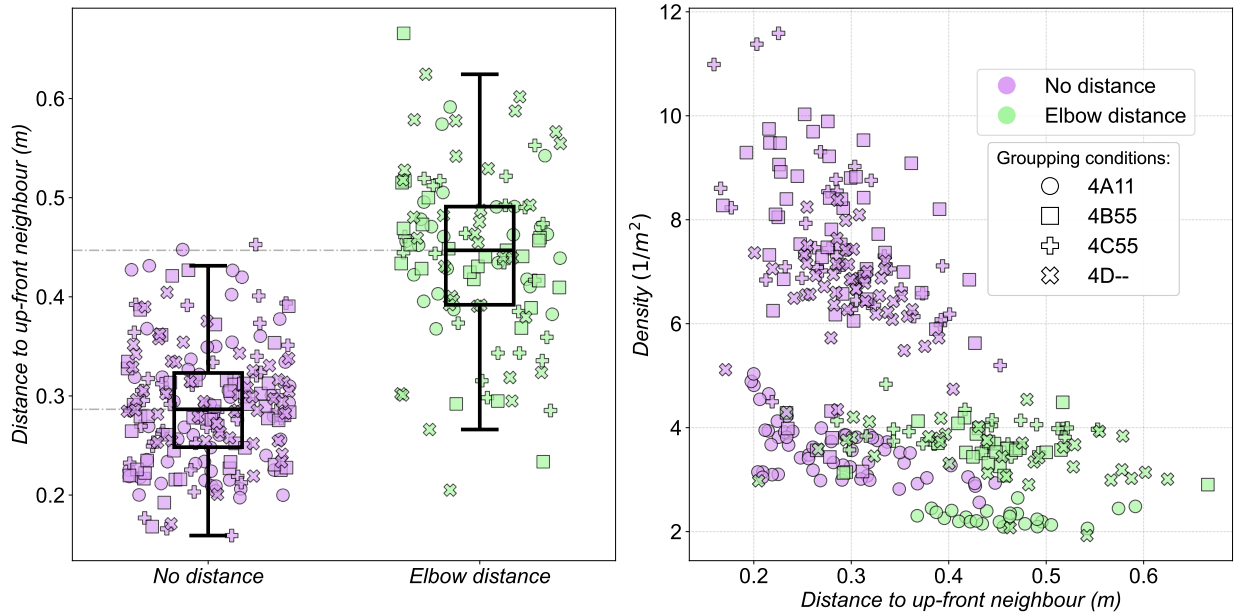


Figure 9: Left-hand side: Distribution of the distance to first up-front neighbour for each experimental distance condition. Right-hand side: Density distribution compared to the distance to first up-front neighbour. Data points are colored by experimental distance condition. For all grouping conditions, density was computed using a *Voronoi density* method except for condition 4A11 (single line condition) where a 1D density definition was used.

seen as an Analysis of Covariance (ANCOVA) to study the effect of the experimental distancing condition on the characteristics of the first recovery steps. In order to assess the effect of the model parameters, the p-value of a t-test on the significance of each parameter was computed. The null hypothesis of this test is that the considered parameter has no significant effect on the model. Therefore, the parameters associated with the distancing conditions should have a p-value for this test below $5 * 10^{-2}$ to indicate a statistical effect on the step characteristics.

The linear models were obtained with the statsmodels python package. The quality of the models was assessed using the Coefficient of Determination (R^2), the Root-Mean-Square Deviation (RMSE), and Shapiro-Wilk tests over the residual. R^2 represents the proportion of the total variation of the considered quantities accounted for by the regression model. The RMSE is the root-mean-square of the average squared difference between the experimental data and the regression model. Shapiro-Wilk test assesses the normality of a distribution, here used to study the distribution of the residuals i.e. the difference between the experimental data and the linear models.

3. Results

3.1. Distancing Conditions and Density

The distribution of distance to first up-front neighbour and the density distribution compared to the distance to first up-front neighbour are shown in Fig. 9. The median distance to first up-front neighbour was 29cm for the *No distance* condition and 45cm for the *Elbow distance* condition. Standard deviation for each of the conditions were 6cm and 9cm respectively. Overlaps between the two experimental distancing conditions can be noticed. These are particularly visible when looking at the estimated local density around participants, especially between 2 and 5 persons per square meter.

