Some studies on safe maximum packing of live agents in crowds or containers

O. Córdoba-Rodríguez, M. del Castillo-Mussot*, and J.A. Montemayor-Aldrete
Instituto de Física, Universidad Nacional Autónoma de México,
Apartado Postal 20-364 México, D.F. 01000 México.

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We study the geometrical and physical conditions for maximizing the safe packing of live agents in crowds or in containers, like wagons or subways. In order to accommodate small children in interstitial spaces among adults, we firs approximate standing-up people, as observed from above, as circles or ellipses. According to our results, in very crowded conditions babies are better protected only among "athletic" adults (in the sense that their shoulder-shoulder lateral distance is sufficientl larger than their lateral waist) by positioning them on the adults flan at kidney level. In several adults we applied sustained pectoral or thoracic pressure in order to fin the applied force dependence of the chest compression, and the maximum chest compression before not being able to breathe. For every f ve people barely fittin in a container, we can barely accommodate one more person, due to the chest compression of all persons. Practical recommendations are given in very crowded situations.

Keywords: Granular systems; medical physics; elasticity; pressure or forces in macroscopic solids.

Estudiamos las condiciones geométricas y físicas para maximizar el transporte seguro de agentes vivos en contenedores, como en vagones o metros subterráneos. Para acomodar a niños pequeños en espacios intersticiales entre adultos, primero aproximamos a las personas vistas desde arriba, como círculos o elipses. Según nuestros resultados, en aglomeraciones muy densas los bebés están mejor protegidos solo entre los adultos "atléticos" colocándolos a un costado a la altura de los riñones. En varios adultos aplicamos presión pectoral o torácica sostenida para encontrar la dependencia de la compresión pectoral en la fuerza y la máxima compresión pectoral antes de no poder respirar. Por cada cinco personas apenas ajustadas en un contenedor, podemos acomodar a otra persona más, comprimiendo los pechos de todos. Se dan recomendaciones prácticas in aglomeraciones muy densas.

Descriptores: Sistemas granulares; física médica; elasticidad; presión o fuerzas en sólidos macroscópicos.

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1. Introduction

In frequent situations, humans and animals are densely confine or packed in both small (cars, wagons, etc) or large containers (stadiums, discotheques, temples, etc). For example, an important process is the transportation of people or animals, because a large fraction of the Gross National Product of every country is absorbed by passenger and freight transportation costs, causing air pollution. As examples of recent studies on traffi and related vehicular emissions see Refs. 1-3. Furthermore, in the near future, transport costs may increase, due to the increasing technical difficultie in obtaining fuel for air and road transportation from exhausting oil sources [4]. Therefore, a growing share of passenger transportation will be carried on by collective transportation media. In order to save fuel, the use of collective human transportation media yields unfortunately to other types of problems associated with human crowds and packing. There are many studies about human fl ws in crowds, a topic considered to be interdisciplinary. In the normal pedestrian movement, the changes in fl w density occur smoothly without any jamming or crushing problems, but when in a relatively small place a high packing density is present, then very serious accidents may happen. See for instance reports and studies on some Muslim pilgrimages to Mecca [5], and sport events [6,7].

Human transportation process in containers involves relative movements between the different components forming the system, which gives rise to dynamical inertial forces which could imply serious possibility of damage for the live agents. Many physical and medical aspects of damage appear when inertial accelerations produce dangerous forces and pressures on the live beings and when violent collisions occur between transportation vehicles [8-14].

In this paper we study important and simple aspects of safe transport and packing of live beings when their densities are very high and they are confine by walls in relatively reduced spaces. We will focus on the study of the physical conditions which exist during transportation in order to accommodate the greatest number of people avoiding pectoral or thoracic injuries. The present work is divided into two parts. First we analyze geometrical conditions for the safe arrangement of children among adults, and, secondly, maximum thoracic sustained pressure tolerated by adult passengers during transportation in containers. The firs analysis is mathematical in nature, and the second is basically an experimental one.

2. Packing of small children among adults

2.1. Approach of human transversal sections by means of circles

As a firs approach we model the standing-up animals or people as circles when they are observed from above. Thus, in two dimensions, the problem of findin optimal packing conditions for *only* two types of people (adults and children) is reduced to findin the unknown radius r inserted in the adult interstitial circular spaces of radius R. This simple problem is the firs step toward solving a granular system applied to packing animals or people.

