Use of Dimensional Analysis in the X-, Y-, and Z-Axis to Predict Occurrence of Injury in Human Stampede

Abdullah Alhadhira, MD; Michael S Molloy, MB; Marcel Casasola, MD; Ritu R Sarin, MD; Michael Massey, PhD; Amalia Voskanyan, RN; G.R. Ciottone, MD

ABSTRACT

Background: Human stampedes (HS) may result in mass casualty incidents (MCI) that arise due to complex interactions between individuals, collective crowd, and space, which have yet to be described from a physics perspective. HS events were analyzed using basic physics principles to better understand the dynamic kinetic variables that give rise to HS.

Methods: A literature review was performed of medical and nonmedical sourced databases, Library of Congress databases, and online sources for the term human stampedes resulting in 25,123 references. Filters were applied to exclude nonhuman events. Retrieved references were reviewed for a predefined list of physics terms. Data collection involved recording frequency of each phrase and physics principle to give the final proportions of each predefined principle used a single-entry method for each of the 105 event reports analyzed. Data analysis was performed using the R statistics packages "tidyverse", "psych", "lubridate", and "Hmisc" with descriptive statistics used to describe the frequency of each observed variable.

Results: Of the 105 reports of HS resulting in injury or death reviewed, the following frequency of terms were found: density change in a limited capacity, 45%; XY-axis motion failure, 100%; loss of proxemics, 100%; deceleration with average velocity of zero, 90%; Z-axis displacement pathology (falls), 92%; associated structure with nozzle effect, 93%; and matched fluid dynamic of high pressure stagnation of mass gathering, 100%.

Conclusions: Description or reference to principles of physics was seen in differing frequency in 105 reports. These include XY-axis motion failure of deceleration that leads to loss of human to human proxemics, and high stagnation pressure resulting in the Z-axis displacement effect (falls) causing injury and death. Real-time video-analysis monitoring of high capacity events or those with known nozzle effects for loss of proxemics and Z-axis displacement pathology offers the opportunity to prevent mortality from human stampedes.

Key Words: human stampede, mass gathering medicine, mass casualty incidents, disaster medicine, disasters

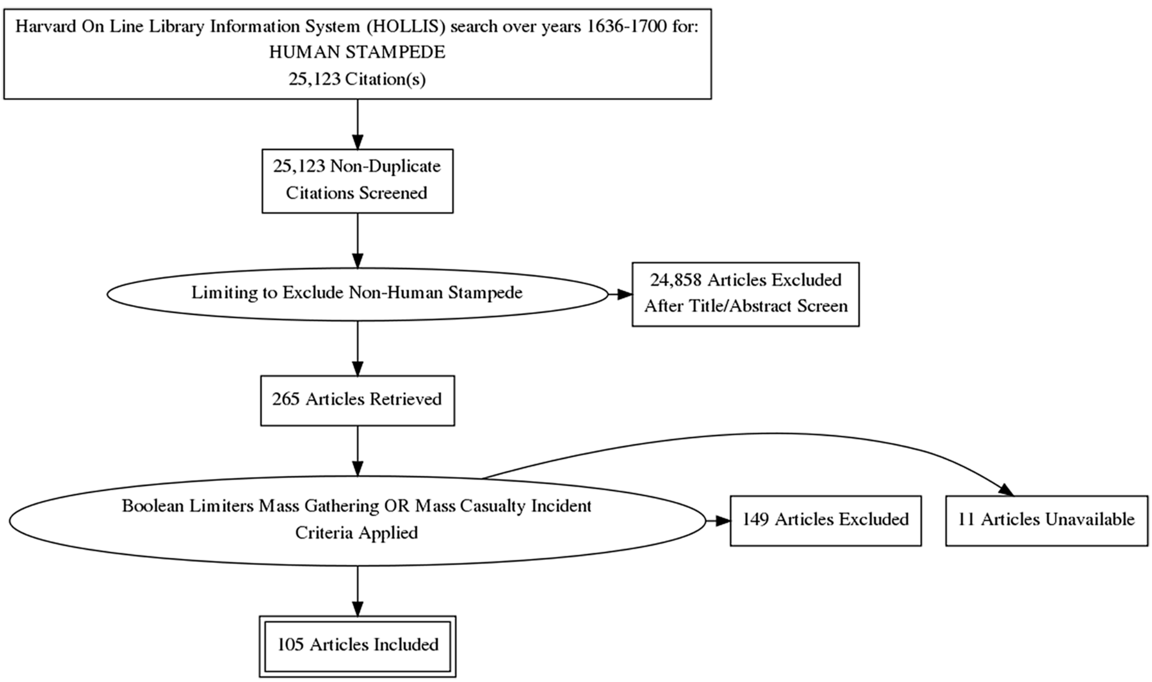
A human stampede (HS) often results in a mass casualty incident (MCI) when it occurs in a mass gathering (MG) event setting and can be associated with serious injuries and/or death, both frequently reported in medical and nonmedical literature.[1-4] Investigators have simulated crowd dynamics and MG behavior using computerized mathematical formulae to understand motion dynamics in different MG event scenarios, including religious, recreational, and rush reaction scenarios.[5] Video analysis techniques have been used to evaluate the architectural design,[6,7] flow dynamics,[8] and MG event themselves[9] as composite factors that may lead to HS events resulting in casualties.[10] There is a knowledge gap among medical professionals concerning the basic principles of mass gathering physics along with the application of human body dynamics and kinetics of motion as a single unit of mass in the complex mass gathering events.[11] As there is currently no standard international reporting system for HSs, HS events are often reported as independent incidents and not grouped and examined for shared variables that may determine HS mechanisms of injury. In this manuscript, we apply principles of physics to crowd dynamics in historical HS events that have resulted in mass casualties to better understand the mechanisms of injury. The goal is to identify variables that may have predictive value when applied proactively to the preparedness and response phases of mass gatherings.