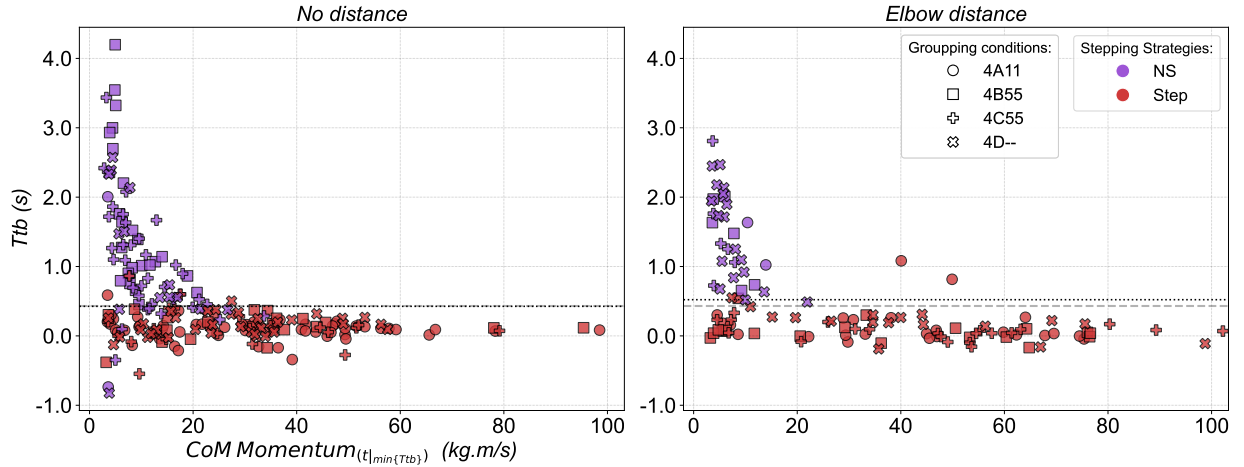


Figure 10: Distribution of the Minimal *Time to Boundary* (Ttb) of participants compared to their CoM momentum for each experimental distance condition. The minimal value was computed before step initiation for trials involving a step (red markers) and for the entire recorded motion for trials not involving a step (purple markers). Decision boundaries between trials with and without steps (NS) are represented for each experimental distance condition by black dotted lines. The gray dashed line represents the decision boundary of the logistic model obtained for the experiment with single individuals for perturbations in the anteroposterior direction.

Table 2: Characteristics of the logistic models to separate trials with and without steps (NS) using minimal values of Ttb during trials. Models were created for each experimental distancing conditions.

	Decision Boundary (s)	Accuracy (%)	Sensitivity (%)	Specificity (%)
Single Individuals (Chatagnon et al., 2023)	0.44	99	99	100
Dense Groups No Distance	0.43	92	97	83
Dense Groups Elbow Distance	0.52	94	95	93

3.2. Limit of Standing Balance in Dense Groups

Logistic models keep an overall accuracy above 90% (see Table 2) for both experimental distancing conditions. We can see in Fig. 10 that most recovery strategies achieved without stepping were done with a CoM momentum under 20 kg.m/s at the moment of minimal Ttb. The separation boundary for the *Elbow Distance* condition is 0.52 s based on the logistic model. This is more than 15 % higher than the separation boundary of the model based on the *No Distance* condition at 0.43 s . The effect of the experimental distancing conditions is also visible from a statistical point of view given the low p-value of the Fixed Effect Omnibus test of the LMM based on the present data (see Table 3). Eventually, in 211 trials out of the 221 trials for which a stepping strategy was used, i.e. 95%, the moment on minimal Ttb corresponds with the moment of step initiation detection regardless of the experimental condition distancing.

3.3. First Recovery Steps Characteristics in Dense Groups

We can see in Fig. 11.a-b and Table 4 that the relationship between the first recovery step length or average speed and the CoM momentum of participants more closely follows the linear model for the observations made in the experiments with single individuals.

Both the step length and average speed during the considered dense groups experiment show mainly lower value for a given CoM momentum than the regression created using data from the experiment with single

Table 3: Characteristics of the *Logistic Mixed Models* (LMMs) between trials with and without steps (NS). The covariate is the quantity on which the regression is based (here, the minimal Ttb during trials).

	$R^2_{conditional}$	$R^2_{marginal}$	p-value : Fixed Effect Omnibus tests	
			Distancing Condition	Covariate (Min. Ttb)
NS/Step - Min. Ttb	0.88	0.88	$2.90 * 10^{-2}$	< 0.001

Table 4: Quality assessment metrics associated to the linear models based on the observation from the dense groups experiment and on the experiment with single individuals (Chatagnon et al., 2023). Stars here highlight the p-values of the Shapiro-Wilk test on the residuals of the models. One star (*), two stars (**), and three stars (***) indicate p-values below 0.05, 0.01 and 10^{-3} respectively. Smaller p-values indicate that the residuals in the model are not normally distributed.

		R^2	RMSE	p-value: Shapiro-Wilk test (residuals)
y: Step Length x: CoM Momentum (Fig. 11.a)	Single Individuals	0.659	$6.08 * 10^{-2}$	$7.63 * 10^{-2}$
	Dense Groups	0.166	$9.11 * 10^{-2}$	$3.30 * 10^{-4}$ ***
y: Step Avg. Speed x: CoM Momentum (Fig. 11.b)	Single Individuals	0.690	0.253	0.503
	Dense Groups	0.370	0.411	0.496
y: Step Avg. Speed x: Step Length (Fig. 11.c)	Single Individuals	0.754	0.225	$9.61 * 10^{-3}$ **
	Dense Groups	0.711	0.278	0.152

individuals (Chatagnon et al., 2023) (see Fig. 11.a-b). In addition, we can see in Fig. 11.a-c and in Table 5 that the experimental distancing conditions tested during the dense groups experiments have a significant effect on the speed of the first recovery steps. This can be seen in the linear models with faster recovery step motion used when participants were at *Elbow Distance* compared to the *No Distance* condition.

The relation between the first recovery step length and average velocity is comparable in every experiment (see Fig. 11.c). This can be seen in Table 5 with the comparable coefficient associated with the covariate variable in the models (i.e. the coefficient associated to the Step Length).

Regarding the step deviation angle, we observed in Fig. 11.(d) a more dispersed data repartition than what was observed for the experiment with single individuals. Unlike the observations made for the experiment with single individuals (see Fig. 12), here the deviation angle did not seem to decrease as the CoM momentum of participants increased. This can also be seen through the high standard deviation in Table 6.

3.4. Hand raising and Step initiation

Here we compare trials for which participants used a stepping recovery strategy and raised their hands in preparation to physical interactions with neighbours. We can see in Fig. 13 that for most of these trials we observe a positive delay between the moment of hand raising initiation and the moment of step initiation (t_{begin}). This indicates that hand raising occurred in majority before step initiation. However, we can also observe that this delay can also be negative. For trials with negative delay, steps were initiated before hand raising. This happened especially when the CoM momentum of participants at hand raising initiation was above 10 kg.m/s and seems to increase with the CoM momentum. Eventually, one should note that hand raising behaviour was only observed in a large minority of trials involving stepping recovery strategy, i.e. 100 trials out of 221. In the other trials where only a stepping recovery strategy was used, participants' hands seemed to remain in a lower position.