In Fig. 1, the triangle formed by the three centers of three equal-size circles is shown as an equilateral triangle with sides equal to 2R, where R is the radius of the circles representing adults. As we know, the circum center (intersection point of the median lines of the sides of the triangle) and the orthocenter (intersection point of the heights of a triangle) of an equilateral triangle are the same point (point O in Fig. 1), which are equidistant from any of the three triangle vertices. This point is the center of the central circle of radius r.

The radius r of the central circle is the difference between the distance OC (called x in our analysis) and R. Therefore r = x - R can be calculated from the OCA triangle, where θ is the angle formed by the median line of the vertex C. Since θ=30°, and from the OCA triangle we have:

$$\cos\theta = \frac{R}{x} \tag{1}$$

$$x = \frac{R}{\cos\theta} = \frac{R}{\frac{\sqrt{3}}{2}} = \frac{2R}{\sqrt{3}} \tag{2}$$

$$r = x - R = \frac{2R}{\sqrt{3}} - R = R(\frac{2}{\sqrt{3}} - 1) \tag{3}$$

The last equation gives a value of $r$with approximately 15% of value R. If we recall that we model sizes of people with these parameters, then this value is very small compared with R.

2.2. Approximation of human transversal sections by means of ellipses

A more realistic model of the human body for safe packing conditions is to consider the transversal sections of persons as ellipses, as seen from above, to simulate the difference between chest and shoulders. It is possible to employ a linear transformation which transforms the circle into an ellipse by extending or shortening the horizontal or vertical axes of the circle. The required linear transformation is

$$T(C(x,y)) = \left(\frac{\beta}{R}x, y\right) \tag{4}$$

where β is the horizontal axis of the ellipse and its vertical axis is R. Thus, to have an ellipse with horizontal axis β and vertical axis R, it is only necessary to apply the transformation (4) to a circle with radius R. We show in Fig. 2 the ellipses obtained by applying linear transformation. The ellipse with axes "a" and "b" that fit between the three large ellipses were the result of the same distortion of the corresponding circles.

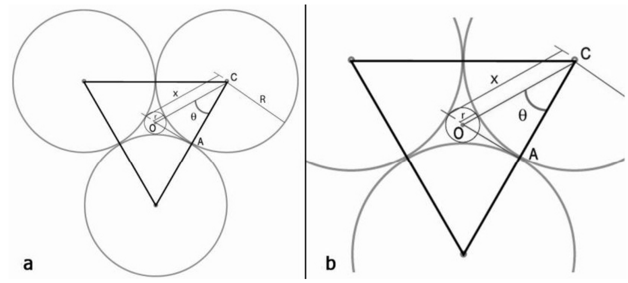

FIGURE 1. a) The small circle of radius r, between the three major circles representing adult passengers. b) An enlarged section of a).

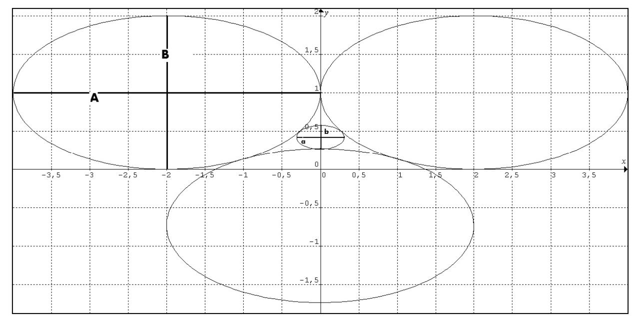

FIGURE 2. Example of the 3 ellipses with R=1 and b=2a. The semimajor axes (denoted by *a or A)* and the semiminor axes (denoted by *b or B*) are one half of the major and minor diameters, respectively.

2.3. Relevant sizes of adults and children

In order to apply this geometrical model in packing adults and children, we need to know their chest-to-back and shoulder-to- shoulder sizes. Dimensions of some young Mexican adults (only men) were measured, and similar data for babies were obtained the literature [15]. Thorax measurements were made in their "width" size (from chest to back) and "length" size (from shoulder to shoulder). Also "lateral waist" as define by the distance B in Fig. 3 was measured. In Tables I, II and III we present results and their average for Mexican adults of 20, 25 and 30 years old, respectively. In Table IV, we show results of cephalic radii of babies of different ages (and their average) extracted from the US Health Survey of the National Center of Health Statistics [15].

