A scientific investigation of risk in large gymnastic formations

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Abstract—Japanese schools hold field-day events in spring and autumn, and large gymnastic formations are frequently performed at these events. Over 8,000 accidents related to these formations occur each year, one in four of which involves bone fractures. One factor behind these accidents is attempts at increasingly high human pyramids and towers. This paper calculates the structural loads involved in such human pyramids and demonstrates the dangers involved.

Keywords—gymnastic formation, human pyramid, structural load, accident, risk management

1. Collapse of a ten-tier human pyramid

On 1 October 2015, a ten-tier human pyramid (Fig. 1) collapsed at a field day event at an Osaka junior high school, resulting in bone fractures in two students and other injuries in six additional students. In May 2014, the collapse of a different ten-tier human pyramid at a junior high school in Kumamoto Prefecture injured a student on the bottom level, causing a lumbar fracture that required one month to heal. Shocking videos of these events were widely shown on news broadcasts, raising awareness of gymnastic formations as a social problem.

Fig. 1: A ten-level human pyramid.

Associate professor Ryo Uchida of Nagoya University first raised the topic of the risk involved in increasingly large gymnastic formations.[1] Uchida presents arguments from the standpoint of educational sociology, but I have performed an investigation based on mathematics and engineering, and found that the maximum structural load in a ten-tier human pyramid is 3.9 persons.

I first became interested in this issue in September 2015, when the Osaka Board of Education announced restrictions on gymnastic formations, with limits of five tiers for pyramids and three tiers for towers. (Here, a "pyramid" refers to a triangular or triangular pyramid form, while a "tower" refers to a cylindrical form.) In the gymnastic formations that I partook in during the 1960s, sixth-graders formed three-tier pyramids, and ninth-graders formed four-tier pyramids. I had never heard of a ten-tier pyramid, and so at first did not understand the need for this new restriction.

Watching the collapse of these ten-tier pyramids reminded me of the 1978 Miyagi Earthquake, in which 18 people died due to the collapse of an unreinforced concrete block wall. Human pyramids are supported solely by the students forming them, so I wondered whether school staff had considered what would happen to the 150 students involved if an earthquake occurred while a pyramid was being formed.

2. Accidents related to gymnastic formations

According to statistics from the Japan Sport Council, in 2014 there were 8,592 injuries at elementary and junior high schools related to gymnastic formations, 1,241 of which occurred in tower formations, 1,133 in pyramid formations, and the remainder to other formations. The accident rate has remained largely stable, at over 8,000 incidents every year since 2011.[2] In the past 46 years, there have been 9 deaths in gymnastic formation accidents, and 92 children left with permanent disabilities. While details of the fatal accidents are not generally available, I found descriptions of three cases in newspaper archives.

The first was a sixth-grade girl, who died while practicing a gymnastic formation in Gunma prefecture in 1983. The newspaper reported that two students were squatting while facing each other with their arms entwined, and another student standing on their shoulders. When the two tried to stand up, she fell onto their backs. This description corresponds to what is today called a two-tier (three person) tower.

The second fatal accident occurred in 1988, when a sixth-grade boy at a school in Ehime prefecture died while performing a human pyramid for a graduation photo. Newspaper reports state that, under faculty instructions, 13 male students were forming a pyramid with tier sizes of 5, 4, 3, and 1 students, and the pyramid collapsed while forming the third tier. This thus corresponds to a 13-person, four-tier pyramid.

The third incident occurred at a Kanagawa prefecture school, where a ninth-grade student died while practicing forming a tower. The tower was formed by 5 students standing on the shoulders of 10 students in the first tier, 3 students atop the second tier, and 1 in the top tier. This therefore corresponds to a four-tier tower formed by 19 students. When the tower collapsed, one of the students in the second tier landed face up on the ground, where he broke his neck.

These cases suggest that accidents commonly occur during practice, not during field-day events. Also, there are more accidents in towers, and even students in the second tier can die of injuries from the accident.

3. From flat to three-dimensional formations

There have been many court cases related to serious injuries from accidents related to gymnastic formations. The court ruling in one such incident allows us to see details of the event.[3]

In 1990, a high school in Fukuoka planned to attempt an eight-tier pyramid. In a collapse during practice, a student in the center of the first tier experienced a cervical spine fracture, resulting in a first-degree physical disability. In 1994, the Fukuoka Prefecture High Court confirmed a 1993 ruling by the Fukuoka District Court for compensation of over 100 million yen.