METHODS

A systematic review was undertaken using the Harvard On Line Library Information System (HOLLIS) interface

FIGURE 1

PRISMA Chart.



using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) standard.[12] Within the date range of 1636-2017, the search filter was used for the following databases Academic Search Premier (EBSCOhost), Business Source Complete, Google Scholar, JSTOR, LexisNexis Academic, MLA Int'l Bibliography, ProQuest Dissertations and Theses, PsycINFO (EBSCOhost), PubMed (MEDLINE), Web of Science, WorldCat (FirstSearch), Medbox.org, and Disasterlit. Medical Subject Headings (MeSH), title, abstracts, and body text were searched for the term << HUMAN STAMPEDE>> resulting in 25,123 references. Limiting results to exclude nonhuman "STAMPEDE" events restricted the set to 265 unique references. Further Boolean limitations using the terms << MASS GATHERING>> AND << MASS CASUALTY INCIDENT >> resulted in a final set of 105 references as seen in Figure 1.

These 105 references met enrollment criteria for HS reports available for review (Table 1), and of these, 73 reports had either photographic images, video footage, or both available for analysis. Predefined physics principles variables were identified by a physicist including unit mass, density change, average velocity, XYZ-axis motion dynamics, fluid dynamics principles, and nozzle structure effects (Table 2).[13] Data collection used a single source entry method for each HS event by the primary investigator in Microsoft Excel (Microsoft Excel 2016 version 16.0, Redmond, WA). Each report was analyzed, and frequency of occurrence of these principles was abstracted by shared variables and grouped accordingly.

The phrases included the following: *Density and capacity phrases:* MG event, numbers of persons in attendance, capacity [space], number of tickets sold. *Average velocity of zero phrases:* pull and push, fast then stopped, jammed against, pushed against. *Motion phrases:* fast, rush, slow, stopped by, stand still, not moving, blocked by. *XYZ-axis displacement force phrases:* fall, jumped off, pushed up, stamped on, climbed, fell off. *Architectural evidence of nozzle effect:* gates, doors, exits, stairs, narrow street, ditch, mud, pits, bridge, barrier, rail, alley, corridor, passageway, tunnel. *High pressure stagnation phrases:* proxemics < 10 cm, no indicator of free motion, push and pull, fear reaction, squeezed, crushed, on each other (Table 2).