TABLE I. Thorax sizes of 20 year- old adults.

Person	From chest to back (± 0.5cm)	From shoulder to shoulder (± 0.5cm)	Lateral waist (± 0.5cm)
1	24.1	35.5	30.7
2	24.7	38.4	33.4
3	22.4	36.9	27.6
4	23.1	34.8	32.3
5	23.6	35.1	28.1
Avg.	23.6	36.1	30.4

TABLE II. Thorax sizes of 25 year-old adults.

Person	From chest to back (± 0.5cm)	From shoulder to shoulder (± 0.5cm)	Lateral waist (± 0.5cm)
1	28.4	39.7	34.3
2	28.6	38.6	32.5
3	27.8	38.4	32.2
4	29.7	41.9	35.7
5	28.9	40.4	34.2
Avg.	28.6	39.8	33.7

TABLE III. Thorax sizes of 30 year- old adults.

Person	From chest to back (± 0.5cm)	From shoulder to shoulder (± 0.5cm)	Lateral waist (± 0.5cm)
1	32.7	42.8	37.6
2	31.4	43.7	37.1
3	31.9	42.9	36.9
4	30.8	43.8	36.7
5	31.2	44.3	37.8
Avg.	31.6	43.5	37.2

TABLE IV. Cephalic sizes of babies of different ages.

Age of babies (months)	Cephalic Perimeter (cm)	Cephalic Diameter (cm)	Cephalic Radius (cm)
Birth	36.2	11.5	5.75
1	38.4	12.2	6.1
2	40.1	12.7	6.35
3	41.6	13.3	6.65
4	42.8	13.6	6.8
5	43.6	13.8	6.9

For babies approximately younger than one year old, the cephalic perimeter is the largest perimeter of their bodies [16]. It has been established in Ref. 17 that these data can be applied to Mexico, which is useful because we can try to see if Mexican babies fi between Mexican adults

2.4. Safe space for babies in a container at full adult capacity

For the case of the babies we approximate their heads as circles, as seen from above, to compare their sizes to the free space in Table V.

Therefore, our results show, for purely geometrical reasons, that the interstitial space left in close-packed adults arrangement is *too* small to accommodate the smallest baby (newly born), even in the case of 30 year- old adults, who represent the larger ellipses.

2.5. Protecting infants by positioning them on the adult flank

Since the interstitial space left at thorax level is too small, here we will show that an alternative way to protect an infant is to guard him on the flan of the adult around the level of the kidneys.

In a firs approximation the torso of a person could be considered as a trapeze with the greater base A at the shoulders and the smaller base at the waist B (Fig. 3), leaving between them a lateral free space X for the baby, which is the subtraction of A and B. In Table VI the corresponding results obtained from using the same-age-average data from Tables I, II, III, and IV are presented.

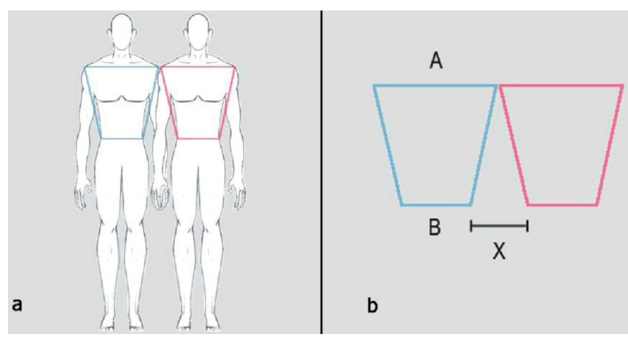

FIGURE 3. (a) Two people arrangement with torsos as trapezes are shown, (b) Distance X due to the difference between shoulders and waists; X= A – B.

TABLE V. Sizes of large ellipses (adults) and free spaces created by three contiguous adults compared with average newly born cephalic diameter.

Age of adults (years)	Dimensions from compressed from chest to back (± 0.5cm)	Dimensions from shoulder to shoulder (± 0.5cm)	Maximum space between three contiguous adult people (± 0.5cm)			Since the size of cephalic diameter (cm) of a newly born is 11.5, then
			2b	2a	Avg.	
20	23.6	36.1	7.0	10.8	9.0	the space is too small
25	28.6	39.8	8.6	12.0	10.2	the space is too small
30	31.6	43.5	9.4	13.0	11.2	the space is too small

TABLE VI. Comparison between free spaces on the flan of the adults and the radius of the babies' chest.