The eight-tier pyramid in this case was a stacked plane formation formed by 58 students, with eight tier comprising four upper tiers atop four base tiers. The accident occurred after formation of the four base tiers, when the fifth tier began wobbling as the sixth tier was attempting to form. Figure 2 shows the load distribution in a five-tier pyramid, and shows that the injured student was bearing a load of 3.9 students.

				0	0	0	0				
			0	0.5	1.0	1.0	1.0	0.5	0		
		0.5	1.3	1.8	2.0	2.0	1.8	1.3	0.5		
	0.8	1.9	2.5	2.9	3.0	2.9	2.5	1.9	0.8		
	0.9	2.3	3.2	3.7	3.9	3.9	3.7	3.2	2.3	0.9	

Fig. 2: Load distribution in the collapsed pyramid at a Fukuoka high school

This collapse of an eight-tier pyramid brought about changes in how acrobatic formations are performed. For simple stacked planar formations, an upper limit of five tiers was established, and starting around the year 2000, square and triangular pyramids began to be formed. Such solid shapes were formed in more than five tiers: first seven and eventually even ten.

Considering the simple stacking pyramids as “planar” and the more recent pyramid forms as “solids,” human pyramids have thus evolved from two-dimensional to three-dimensional shapes.

4. Calculations of load in pyramids

(1) Planar loads

Let’s calculate the loads in a ten-person, four-tier planar pyramid. For this simplified calculation, we will assume that all students weigh the same.

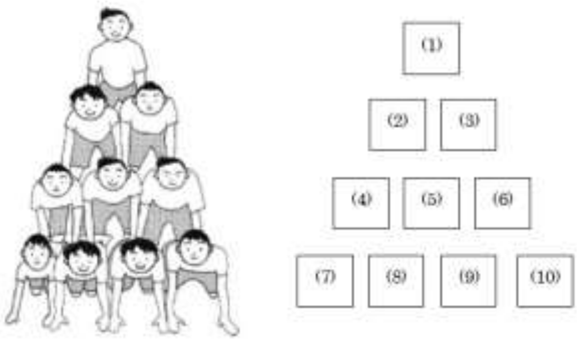


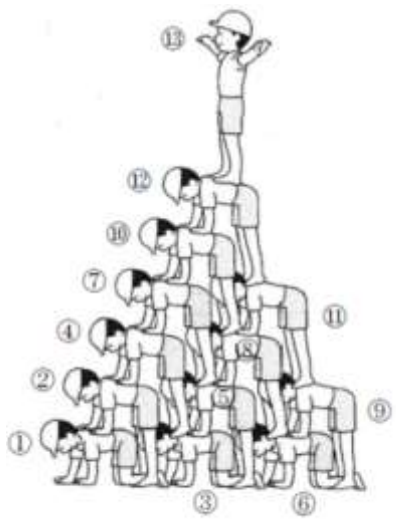
Fig. 3: A four-tier, planar pyramid[7]

This pyramid is formed with 4 students in the base tier, 3 in the second tier, 2 in the third tier, and 1 on top. We will calculate the load from top to bottom. There is no one atop student (1) in Fig. 3, so his load is 0. The two students in the next tier down (third tier) share the load of the student above, so the load on students (2) and (3) is 0.5 each. Student (4) in the second tier directly bears half the load of (2), but it would be a mistake to think that this means a total load of half of 0.5. Indeed, we must add the weight of (2) himself to his 0.5 load, so the total load is half of 1.5, as follows:

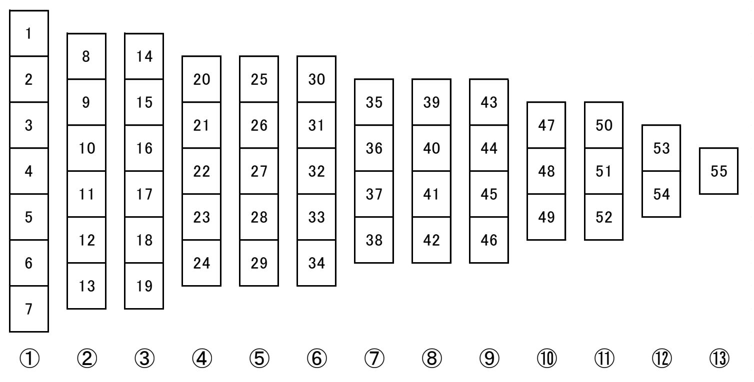
$$(0.5 + 1) \div 2 = 1.5 \div 2 = 0.75.$$

From symmetry, students (6) and (4) both bear a load of 0.75. Student (5) receives half the loads of (2) and (3), so the load there is $1.5 \div 2 + 1.5 \div 2 = 1.5$. Continuing in this manner, students (8) and (9) bear the highest loads, of 2.125. The total loads for each student are thus 0, 0.5, 0.5, 0.75, 1.5, 0.75, 0.875, 2.125, 2.125, and 0.875 for the students in order from (1) to (10).