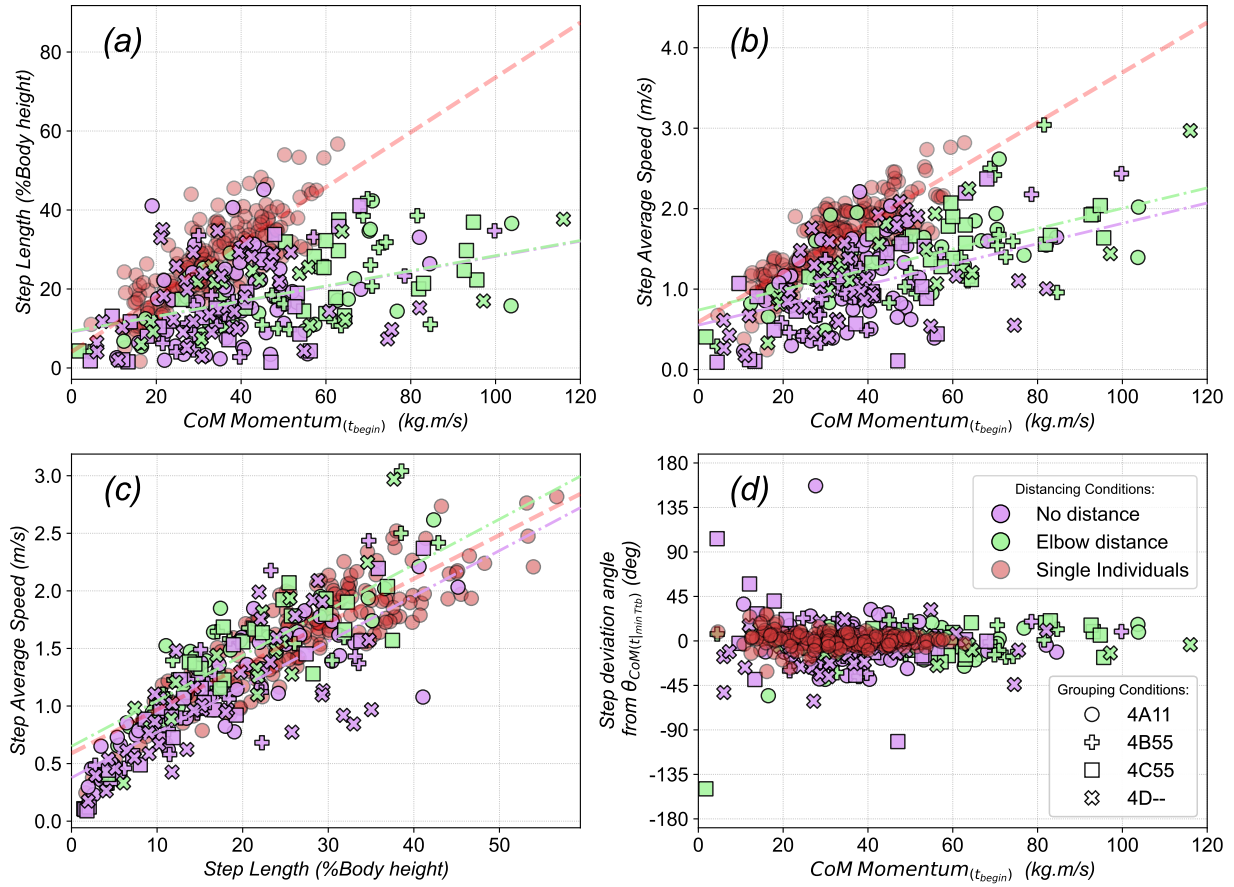


Figure 11: (a) Representation of the first recovery step length compared to the CoM momentum at step initiation. (b) Representation of the average speed of the foot during first recovery step compared to the CoM momentum at step initiation. (c) Representation of the average speed of the foot during first recovery step compared to the step length. (d) Representation of the step deviation angle compared to the CoM momentum at step initiation. Markers are coloured by experimental interpersonal distancing (*No Distance* or *Elbow Distance*) and shaped according to the grouping condition of considered trials. The broad dashed lines represent the linear models on FS recovery strategies created using data from the experiment with single individuals. The thinner dashed and dotted lines in (a), (b) and (c) represent the linear models based on the dense groups experiment. The dashed and dotted line in (d) represent the median of the step deviation angle at $-2.90\ deg$.

Median and standard deviation of the delay between hand raising and step initiation can be found as well as the number of trials considered in this study in Table 7.

4. Discussion

Distancing Conditions and Density

Two experimental distancing conditions were studied during these dense groups experiments, the *No Distance* condition and the *Elbow Distance* condition. It can be seen in Fig. 9 that the simple instruction given to the participants during the experiments resulted in two different ranges of interpersonal distance and density. These ranges of interpersonal distance were associated with different density levels during the experiment. Density levels were comparable to the ones observed during dangerous mass events (Rahman et al., 2017; Sieben and Seyfried, 2023; Feliciani et al., 2023).

One can also see that density estimation also depends on the method used. For the line formation (4A11) a 1D method have been used to estimate density, this method results in lower density estimations than the

Table 5: Coefficient of the linear models based on the observation from the dense groups experiment and on the experiment with single individuals (Chatagnon et al., 2023). Stars are associated with the p-values of the t statistics for each coefficient. One star (*), two stars (**) and three stars (***) indicate p-values below 0.05, 0.01 and 10^{-3} respectively.

		Intercept	Coef. Covariate (x)	Coef. Factor (<i>Distancing Condition</i>)
y: Step Length x: CoM Momentum (Fig. 11.a)	Single Individuals	$4.08 * 10^{-2}$ **	$6.95 * 10^{-3}$ ***	-
	Dense Groups	$9.08 * 10^{-2}$ ***	$2.17 * 10^{-3}$ ***	$1.73 * 10^{-3}$
y: Step Avg. Speed x: CoM Momentum (Fig. 11.b)	Single Individuals	0.590 ***	$3.10 * 10^{-2}$ ***	-
	Dense Groups	0.552 ***	$1.26 * 10^{-2}$ ***	0.187 **
y: Step Avg. Speed x: Step Length (Fig. 11.c)	Single Individuals	0.590 ***	3.79 ***	-
	Dense Groups	0.377 ***	3.94 ***	0.27 ***

Table 6: Recapitulate table of the step deviation angles median values and standard deviations. In this table, observation from the dense groups experiment and the experiment with single individuals (Chatagnon et al., 2023) are compared.

	Median (deg)	Standard Deviation (deg)	Number of Values
Single Individuals	0.37	7.68	185
Dense Groups <i>Elbow Distance</i>	-3.77	22.0	81
Dense Groups <i>No Distance</i>	-2.41	26.34	140

Table 7: Recapitulate table of the medians and standard deviations of the delay between hand raising and step initiation of the participants who used both strategies. Results are given for each experimental distancing conditions as well as for the overall observations.

	Median (s)	Standard Deviation (s)	Number of Values
<i>Elbow Distance</i>	0.27	0.37	47
<i>No Distance</i>	0.22	0.73	53
Overall	0.25	0.59	100

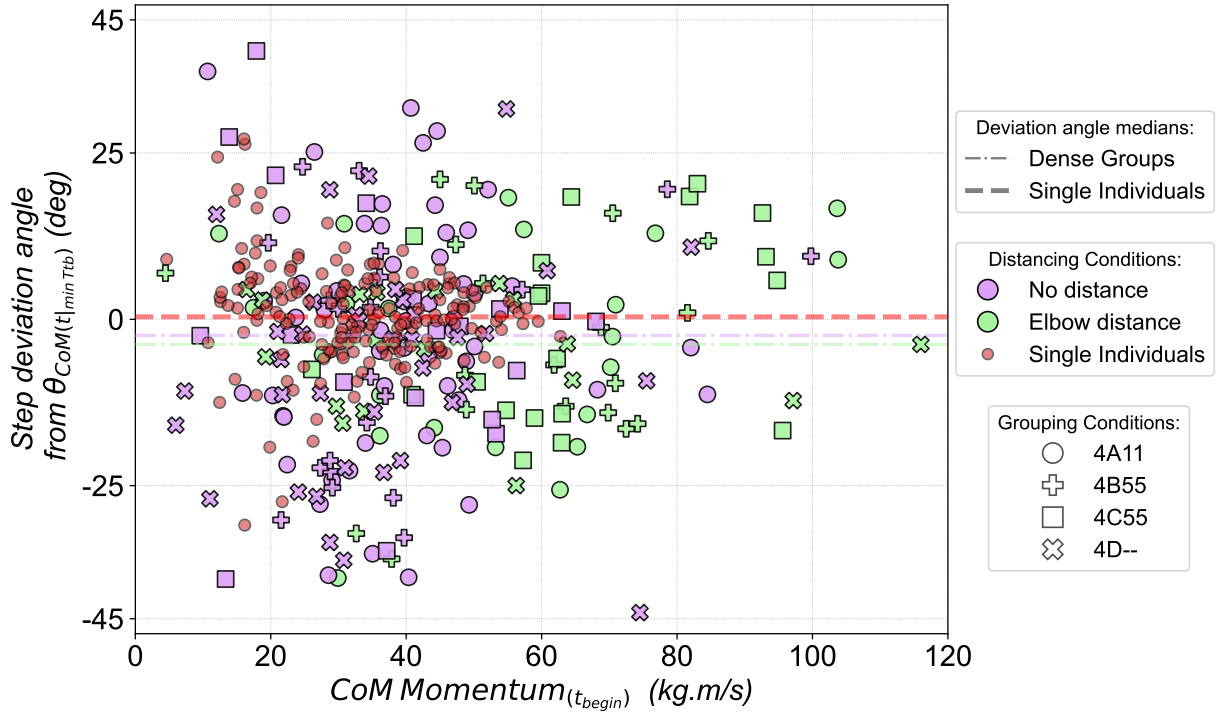


Figure 12: Representation of the step deviation angle compared to the CoM momentum at step initiation. This figure is a zoomed-in representation of the results shown in Fig. 11.d in which are compared results from the dense groups experiment as well as from the experiment with single individuals.

Voronoi Density used for the other group formations regardless of the actual interpersonal distance with the direct neighbours.

Limit of Standing Balance in Dense Groups

The limit of Standing balance was studied here using the minimal *Time to boundaries* (Ttb) of participants during the considered trials. However, one may question this method as more complex *change-in-support* may be used by participants in this context, such as contacts with other individuals using their arms and upper body.

To validate our approach by going back to the meaning of the moment of minimal Ttb. As the Ttb correspond to the time needed by the CoM to exit the BoS at given its current velocity, the moment when the minimal value of this metric is reached can be associated with the moment for which standing balance is in the most critical situation. During this experiment, we observed that 95% of the stepping recovery strategies were initiated at the moment of minimal Ttb. In other words, the majority of participants were initiating stepping strategies as their body was in the most unstable position. This means that other *change-in-support* which could be used by participants had a limited effect on the Ttb. Thus, other possible *change-in-support*, such as upper body contacts, did not fully prevent critically unbalanced situations for which stepping strategies were initiated. In the light of this observation, we considered that the *Limit of Standing Balance* could then still be defined as the limit after which stepping recovery strategies were used by participants to regain balance.

Trials for which stepping recovery strategies were initiated after the minimal recorded Ttb correspond to situations where participants step several seconds after the perturbation. For these trials, step initiation seemed not to result from a necessary *change-in-support* to maintain balance but were rather used by participants to reposition themselves relative to the other participants after the perturbation. For some trials, the difference between the moment of minimal Ttb and moment of step initiation was only different by

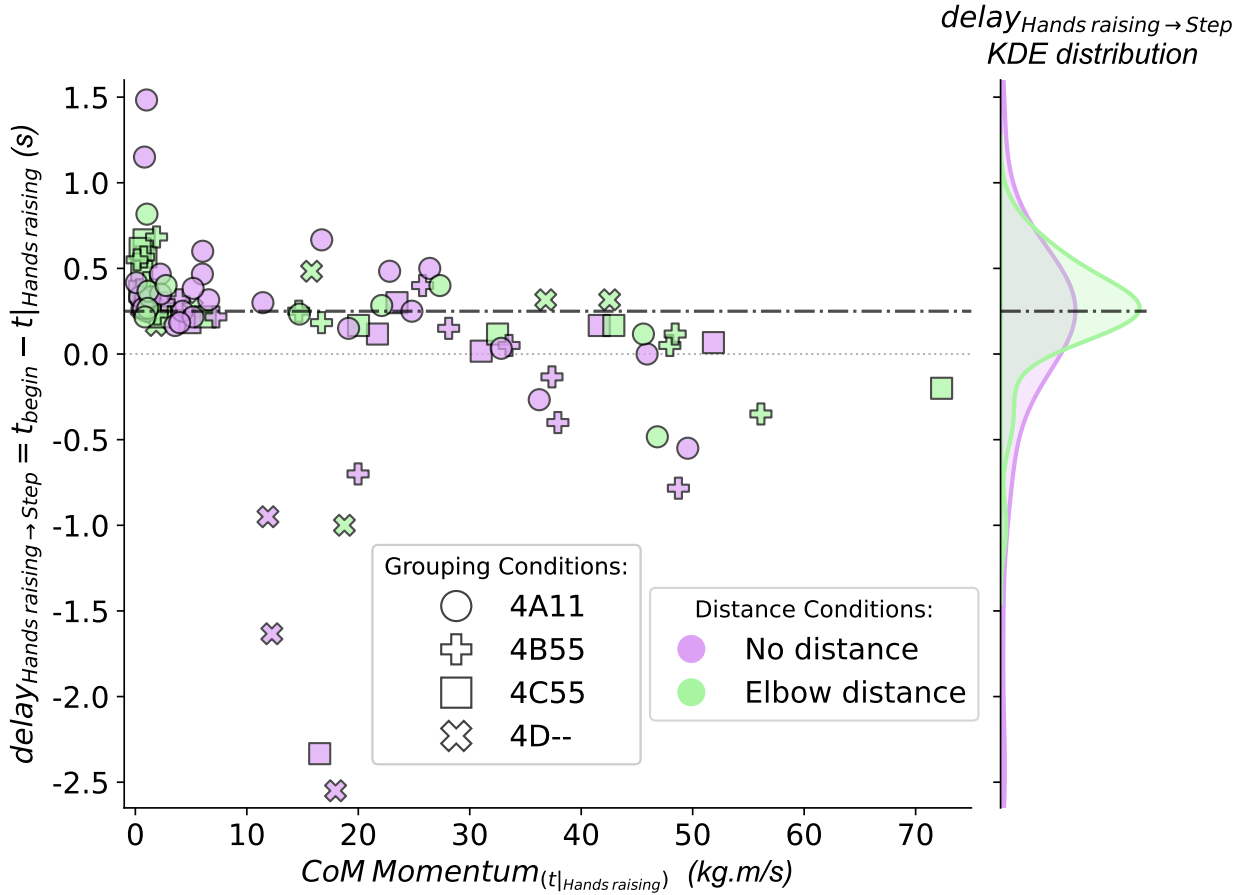


Figure 13: Distribution of the delay between the moments of hand raising initiation and step initiation compared to the CoM momentum at the moment of hand raising initiation. Data are colored by experimental distance condition. A positive delay reveals that hand raising occurred before step initiation. A *Kernel Density Estimation* (KDE) representation of the delay distribution is displayed in the right-hand margin. The black dashed line corresponds to the overall median of the delay distribution.

less than a few recorded frames. In this situation the step detection method may have detected the motion of the step slightly later than the actual step motion initiation leading to a minor increase of the distance between the CoM and the BoS and an augmentation of the Ttb before step detection.

Regarding the effect of the experimental distancing conditions, we observed that the separation between recovery with and without steps for the *No Distance* condition was almost the same as the limit obtained during the experiment with single individuals. However, the accuracy of the separation model in this dense groups experiment is lower than the one created with single individuals reactions due to recovery strategies with lower and negative values of Ttb. We also observed that separation boundary of the logistic model was significantly higher when looking at the *Elbow* distancing condition (see Table 3 and Fig. 10). This suggests that participants reacted with stepping strategies for less critically unbalanced postures i.e. with higher values of minimal Ttb. One possible explanation of this phenomenon may be linked to the social dimension of the situation. Participants may indeed try to use more effective recovery strategy (i.e. stepping strategies), even at higher level of standing balance, in order to prevent or reduce physical interactions with other participants. This would explain why the Limit of Standing Balance is similar between groups with *No Distance* and the experiment with single individuals, as in both case social rules did not apply (either due to

already existing contacts or complete absence of possible contacts). Deeper investigation on that matter should however be conducted to draw any further conclusions.

Non-stepping recovery strategies with low and negative minimal Ttb are also an interesting feature of Fig. 10. Such balance recovery is not possible for single individuals since a negative Ttb indicates that the CoM's ground projection is outside the BoS. Having a CoM's ground projection outside the BoS is a critical situation for which standing balance cannot be regained without using a *change-in-support* (Maki and McIlroy, 1997). In these situations, the main *change-in-support* is made through contacts with the neighbours and not by the use of steps, as we observed in the majority of trials with minimal Ttb beyond the model limit. This recovery strategy was only observed in a very limited number of trials, but such behaviour could lead to dangerous situations. Leaning on others can increase the static load on the front participants, causing physical discomfort and anxiety. In the worst possible scenario, this may lead to collective falls and asphyxiation if the loaded participants are unable to step out of the situation (Rahman et al., 2017; Wang et al., 2019; Sieben and Seyfried, 2023). Further investigation of interpersonal contact is needed to better understand the role of physical interactions for balance recovery in this context.

First Recovery Steps Characteristics in Dense Groups

Regarding recovery steps characteristics no visible effect due to the distancing condition have been observed on the first step length (see Fig. 11 and Table 5). However, significant statistical difference are highlighted by the linear models showing that first recovery steps motion was faster during trials at *Elbow Distance*.

In addition, some major differences were observed in comparison with the experiment involving single individuals (Chatagnon et al., 2023). Specifically, the step length and average speed of participants in dense groups appeared to be lower than those observed in the experiment with single individuals for a given CoM momentum at step initiation. This effect is likely to be associated with the available stepping area as well as limited visibility of the ground for densely packed situations.

Smaller steps in dense crowds seems to prevail over the larger recovery steps observed during the experiment with single individuals. However, the average speed and the length of the first recovery steps seem to follow similar linear relationships in all experiments. This suggests a constant step duration regardless of the density of the crowded environment. A constant step duration after external perturbations was also observed in Zhang and Fu (2018) with a longer step duration than in the present experiments.

Another hint of the lack of available area to perform step recovery in dense groups is shown in Fig. 12. One can see that the distribution of the deviation angles during the dense groups experiment is more scattered than the one observed during the experiment with single individuals. Moreover, this dispersion does not seem to decrease as the CoM increases, as it was observed during the experiment with single individuals.

All of this seems to indicate that in the dense groups experiment, the recovery steps were not placed in the most convenient position for the participants, but rather on the closest available area of the floor.

Hands raising and Step initiation

When both hand raising and stepping recovery strategies were triggered during a trial, we observed that the hand raising seemed to be initiated before the stepping strategy (see Fig. 13). The median delay between hand raising and step initiation is of the same order of magnitude as the typical reaction time of young adults, i.e. from 0.18 s to 0.3 s for reactions to haptic or visual stimuli (Peon and Prattichizzo, 2013; Jain et al., 2015). However, hand raising was only observed in 45% of the trials where participants used stepping recovery strategies. In the other trials hands seemed to be kept in a lower position. Therefore, hand raising behaviour was not systematic during balance recovery in this studied context. Nevertheless, this behaviour was observed in many recordings and thus may have a beneficial effect on participants' balance recovery in this densely populated environment.

This behaviour may be related to a more social aspect of balance recovery in this situation. Raising the hand is a limited intrusion into another participant's personal space (up to the point of physical contact), compared to stepping strategies that involve the motion of the whole body. In addition, raising the hands is also a way of ensuring that the potential physical contact with the up-front participants is done in a

controlled manner using the arms to damp the perturbation. This creates a gradual loading on the up-front neighbours, allowing them to brace for the perturbation before it reaches its maximal intensity. In other words, having the hands up may allow individuals to touch their neighbours before reaching a maximal momentum and thus to propagate the information about the upcoming perturbation faster than the induced momentum propagation. All these discussions are only assumptions based upon observations and more investigations are required to draw any strong conclusions.

Limitations

The proposed study also comes with limits that have to be acknowledged in order to fully grasp the context of validity of the previous results.

First, the motion recording technique used in this experiment is different from the one used in the experiment with single individuals. Here a commercial IMMU based solution has been used. This enabled the recording of motion in a dense group which couldn't have been done otherwise. However, this method only provides estimation of the limb position and these estimations cannot be directly compared with ground truth motion. This reconstruction may induce a lower accuracy regarding the positions of the limb as raw sensor data have to be integrated for reconstruction purposes. In such context we observed few unrealistic BoS for which both reconstructed feet positions were partly overlapping at rest position. These observations were made in 14 of the 221 trials involving steps and indicate that the actual BoS limits may be different from the reconstructed recordings.

The reconstruction error may however have a limited impact on the computation of the Ttb here. For most of the steps considered in this study, the front boundary of the BoS was crossed by the ground projection of the CoM. The position of this boundary is governed by the feet length and directions. As the feet lengths is a given parameter for the reconstruction process and the directions of the feet showed no particular reconstruction artifacts, one can assume that the location of this boundary is close to the actual BoS of participants. Therefore, we believe that minimum values of Ttb may be compared between all experiments regardless of the motion capturing technique used.

In addition, a biomechanical model was fitted on these reconstructed recordings in order to compute biomechanical quantities such as the CoM. The accumulation of models may result in a reduced accuracy due to the accumulation of estimations. However, further investigations are required to understand the effect of these errors on the presented results.

Eventually, regarding the hand raising behaviour, participants seemed to raise their hands in preparation for physical interactions. However, the method only provides information about the movement of the hands. We cannot know if a contact actually happened and when it happened following the hand were raised. Contact may also have already occurred at the moment the hand raising was initiated. New investigations regarding interpersonal contacts are required for further conclusions on this matter.

5. Conclusion

In this study the reaction of young individuals in dense group formations was investigated following force controlled perturbations. The participants' recovery in this context was compared with the reaction of single individuals to external force-controlled perturbations.

In particular, we have seen that the *Limit of Standing Balance* obtained using the minimal value of the *Time to boundary* in the context of dense group formations remains close to the one observed during the experiment with single individuals when participants were asked to stand next to their neighbour without any interpersonal distance. For the *Elbow* length distancing conditions, participants initiated stepping strategies for less critical situations i.e. higher values of minimal *Time to boundary*.

Characteristics of the first recovery steps did not strictly follow linear models with the *Center of Mass* momentum as this was observed for the experiment with single individuals. However, the relationship between the length and the average speed of the first recovery step seems to remain similar between all experiments. In addition, for recovery in dense groups, the first recovery steps direction seem to deviate more from the estimated perturbation direction. The length of the first recovery step remained unchanged by the

experimental interpersonal distancing conditions studied here, but a statistical effect is visible for step speed. Faster steps were taken when participants had no prior contact with their neighbour before the perturbation.

Eventually, external perturbation in dense groups involved physical interactions between participants. This was visible through the leaning strategies which involved lower and negative minimal values of *Time to boundaries* that were not followed by stepping recovery strategies. We also observed that participants seemed to react by first raising their hands before initiating stepping strategy following external perturbations.

This experimental dataset can be used to further investigate balance recovery strategies in dense crowds. For example, by combining motion capture recordings and head trajectories. This method has been proposed in Feldmann and Adrian (2023) and may lead to further insights on recovery strategies in dense crowds situations. In particular, relative foot placement may be investigated using this method.

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Declaration of interest

None

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