Person (age in years)	Shoulders (A) (±0,5(cm)	Waist (B) (±0,5cm)	Value of X (A-B) cm	Since the size of cephalic diameter (cm) of a newly born is 11.5, then
20	36.1	30.4	5.7	the space is too small
25	39.8	33.7	6.1	the space is too small
30	43.5	37.2	6.3	the space is too small

TABLE VII. For athletic people, comparison between the space of the flan of the adults created by the difference of width between shoulders and the waist, and the cephalic diameter of the chest of the babies.

Person (age in years)	Shoulders (A) (±0.5 cm)	Waist (B) (±0.5 cm)	Value of X (A-B) cm	Cephalic diameter of almost newly born babies (cm) (± 0.5cm) Babies ages (months)
20	39.5	28.2	11.3	11.3 (newly born babies)
25	43.2	31.4	11.8	11.8 (newly born babies)
30	45.6	33.2	12.4	12.4 (one- month babies)

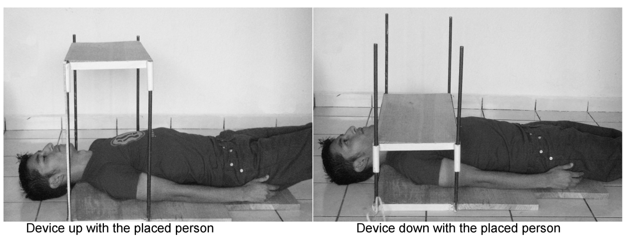

FIGURE 4. The load device used to apply pressure on the thorax consists of a sliding wood platform supporting different weights.

Therefore for the set of people mentioned here in Table VI, the babies can not be protected by adults at the best position, which is in general at kidney level. However for men with largest values of X (namely "athletic people") it is possible to protect babies at kidney level, as shown in Table VII.

In summary, according to the results of Table VII, which have been obtained only on geometrical grounds, it is possible to accommodate one month-old babies and younger at the free space of human flank when they are packed laterally, only in the case of athletic adults, in the sense that their shoulder-shoulder lateral distance is sufficientl larger than their lateral waist.

Of course, a few extra centimeters may be won by elastic compression of the lateral bellies of adults.

3. Forces on adult thorax and breathing capability

People in crowds or travelling in collective transport media are facing potential risk of suffering asphyxia during the events of human agglomeration. It is possible that some of the passengers (especially children) may not have enough space to perform their natural breathing movements. In addition, crushing stresses could be induced by dynamical accelerations on containers, which also produce hazardous situations. In this section we restrict our experimental study only to *very slow* changes of pressure applied on the human thorax. That is, we do not study the effects of sudden and strong changes of applied force which occur in collisions, for instance.

3.1. Experiments

In order to fin the maximum distributed force on human thoraxes just before producing lack of breath, we performed experiments consisting in adding masses of different weights upon chests of several young adults human who are lying down (see Fig. 4). An experimental limit was imposed to the total weight in order not to surpass long periods or levels without breathing. Several other safety measures were taken.

The experiment could be done in two ways.

i) One method in which weights are slowly added with a time lag between one step and another, to help the person to recover after each measurement. However, since the weights were added slowly, little by little, people got physically tired since the whole process took a long time, despite the fact that we allowed people to recover after each measurement.

ii) The second method was to rapidly increase the weights, so the time of physical stress was shorter, allowing the use of heavier loads.

Of course, this last method is more dangerous and it requires more care, so for safety reasons we tried firs the slower method described in i), which gives an estimation of the people's ability to tolerate weights.

The persons who collaborated in these experiments were the same as those who were measured to obtain the data in Tables I, II and III.

TABLE VIII. Forces (kg) for which it was no longer possible to breath.

Person	20 years	25 years	30 years
1	36	40	39
2	34	41	38
3	35	41	41
4	36	43	39
5	37	42	41
Avge.	35.6	41.6	39.6

TABLE XIX. Deformation before losing one's breath.

Age	Weigth (±0.5Kg)	Deformation (±0.5cm)	Initial chest to distance back	Deformation (%)
20	35	5.4	23.6	22%
25	41	6.4	28.4	22%
30	39	4.2	31.7	13%

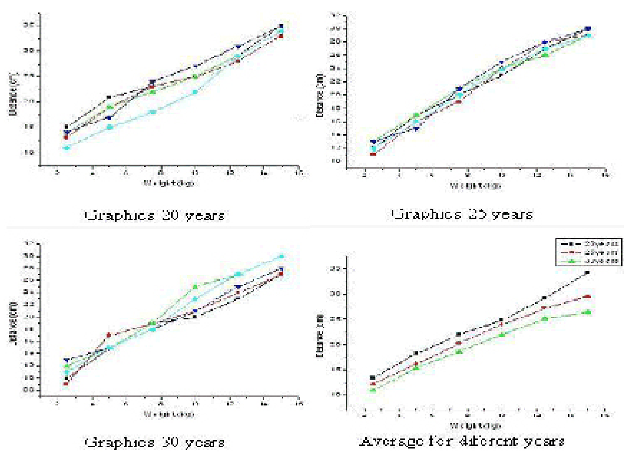

FIGURE 5. Plots of downward chest displacement caused by application of weight, and their average vs. applied force on human thorax for people of different ages; 20, 25 and 30 years old, respectively. Each color or symbol represents one person.

Our experimental data for elastic deformation response of adult chests is shown in Fig. 5 with the slow method described in i) above. The downward displacement of human chests (or chest to back) due to the action of the applied weights were measured. Experimental data show that the decrease in chest height (contraction) is more or less directly proportional to the applied force, therefore following Hooke's law. This is an important result, because it allows us to extrapolate to values that we could not test experimentally, due to possible health risks (asphyxia or rib fracture).

Also, following the fast method described in ii) above, we obtained and show in Table VIII the maximum weight that could be supported before lack of breathing occurred due to the failure to execute the necessary muscular movements to expand the chest. The results presented in this table were obtained independently from those presented in Fig. 5. The corresponding results for chest-to-back compression distances before losing one's breath and the percentage of deformation before this occurs are shown in Table XIX.

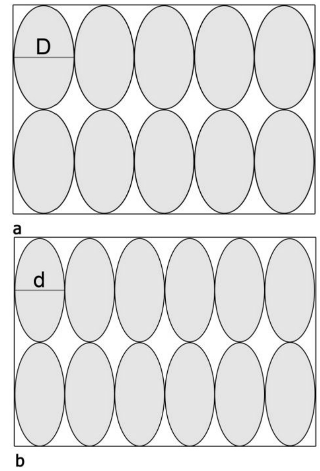

FIGURE 6. We fin that for each 5 people fittin in a container, we can accommodate one more person, due to uniform contraction of D to become d.

3.2. Fitting six instead of five

We found that the maximum chest compression measured here, beyond which the person is not able to breathe, is approximately 20% of the chest to back dimensions. That is, at best, in young adults, the chest can be carefully contracted by 20%, to remain within the safety limit. Therefore, in a pack of f ve people in a container without suffering compression, another person can be accommodated under maximum compression conditions at risk. In other words, we can accommodate up to 6 people in a container designed for 5 (Fig. 6). In a moving container, this is valid for very low acceleration or deceleration conditions, as compared with acceleration of gravity.

It is important to mention an almost unknown method to protect persons under pressure, which is a kind of stampede protection belt a patented invention [18], which is simply a ring placed around the chest, with can be modificate to wear it confortably.

4. Concluding remarks

In summary, since finit fossil fuels become more expensive, due to their future depletion as populations increase, all human collective transportation will be under very high usage pressure. So in a near future the trend will be to accommodate the highest possible density of people (children and adult) inside buses, trains or subway containers. We focused our efforts on simple but useful aspects of optimal packing conditions in crowds. We must take into account the fact that children are more susceptible to suffer injuries.

Of course, the best way to protect babies or children from accidents in crowd agglomerations or in mass transportation media is to avoid taking them with us. But if they have to be transported, an alternative is to accommodate the babies on adult flank in order to diminish the probability of asphyxia or rib fracture of the babies. Another possibility for protection is to promote the use of a modificatio of the stampede protection belt [18], and its variations. We hope that this work may stimulate and promote further safety measures and policies for people in crowds, including the weakest of them: children, handicapped the disabled, and the elderly. We acknowledge useful discussions with G.G. Naumis, C. Anteneodo, W.A.M. Morgado, technical help from J. Moguel, and partial financia support from DGAPA-UNAM, México, through Grant No IN114208.

∗ e-mail: marcelodlcstll@yahoo.com

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