(2) Load in three-dimensional forms



1. Pyramid viewed from the side[5]



2. Rows prior to assembly, viewed from above

Fig. 4: A three-dimensional seven-tier pyramid

Let's calculate the loads in a 55-person, seven-tier triangular pyramid, following Fig. 4. Here again, we will assume that all students weigh the same. We will furthermore assume relative limb support strengths of 3 for arms and 7 for legs.

The pyramids we are familiar with from Egypt have four sides, but the three-dimensional human pyramid form that has recently become popular is a triangular pyramid shape with three sides. This form is probably chosen because it involves fewer people. Viewed from the side, we get an image like that in Fig. 4.1. We will number the rows formed by the fifty-five students as 1–13, from bottom to top. Figure 4.2 shows expansions of the rows.

The first row has 7 students, with hands and knees on the ground. The second row has 6 students, with feet on the ground and hands on the backs of students in the first row. The third row has 5 students, with hands and knees on the ground and heads between the legs of the students in the second row. The fourth row has 5 students, with feet on the shoulders of those in the third row and hands on the backs of those in the second row. The fifth row has 5 students, with feet on the ground, hands on the backs of those in the third row, and heads between those in the fourth row.

A similar procedure is followed from the 5 students in the sixth row through 1 student in the thirteenth row. Calculation of loads in the solid follow a pattern similar to used that for the planar form, starting with the uppermost row (student 55 in row 13) and proceeding down. This can easily be calculated using a spreadsheet, but doing so requires establishing relations between the 55 students. For example (indicating right as R, and left as L, hands as H, and feet as F), on the back of student 32 in row 6 we find the left foot of student 40 in row 8 (40LF) and the right foot of student 41 (41RF), the left hand of student 44 in row 9 (44LH) and the right hand of student 45 (45RH).

We begin calculating from student 55 in row 13, who has no one above and thus a load of 0. Next, student 54 in row 12 has one foot, and so a load of 0.5, as does student 53. One foot of student 53 in row 12 is on student 50 in row 11, but because we are distributing loads as 3:7 between arms and legs, we have a load of

$$(0.5 + 1) \times 0.7 \div 2 = 0.525.$$

We proceed in a similar way, referencing the relations from top to bottom. For example, the load on student 32 in row 6 is calculated as the total from four separate loads (40LF, 41RF, 44LH, 45RH), and this student has the maximal load, of 2.41.[11]

Planar and three-dimensional pyramids have highly different characteristics that deserve particular attention. Notably, students on the faces of a ten-tier pyramid bear loads of no more than 0.5. Among the students in this three-dimensional form, a similar calculation to that performed above shows that the largest load of 3.9 is borne by student 32 in row 6. This student is in the middle of the pyramid, and thus cannot be viewed from the outside. Furthermore, since pyramids will tend to collapse toward the middle, posting faculty members around the periphery of the pyramid will not improve safety.

5. Comparison of planar and three-dimensional forms

The average weight of a ninth grader in Japan is 54 kg., so a maximum load of 3.9 students is in excess of 200 kg. At least, this is the static load (the weight one obtains by placing an object on a scale); it does not well represent the dynamic load experienced when the pyramid wobbles, nor the impact load when it collapses.

Table 1 compares maximum loads in planar and three-dimensional human pyramids, and shows the number of persons required to form pyramids of up to ten tiers. As that table shows, the maximum loads in a planar pyramid are 0.5 persons for a two-tier pyramid, 1.5 for three tiers, 2.1 for four tiers, 3.1 for five tiers, and 3.8 for six tiers. I could not find record of a successful seven-tier planar pyramid.

Table 1: Comparison of planar and three-dimensional pyramids

Tiers	Planar pyramid		Three-dimensional pyramid	
	# persons	Max. load	# persons	Max. load
2	3	0.5		
3	6	1.5		
4	10	2.1	13	1.1
5	15	3.1	22	1.5
6	21	3.8	37	1.7
7	28	4.8	55	2.4
8			81	2.8
9			111	3.1
10			151	3.9

Comparing forms with the same number of tiers, three-dimensional pyramids have lower loads than do the planar forms. These are generally created for four-tier structures and higher, in which the maximum load is 1.1 persons. This progresses to 1.5 for a five-tier structure, 1.7 for six tiers, 2.4 for seven tiers, 2.8 for eight tiers, 3.1 for nine tiers, and 3.9 for ten tiers.