The reports were independently reviewed by a physicist who predefined the physics principles that matched mass gathering flow dynamics. The physicist also matched the extracted phrases to specific principles and variables such as unit mass, density change, average velocity, XYZ-axis motion dynamics, fluid dynamics principles, and nozzle structure effects. To measure the occurrence of repeated equally weighted phrases, a scoring system was created, with a score of 1 indicating the presence of a phrase related to a specified physics principle, and a score of zero, indicating its absence. Scores were entered

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TABLE 1

The Final Reports

Matched Reports Report No.	Reference:	Date	Country	Written Report Media	Media P/F Photography
Report 1	Non - Medical	10/11/1711	France	Yes	Yes
Report 2	Non - Medical	03/29/1809	Portugal	Yes	Yes
Report 3	Non - Medical	02/12/1823	Malta	Not Found	Yes
Report 4	Non - Medical	10/10/1872	Poland	Not found	Not Found
Report 5	Non - Medical	12/05/1876	USA	Not Found	Yes
Report 6	Non - Medical	05/30/1883	USA	Yes	Yes
Report 7	Non - Medical	06/16/1883	UK	Yes	Yes
Report 8	Non - Medical	05/18/1896	Russia	Yes	Yes
Report 9	Non - Medical	9/19/1902	USA	Not Found	Yes
Report 10	Non - Medical	12/30/1903	USA	Yes	Yes
Report 11	Non - Medical	1/11/1908	UK	Yes	Yes
Report 12	Non - Medical	3/4/1908	USA	Not found	Yes
Report 13	Non - Medical	12/24/1913	USA	Not Found	Yes
Report 14	Medical	12/31/1929	Scotland	Yes	Yes
Report 15	Non - Medical	1/8/1934	Japan	Not Found	Yes
Report 16	Non - Medical	10/23/1942	Italy	Not Found	Yes
Report 17	Non - Medical	3/3/1943	UK	Not Found	Yes
Report 18	Medical	6/6/1944	USA	Yes	Yes
Report 19	Medical	3/9/1946	UK	Yes	Yes
Report 20	Medical	4/9/1952	Venezuela	Not Found	Yes
Report 21	Medical	2/3/1954	India	Yes	Yes
Report 22	Non - Medical	1/1/1956	Japan	Not Found	Not Found
Report 23	Medical	1/1/1961	UK	Yes	Yes
Report 24	Medical	5/24/1964	Peru	Yes	Yes
Report 25	Non - Medical	9/1/1996	Turkey	Not Found	Not Found
Report 26	Non - Medical	6/23/1968	Argentina	Not Found	Yes
Report 27	Non - Medical	1/2/1971	Scotland	Yes	Yes
Report 28	Medical	12/3/1979	USA	Yes	Yes
Report 29	Medical	10/20/1982	Russia	Yes	Yes
Report 30	Medical	5/29/1985	Belgium	Yes	Yes
Report 31	Medical	7/31/1987	Saudi Arabia	Yes	Yes
Report 32	Non - Medical	3/13/1988	Nepal	Yes	Yes
Report 33	Medical	8/20/1988	UK	Yes	Yes
Report 34	Medical	4/15/1989	UK	Yes	Yes
Report 35	Medical	7/9/1989	Saudi Arabia	Yes	Yes
Report 36	Medical	7/2/1990	Saudi Arabia	Yes	Yes
Report 37	Medical	1/13/1991	South Africa	Yes	Not Found
Report 38	Medical	2/13/1991	Mexico	Not Found	Yes
Report 39	Non - Medical	9/24/1991	China	Not Found	Yes
Report 40	Medical	12/28/1991	USA	Not Found	Yes
Report 41	Medical	6/27/1992	Germany	Not Found	Not Found
Report 42	Non - Medical	1/1/1993	Hong Kong	Yes	Yes
Report 43	Medical	10/30/1993	USA	Yes	Yes
Report 44	Medical	5/23/1994	Saudi Arabia	Yes	Yes
Report 45	Medical	11/23/1994	India	Not Found	Yes
Report 46	Medical	10/16/1996	Guatemala	Yes	Yes
Report 47	Medical	1/1/1997	Scotland	Not Found	Yes
Report 48	Medical	4/9/1998	Saudi Arabia	Yes	Yes
Report 49	Medical	1/15/1999	India	Yes	Yes
Report 50	Non - Medical	5/30/1999	Belarus	Not Found	Yes
Report 51	Medical	12/4/1999	Austria	Not Found	Yes
Report 52	Non - Medical	6/30/2000	Denmark	Not Found	Not Found
Report 53	Medical	3/5/2001	Saudi Arabia	Yes	Yes
Report 54	Medical	4/11/2001	South Africa	Yes	Yes
Report 55	Non - Medical	5/9/2001	Ghana	Yes	Yes
Report 56	Non - Medical	7/21/2001	Japan	Not Found	Yes
Report 57	Medical	12/21/2001	Bulgaria	Not Found	Yes
Report 58	Medical	2/11/2003	Saudi Arabia	Yes	Yes
Report 59	Non - Medical	2/17/2003	USA	Yes	Yes

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TABLE 1

Continued

Matched Reports Report No.	Reference:	Date	Country	Written Report Media	Media P/F Photography
Report 60	Non - Medical	2/20/2003	USA	Yes	Yes
Report 61	Non - Medical	2/4/2004	China	Yes	Yes
Report 62	Medical	2/1/2004	Saudi Arabia	Yes	Yes
Report 63	Medical	4/12/2004	India	Not Found	Yes
Report 64	Medical	9/1/2004	Saudi Arabia	Not Found	Yes
Report 65	Medical	1/1/2005	India	Yes	Yes
Report 66	Medical	8/31/2005	Iraq	Yes	Yes
Report 67	Medical	12/1/2005	India	Not Found	Not Found
Report 68	Medical	1/12/2006	Saudi Arabia	Yes	Yes
Report 69	Non - Medical	2/4/2006	Philippines	Yes	Yes
Report 70	Non - Medical	9/12/2006	Yemen	Yes	Yes
Report 71	Non - Medical	6/2/2007	Zambia	Yes	Yes
Report 72	Medical	10/3/2007	India	Yes	Yes
Report 73	Non - Medical	10/5/2007	North Korea	Not Found	Yes
Report 74	Non - Medical	11/11/2007	China	Yes	Yes
Report 75	Medical	3/27/2008	India	Yes	Yes
Report 76	Non - Medical	6/20/2008	Mexico	Not Found	Yes
Report 77	Medical	8/3/2008	India	Yes	Yes
Report 78	Non - Medical	9/14/2008	Congo	Not Found	Not Found
Report 79	Medical	9/30/2008	India	Yes	Yes
Report 80	Non - Medical	10/2/2008	Tanzania	Yes	Yes
Report 81	Non - Medical	11/28/2008	USA	Yes	Yes
Report 82	Non - Medical	3/29/2009	Ivory Cost	Yes	Yes
Report 83	Medical	9/9/2009	India	YEs	Yes
Report 84	Medical	11/15/2009	UK	Yes	Yes
Report 85	Medical	12/8/2009	China	yes	Yes
Report 86	Medical	3/4/2010	India	Yes	Yes
Report 87	Non - Medical	5/4/2010	Amsterdam	Yes	Not Found
Report 88	Medical	6/6/2010	South Africa	Yes	Yes
Report 89	Medical	7/24/2010	Germany	Yes	Yes
Report 90	Medical	11/22/2010	Cambodia	Yes	Yes
Report 91	Medical	1/15/2011	India	Yes	Yes
Report 92	Non - Medical	1/15/2011	Hungary	Not found	Yes
Report 93	Medical	10/19/2011	UK	Yes	Yes
Report 94	Medical	11/8/2011	India	Yes	Not Found
Report 95	Non - Medical	3/18/2012	Egypt	Yes	Yes
Report 96	Medical	11/1/2012	Spain	Yes	Yes
Report 97	Non - Medical	1/1/2013	Ivory Cost	Not found	Yes
Report 98	Non - Medical	1/1/2013	Angola	Yes	Yes
Report 99	Non - Medical	1/27/2013	Brazil	Yes	Yes
Report 100	Medical	2/10/2013	India	Yes	Yes
Report 101	Medical	10/13/2013	India	Yes	Yes
Report 102	Medical	5/15/2014	Nigeria	Yes	Yes
Report 103	Medical	10/3/2014	India	Yes	Yes
Report 104	Medical	10/10/2014	Pakistan	Yes	Yes
Report 105	Non - Medical	11/21/2014	Zimbabwe	Yes	Yes
Report 106	Medical	12/31/2014	China	Yes	Yes
Report 107	Non - Medical	2/8/2015	Egypt	Not Found	Yes
Report 108	Medical	2/17/2015	Haiti	Yes	Yes
Report 109	Non - Medical	7/9/2015	Bangladesh	Not Found	Yes
Report 110	Medical	7/14/2015	India	Yes	Yes
Report 111	Medical	9/24/2015	Saudi Arabia	Yes	Yes
Report 112	Medical	10/25/2015	Afghanistan	Not Found	Yes
Report 113	Non - Medical	11/15/2015	Malta	Yes	Yes
Report 114	Non - Medical	10/2/2016	Ethiopia	Yes	Yes
Report 115	Non - Medical	3/6/2017	Zambia	Yes	Yes
Report 116	Medical	6/3/2017	Italy	Yes	Yes

Note: "Not Found" refers to reports for which the media report and/or photograph/footage (Media P/F) are not available for a variety of reasons, such as not having been photographed, political suppression of an event, or loss of records.

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TABLE 2

Predetermined Physics Terms/Principles		
Density Vs Capacity Changes	**Score**	**Score**
Mass gathering size	1	0
Number of a population	1	0
Capacity of Space	1	0
Number of sold tickets - volume	1	0
Average Velocity of Zero Phrases	**Score**	**Score**
Pull and Push	1	0
Deceleration Phrases	**Score**	**Score**
Stopped by	1	0
Slow movements	1	0
Not moving	1	0
Blocked by	1	0
Acceleration	**Score**	**Score**
Rush	1	0
Running	1	0
High Pressure Stagnation	**Score**	**Score**
Proxemics < 10 cm	1	0
High density > 6.5 people/m²	1	0
No Indicator free motion	1	0
Cannot escape	1	0
Fear reaction	1	0
Open Space Environment	**1**	**0**
Closed space environment	1	0
Nozzle effect	**Score**	**Score**
Gates - doors - exits	1	0
Stairs	1	0
Narrow street	1	0
Bridge	1	0
Barrier - rail	1	0
Closed space - small room	1	0
Alley - corridor - passageway	1	0
Z-Axis Motion Effect	**Score**	**Score**
Fall	1	0
Jumped or climbed	1	0
Pushed up or down	1	0
Stamped on	1	0

Note: Extracted phrases and reading scoring system indicate physics score 1 for present - score zero not present.

in a Microsoft Excel 2016 spreadsheet for analysis. All data processing and statistical analysis were preformed using R 3.4.2 (R Core Team 2017. A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria). Additionally, several R packages were used, including the "tidyverse" (Hadley Wickham 2017; R package version 1.2.1.), "psych" (Revelle, W. 2018; Procedures for Personality and Psychological Research Version = 1.8.4.), "lubridate" (Garrett Grolemund, Hadley Wickham 2011), and "Hmisc" (Frank E. Harrell Jr, 2018; Hmisc: Harrell Miscellaneous. R package version 4.1-1.) packages.

TABLE 3

Rate of Occurrence of Predetermined Physics Principles in Reports ($n = 105$)	
Observed Matched Variables in 105 Reports	**Percentage of**
Mass gathering event	100%
Reported density changes	45%
Evidence of loss of proxemics zone < 45 cm	100%
Evidence of motion deceleration	84%
Evidence of zero average velocity (reported as push and pull)	90%
Evidence of XY-axis 2D high pressure stagnation	100%
Z-axis effect (fall, fight, jumping, climbing, or pushed up or down)	92%
Human stampede incident outcome death or injury	100%

All the results from R system were converted into Excel sheets and sent to primary investigator for final analysis. (R open access language and environment for statistical computing and graphics available from https://www.r-project.org/about.html) was used to calculate descriptive statistics on this final dataset using the frequency of each observed variable. They were then analyzed using an abstracted phrase reading-scoring system to rank the variables based on the extracted phase matching the predefined physics principles. The mode of occurrence for each phrase from each of the 105 events were calculated. These were then used to calculate the frequencies of each phrase within each physics principle group, to give the final proportions of the presence of density change, loss of proxemics, average velocity, XYZ-axis motion dynamics, principles of fluid dynamics, and nozzle structure effects.

RESULTS

In 105 reports of HS resulting in injury or death, 61% of HSs reportedly occurred in an open space and 39% occurred in a closed space (hall, gymnasium, temple, church, mall, mosque). The density change in a limited capacity event correlated in 45% of the reports to a sudden population change in a limited space and, thus, reported more often in closed space situations. XY-axis motion failure was reported to have occurred in 100% of events, loss of proxemics was also found in 100%, and motion deceleration with average velocity of zero occurred in 90%. Z-axis displacement pathology (fall, jump, pushed up, or fall off) was present in 92% of reported events. An associated structural design with a nozzle effect was found in 93% of the cases, while 100% demonstrated a fluid dynamic principle of high-pressure stagnation in the MG (Table 3). To determine how well this research model measured matching

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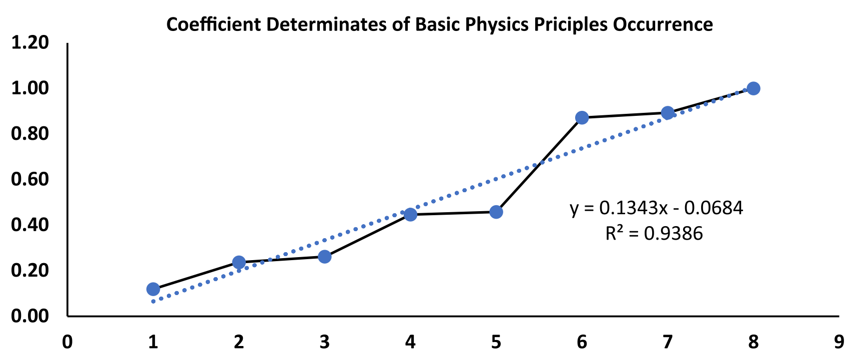
TABLE 4

Basic Physics Principles and Definitions

Mass	The measurement unit of how strongly an object (human bodies) resists acceleration (weight) [7].
Density of a mass gathering	The number of people per unit area.
Volume	Measurement of the spatial size of an object, and if the volume exceeds the shape of a space, this is called limited capacity.
Dynamics	The field of study of motion, which involves mass, force displacement (in units of distance), velocity (distance per unit time), acceleration (distance per unit of time squared), and momentum (mass times unit of velocity).
Rotational dynamics	Refers to movement in a curved path, and involves such quantities as torque, moment of inertia/rotational inertia, angular displacement, angular velocity (radians per unit time), angular acceleration (radians per unit of time squared), and angular momentum (moment of inertia times unit of angular velocity).
Bernoulli's laws	In fluid dynamics, the lower the flow velocity through a fixed area, the higher the pressure on the walls [8].
Nozzle effect	Converging – diverging structural design in which a nozzle (stairs, exits, gates, bridges, ally, streets, etc.) are used to control the rate of flow, speed, direction, mass, shape, and/or the pressure of the stream that emerges from them [9].
Stagnation pressure	Explained by Bernoulli's law, and is the flow field where the local velocity of the fluid is zero [10].
Proxemics	Refers to the human use of space, and the effects that population density has on behavior, communication, and social interaction [11,12].
Inelastic collision	Refers to when macroscopic bodies, such as a human body, hit other macroscopic bodies, and they stick to each other.

FIGURE 2

Coefficient of Determination (R^2).



the descriptive phrases to reports of HSs with casualties, the coefficient of determination (R^2) was calculated and found to be 0.94 (with 1.0 being highest "goodness-of-fit") (Figure 2).

DISCUSSION

The first well-documented HS with photographic or illustrative evidence occurred on the bridge of the Guillotière in Lyon, France, on 11 October 1711. Two hundred forty-five were killed in this event initiated by the coach of Madame Servient situated in the middle of the bridge while crowds were returning from a festival on the other side of the Rhône. Death during HS events often occurs from traumatic asphyxia due to loss of proxemics and crowd stagnation, with Gill and Landi concluding from autopsy findings that victims who die typically do so standing up as a result of compressive forces applied antero-posterior or vice versa and that those experiencing side-side compressive forces were more likely to survive.[14]

This study analyzes more than 300 years of medical and non-medical literature including drawings, photography, and video footage identifying HS as an independent mass gathering emergency event, which can result in severe morbidity, mortality, and have possible political implications. HS can be described with basic physics principles that create pockets of motion under 3 circumstances. Most commonly HSs occur at recreational events[4,15] (music[16], sport[17], shopping, shows, festivals[18]), religious events,[3,19,20] and also in a rush-reactive events[21,22] (rallies, wars, and disasters). In all circumstances, there are shared basic principles of physics variables that relate to the nature of the unit mass, which in this case is the human body.[23] This is why flow dynamics, the nozzle shape of certain spaces (stairs, doors, bridges, narrow streets, and small halls), and understanding the basic principles of motion are factors often seen in MGs and are essential in understanding the dynamics of HSs and mechanisms of injury resulting from them (Table 4).

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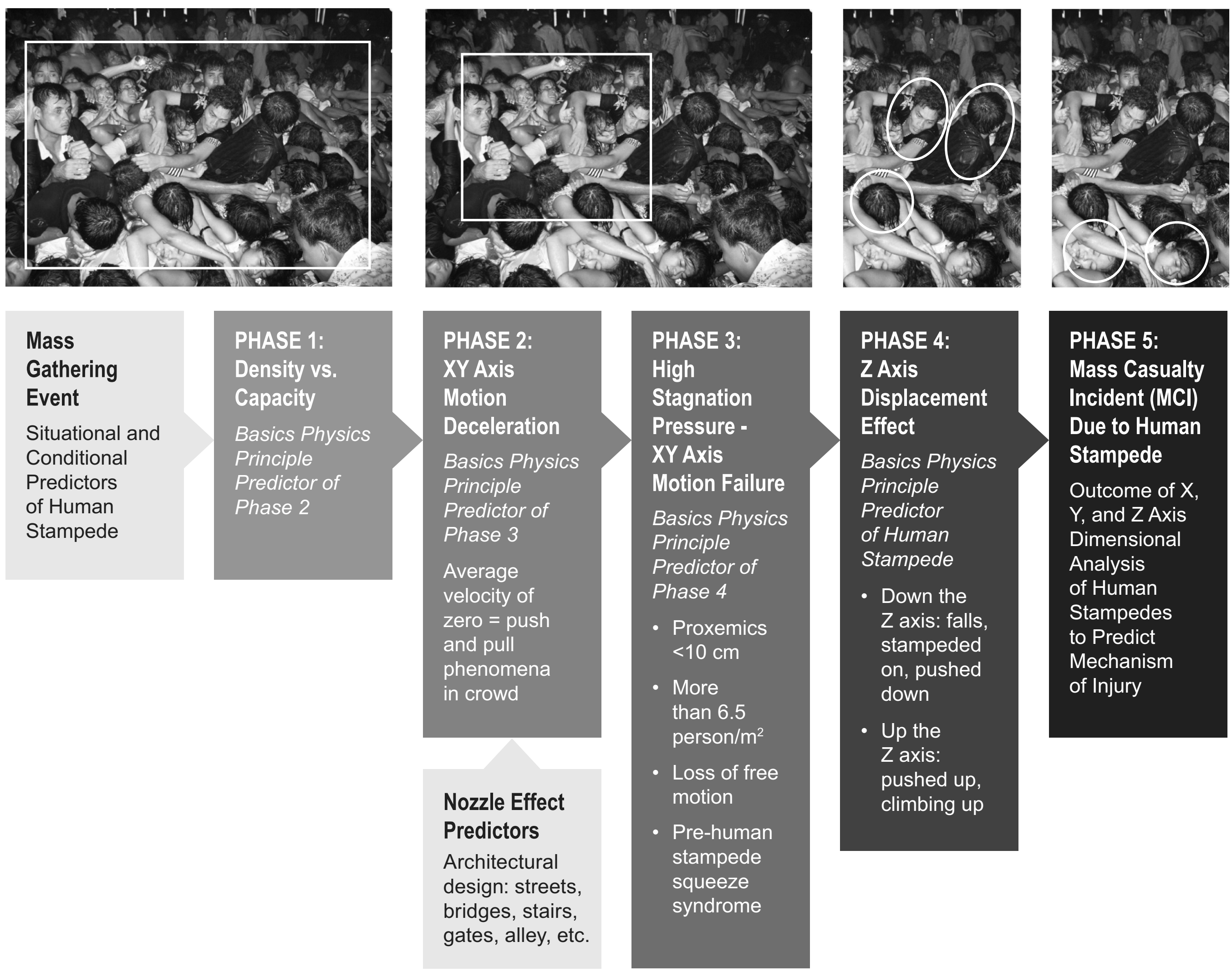
FIGURE 3

Motion Analysis Showing Cascade of Events (Phases) as Predictors of Injury or Death During a Human Stampede. (Image: Human Stampede on Nov. 22nd, 2010. Cambodia, Phnom Penh. Getty Image No. 107401316. Educational: Research and Publications Licence No. 2058233856).



The extracted data support the idea that a cascade of events may take place during a mass gathering that can lead to a HS. Principles of physics that determine the spatial relationship between people can be applied to the understanding of these events as follows. Crowds normally move in a 2-dimensional (XY) environment during a mass gathering, where the motion along the Z-axis is generally zero during stable crowd motion. If Z-axis movement is detected, it may be predictive of unstable crowd dynamics that may lead to injury or death.

The motion in a MG is consistent with concepts of fluid flow dynamics, where the participants are considered as particles. When the number of people increases in a limited space, this can lead to a high density per unit area, and each unit mass (a person) will lose proxemics, resulting in contact between them. When an increase in mass gathering density > 6.5 persons per /m^2 occurs, bodies tend to compress together rather than move apart, which causes the crowd to move in a linear direction.[24,25] In a MG in an open space, this movement will frequently be in a circular motion due to the rotational dynamics caused by the center point creating a torque of inertia.[26] In a closed space with high crowd density, the motion described can be accentuated with any nozzle-like architectural design.[27] Progression leads to motion failure along the XY-axis with high-pressure stagnation on the unit mass. A squeeze phenomenon develops, and the unit mass (person) may exhibit a motion along the Z-axis such as a fall, jump, or climb.

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A third, but less likely, change at such high-pressure stagnations is the MG-induced structural failure (Figure 3).[28]

Identifying the cascade of physical variables in HSs that result in mass casualties may have great predictive value if these factors can be incorporated into preplanning and real-time monitoring of mass gathering events, thereby enhancing mitigation, preparedness, and response. Before high-risk mass gathering events structural modifications can be constructed to limit occurrences of crowd-stagnation, nozzle effects, and loss of proxemics. Installing a real-time monitored video crowd motion analysis system to detect stagnation and sudden Z-axis motion changes may facilitate early protective measures potentially avoiding deterioration into a mass casualty event. Educating ourselves on the physics of crowd dynamics and those predictors of traumatic injury will help to limit morbidity and mortality so commonly seen in HSs. This XYZ dimensional analysis using principles of flow dynamics offers the first step toward realizing that goal.

CONCLUSIONS

Historically, event analyses and simulation models of HSs have not considered the Z-axis displacement effect and the implementation of XY-axis motion failure predictors. This study supports the conclusion that a cascade of physical events during a MG can lead to HS. Real-time video analysis monitoring of high capacity events or those with known nozzle effects for loss of proxemics and Z-axis displacement pathology offers the opportunity to prevent mortality from HSs. Further studies on real-time crowd XYZ-axis motion analysis are required to create predictive modelling scenarios.

About the Authors

BIDMC Fellowship in Disaster Medicine, Department of Emergency Medicine, BIDMC, Boston, Massachusetts (Dr Alhadhira, Mr Molloy, Drs Casasola, Sarin, Massey, Ms Voskanyan, and Dr Ciottone); Department of Emergency Medicine, BIDMC, Boston, Massachusetts (Drs Alhadhira, Casasola, Sarin, Ms Voskanyan, and Dr Ciottone); Harvard Medical School, Boston Massachusetts (Drs Alhadhira and Ciottone); Johns Hopkins ARAMCO Healthcare, Dhahran, Saudi Arabia (Dr Alhadhira); Emergency Department, Wexford General Hospital, Ireland East Hospital Group, Wexford, Ireland (Mr Molloy) and School of Medicine, University College Dublin, Ireland (Mr Molloy).

Correspondence and reprint requests to Abdullah A. Alhadhira, BIDMC Fellowship in Disaster Medicine, Department of Emergency Medicine, One Deaconess Road, WCC2, Boston, MA 02215, USA Telephone: +1 (617) 412-0660 (e-mail: aalhadhi@bidmc.harvard.edu).

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