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High pressures in room evacuation processes and a first approach to the dynamics around unconscious pedestrians

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HIGHLIGHTS

- High pressures during an emergency evacuation may produce unconsciousness.
- Dodging or passing-through the fallen individuals changes the evacuation performance.
- Dodging worsens the evacuation performance depending on the anxiety levels of the pedestrians.
- Passing-through enhances the evacuation depending on the difficulties to be surmounted.

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ABSTRACT

Clogging raises as the principal phenomenon during many evacuation processes of pedestrians in an emergency situation. As people push to escape from danger, compression forces may increase to harming levels. Many individuals might fall down, while others will try to dodge the fallen people, or, simply pass through them. We studied the dynamics of the crowd for these situations, in the context of the "social force model". We modeled the unconscious (fallen) pedestrians as inanimate bodies that can be dodged (or not) by the surrounding individuals. We found that new morphological structures appear along the evacuating crowd. Under specific conditions, these structures may enhance the evacuation performance. The pedestrian's willings for either dodging or passing through the unconscious individuals play a relevant role in the overall evacuation performance.

1. Introduction

History acknowledges many fatalities during stampedes. Unfortunately, such kind of disasters have increased in frequency because the number and size of massive events (music festivals, sports events, etc.) has become larger [1]. An inspection of the Crowdsafe Database™ through 1992–2002 shows a correlation between the number of concerts and festival events, and the number of injuries [2]. Specially sorrowful are the incidents occurred in the nightclubs *The Station* (Rhode Island, 2003) and *Cromañón* (Buenos Aires, 2004) where 100 and 194 people lost their lives, respectively.

Laboratory experiments and numerical simulations provide some guidelines for a better understanding of these kind of disasters [3]. The exit width raises as one of the major reasons for overcrowding during evacuation processes [4,5]. It has

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been pointed out, however, that other behavioral patterns or environmental conditions are responsible for clogging just before any narrowing of the leaving pathway [3,6–8]. Researchers agree on the fact that pathways as narrow as 0.6–0.7 m reduce the capacity of the pedestrians to leave the room [9,10].

The overcrowding is one of the principal causes of injury or death while people try to escape during crowd disaster. Deaths may happen because of *trampling* or *compression due to crush*. The former occurs when someone falls in a high dense crowd, not being able to stand again due to the movement of the others, unaware of the fallen pedestrian. This produces a continue trampling that finally kills the individual [11].

Compression due to crush is the other cause of death. This effect appears in high dense crowds, preventing the free movement of the pedestrians. If the pressures in the crowd become extremely high, each time an individual breaths out, the pressure restricts the inhalation of the next breath. Thus, compression due to crush causes asphyxia on the individual, evolving to unconsciousness or death after some time [12]. Further information on fatal consequences by asphyxia can be found in Ref. [11].

A brief review of the basic "social force model" can be found in Section 2.1. We include in Section 2.2 an upgrade of the basic model that makes possible to achieve compressional injuries.

In Section 3 we will present experimental data on the injury threshold due to compression. A simple model on the human torso will be examined for further simulations (see Section 4).

All the results of our investigations are presented in Section 5. The corresponding conclusions are summarized in Section 6.

2. Background

2.1. The social force model

The "social force model" (SFM) proposed by Helbing and co-workers [13] is a generalized force model, including socio-psychological forces, as well as "physical" forces like friction. These forces enter the Newton equation as follows.

$$m_i \frac{d\mathbf{v}^{(i)}}{dt} = \mathbf{f}_d^{(i)} + \sum_{j=1}^{N} \mathbf{f}_s^{(ij)} + \sum_{j=1}^{N} \mathbf{f}_g^{(ij)} \qquad (1)$$

where the i, j subscripts correspond to any pedestrian in the crowd. $\mathbf{v}^{(i)}(t)$ means the current velocity of the pedestrian (i), while $\mathbf{f}_d$ and $\mathbf{f}_s$ are the socio-psychological forces acting on him (her). $\mathbf{f}_g$ is the friction or granular force.

$\mathbf{f}_d(t)$ and $\mathbf{f}_s(t)$ are essentially different. The former corresponds to the "desire force", that is, the pedestrians own willings to move towards a desired position. The latter corresponds to the "social force", meaning the tendency of the pedestrians to preserve their *private sphere*. The "social force" prevents the pedestrians from getting too close to each other.

According to the anxiety state of the pedestrian, he (she) will accelerate (or decelerate) to reach any desired velocity v_d that will make him (her) feel more comfortable. Thus, in the social force model, the desired force reads [13]

$$\mathbf{f}_d^{(i)}(t) = m_i \frac{v_d^{(i)}\,\mathbf{e}_d^{(i)}(t) - \mathbf{v}^{(i)}(t)}{\tau} \qquad (2)$$

where m_i is the mass of the pedestrian i and τ represents the relaxation time needed to reach his (her) desired velocity. $\mathbf{e}_d$ is the unit vector pointing to the target position. For simplicity, we assume that v_d remains constant during an evacuation process, but $\mathbf{e}_d$ changes according to the current position of the pedestrian. Detailed values for m_i and τ can be found in Refs. [13,14].

The *private sphere* preservation corresponds to a repulsive feeling between the pedestrians, or, between pedestrians and the walls [13,15]. These repulsive feelings become stronger as people get closer to each other (or to the walls). Thus, in the context of the social force model, this tendency is expressed as

$$\mathbf{f}_s^{(ij)} = A_i\, e^{(r_{ij}-d_{ij})/B_i}\,\mathbf{n}_{ij} \qquad (3)$$

where (ij) represents any pedestrian–pedestrian pair, or pedestrian–wall pair. A_i and B_i are two fixed parameters (see Ref. [16]). The distance $r_{ij} = r_i + r_j$ is the sum of the pedestrians radius, while d_{ij} is the distance between the center of mass of the pedestrians i and j. $\mathbf{n}_{ij}$ means the unit vector in the $\vec{ji}$ direction. For the case of repulsive feelings with the walls, d_{ij} corresponds to the shortest distance between the pedestrian and the wall, while $r_{ij} = r_i$ [13,15].

The granular force $\mathbf{f}_g$ included in Eq. (1) corresponds to the sliding friction between pedestrians in contact, or, between pedestrians in contact with the walls. The expression for this force is

$$\mathbf{f}_g^{(ij)} = \kappa\,(r_{ij} - d_{ij})\,\Theta(r_{ij} - d_{ij})\,\Delta\mathbf{v}^{(ij)} \cdot \mathbf{t}_{ij} \qquad (4)$$

where κ is a fixed parameter. The function $\Theta(r_{ij} - d_{ij})$ is zero when its argument is negative (that is, $r_{ij} < d_{ij}$) and equals unity for any other case (Heaviside function). $\Delta\mathbf{v}^{(ij)} \cdot \mathbf{t}_{ij}$ represents the difference between the tangential velocities of the sliding bodies (or between the individual and the walls).