In Table 1, I have highlighted the maximum load of 3.8 for a six-tier planar pyramid and the maximum load of 3.9 for a ten-tier pyramid, because these correspond to the loads experienced in the 1990 accident in Fukuoka and the 2015 accident in Osaka, the details of which are described above. Looked at another way, this is simply a 25-year reconfirmation that the maximum weight that a junior high school student can support is around 200 kg.

6. Recommendations for seven-tier pyramids

I found three books recommending seven-tier three-dimensional pyramids for fifth and six graders. These are noteworthy because they are books by teaching faculty promoting the formation of large gymnastic formations, written at a time when such formations have become a social problem.

The first is *Instruction for Gymnastic Formations*, edited by Masao Nemoto, which on pages 144–145 provides a detailed description of how to create what it calls a "55-person pyramid."[5] The writer here is Junichi Yokota, but the references include Nobuyuki Motoyoshi's *The 55-person Pyramid in Practice* from the Teacher's Organization for Skill Sharing.

The second book is Masaru Toda's *Commentary on Gymnastic Formations*, which describes large pyramids on pages 34–37.[6] It includes positioning diagrams for square pyramids, which require 113 students to form seven tiers. Toda teaches the formation of large pyramids through the Saitama Prefecture Gymnastic Formation Association.

The third book is *Assured Success in Gymnastic Formations* by the Kansai Physical Education Seminar (KPES), which describes a 55-person pyramid on page 75.[7] The office of the KPES is in the Ikeda Elementary School, which is associated with Osaka Kyoiku University. Until recently, this organization was very active in conducting seminars related to gymnastic formations.

Yoshiro Yoshino, formerly a teacher at Itami Junior High School, actively teaches large pyramid formation through seminars, DVDs, and YouTube videos. In his master's thesis, Yoshino describes four successful formations of a ten--tier three-dimensional pyramid at Tennojigawa Junior High School.[4]

There is much to learn about the basis for gymnastic formations from the works of Seiichi Hamada. The diagrams in his *Illustrated Gymnastic Formations*[8] remind one of the anatomical drawings of Leonardo da Vinci. His "Guidelines for Gymnastic Formations" include the following: "It is not the height attained that matters—the quality of gymnastic formations should be evaluated according to the skillfulness of their composition, the utilization of their component members (by developmental stage and gender), the rhythm and emphasis of the form, cooperative assembly using the right person in the right place, skillfulness of the disassembly process, and the results of practice." Also, "This is not a competition of speed, endurance, or height; pursuing only the surprising and unexpected is dangerous, and deleterious to the sport of gymnastic formations."

It is my hope that educators who continue to promote the formation of giant pyramids will take the time to revisit the works of Hamada.

7. Gymnastic formations at the Diet

Associate Professor Ryo Uchida, mentioned above, started an Internet-based petition called "Toward the realization of safe gymnastic formations: A demand that Hiroshi Hase, Minister of Education, Culture, Sports, Science and Technology, place tier limits on gymnastic formations," and collected 20,000 signatures in a short time.

Of the 700 National Diet members, only Akihiro Hatsushika has taken up the issue of gymnastic formations. He has learned through his own experience the dangers of large formations, and held in the Diet Members' Building a study group titled "Prevention of Serious Injury under School Supervision" to answer questions regarding gymnastic formations from the Education, Culture, Sports, and Science Committee in the Japanese House of Representatives. Following that, a nonpartisan group was established, and the Japan Sports Agency and the Ministry of Education, Culture, Sports, Science and Technology issued warnings to Boards of Education throughout Japan.

Using data from the Japan Sport Council to list the number of accidents by prefecture, we can see that most (2,074) occurred in Osaka, followed by Hyogo (1,890), and then Tokyo (1,476). Examining the data according to the number of injuries per 10,000 students, the most dangerous areas were Hyogo (19.9), Fukuoka (14.7), and Osaka (14.2). There is not necessarily a strong correspondence between the number of injuries and the injury rate. For example, Mie prefecture was in 13th place in terms of number of injuries, but this places them in 4th place according to their injury rate (Table 2).

Table 2: Number of injuries and injury rate by prefecture[10]

Number of accidents in elementary and junior high schools, 2012–2013		Accident rate (number of accidents per 10,000 children)	
1. Osaka	2074	1. Hyogo	19.9
2. Hyogo	1890	2. Fukuoka	14.7
3. Tokyo	1476	3. Osaka	14.2
4. Fukuoka	1233	4. Mie	13.6
5. Saitama	1133	5. