Experimental Study on Pushing Propagation in Moving Pedestrian Queues

Yushan Song[1,2], Haiyang Huang[1,2], Liangchang Shen[1,2,3], and Wenguo Weng*[1,2]

[1]School of Safety Science, Tsinghua University, Beijing, China
[2]Beijing Key Laboratory of City Integrated Emergency Response Science, Tsinghua University, Beijing, China
[3]Department of Architecture and Civil Engineering, City University of Hong Kong, Hong Kong, China

Abstract A series of controlled experiments were conducted on moving 5-pedestrian queues to investigate pushing propagation characteristics under different motion conditions, such as step frequency and gait cycle. The study compared and analyzed the relationships between initial impulse and variables including the propagation distance, propagation speed, and impulse ratios. Results showed that propagation speed decreased in moving conditions compared to static ($p = 0.0258$), and asynchronous stepping reduced the effect of initial impulse on propagation velocity ($p = 0.0297$), highlighting how pedestrian motion influences crowd dynamics.

Keywords Pushing propagation, Impulse, Pressure, Gait characteristics

Instruction

In dense crowds, physical interactions among individuals propagate similarly to shockwaves or turbulence, which have been identified as potential factors contributing to crowd crushes and stampede incidents [1,2]. Recently, pedestrian pushing experiments utilizing flexible pressure-sensing equipment have gained increased attention, aiming to investigate human responses to external forces and elucidate the mechanisms of force propagation within crowds. Wang et al. (2018) examined impulse and pressure propagation patterns in static pedestrian queues [3]. Li et al. (2021) measured mechanical and kinematic parameters involving one or two pedestrians, and analyzed the influence on body posture and stride behavior [4]; Feldmann et al. (2023) introduced inertial motion capturing technology to quantify mechanical responses and three-dimensional kinematics in a static queue of five individuals, assessing pushing propagation velocities from a kinematic perspective [5,6], and subsequently extended their analysis to larger pedestrian groups [7].

However, current controlled pedestrian pushing experiments have predominantly focused on static crowds. To investigate the propagation characteristics of pushes in moving crowds, we conducted a series of pushing experiments in moving pedestrian queues at Tsinghua University. Five male participants aged 22–28 years wore flexible pressure-mapping clothing (Xsensor), enabling continuous measurement of pressure levels on the chest, back, and arms. Additionally, an optical motion-capture system (Qualisys) recorded the three-dimensional trajectories of each participant's head and shoulders. To analyze the influence of movement speed and pedestrian stepping synchronization or asynchronization on pushing propagation, experiments were performed under multiple conditions at an interpersonal distances of elbow length (approximately 20 cm). Stepping frequencies of 45 bpm and 90 bpm represented slow and normal walking speeds, respectively. Gait conditions included synchronous, asynchronous, and random stepping, with two types of movements: swaying and walking. Under each condition, we performed 30 push trials of varying impulse magnitudes. A representative snapshot of the experimental setup is illustrated in Figure 1.

We analyzed the relationships between initial impulse and variables such as the number of individuals involved in pushing propagation, the propagation distance, propagation speed, and impulse ratios between adjacent individuals under different conditions. The results indicated that the pushing propagation threshold was significantly higher in asynchronous conditions compared to synchronous and static conditions. Additionally, the push propagation threshold increased with higher step frequencies, suggesting that pushes encountered greater resistance to forward propagation at higher stepping frequencies. Additionally, our analysis revealed that lateral propagation was more prominent under asynchronous conditions. Propagation velocities were calculated by fitting linear models to trajectory inflection points identified according to the methodology described in [5].

*Email of the corresponding author: wgweng@tsinghua.edu.cn

Statistical analyses demonstrated that propagation velocities were significantly influenced by both stepping conditions and initial impulses. Notably, propagation velocities during motion were significantly lower compared to static conditions ($p = 0.0258$). Furthermore, the interaction term analysis indicated that synchronous stepping conditions had a significant moderating effect ($p = 0.0297$), suggesting a pronounced reduction in the relationship between initial impulse and propagation velocity under asynchronous stepping conditions. Representative results are illustrated in Figure 2.

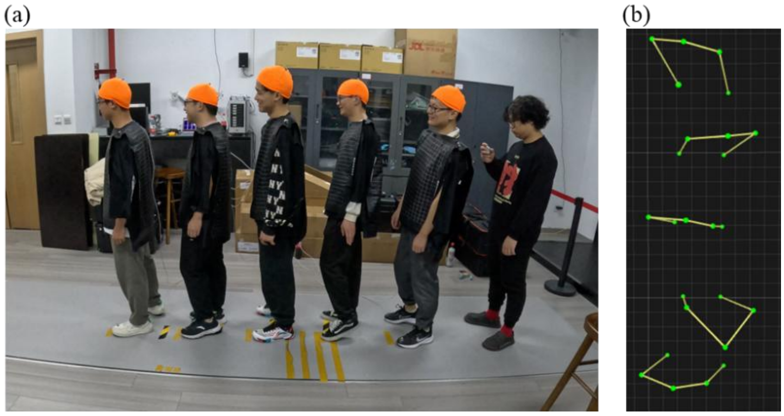

Figure 1: (a) side-view video recording and (b) Top-down view from Qualisys motion capture data, with trajectory points of the head, shoulders, and feet connected for clear differentiation, demonstrating the condition of asynchronous swaying at a step frequency of 45 bpm.

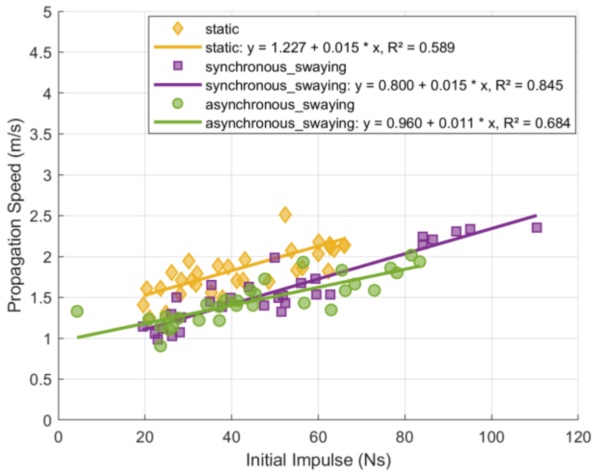

Figure 2: Pushing Propagation speed for different motion conditions and respective linear fitting equations.

Bibliography

[1] A. Bottinelli, D.T.J. Sumpter, J.L. Silverberg, Emergent Structural Mechanisms for High-Density Collective Motion Inspired by Human Crowds, Phys. Rev. Lett. 117 (2016) 228301. https://doi.org/10.1103/PhysRevLett.117.228301.

[2] J.J. Fruin, The causes and prevention of crowd disasters, Eng. Crowd Saf. 1 (1993) 99–108.

[3] C. Wang, W. Weng, Study on the collision dynamics and the transmission pattern between pedestrians along the queue, J. Stat. Mech. Theory Exp. 2018 (2018) 073406. https://doi.org/10.1088/1742-5468/aace27.

[4] X. Li, X. Xu, J. Zhang, K. Jiang, W. Liu, R. Yi, W. Song, Experimental study on the movement characteristics of pedestrians under sudden contact forces, J. Stat. Mech. Theory Exp. 2021 (2021) 063406. https://doi.org/10.1088/1742-5468/ac02c7.

[5] S. Feldmann, J. Adrian, Forward propagation of a push through a row of people, Saf. Sci. 164 (2023) 106173. https://doi.org/10.1016/j.ssci.2023.106173.

[6] S. Feldmann, T. Chatagnon, J. Adrian, J. Pettré, A. Seyfried, Temporal segmentation of motion propagation in response to an external impulse, (2024). https://doi.org/10.48550/arXiv.2402.19024.

[7] S. Feldmann, J. Adrian, M. Boltes, Propagation of Controlled Frontward Impulses Through Standing Crowds, Collect. Dyn. 9 (2024) 1–16. https://doi.org/10.17815/CD.2024.148.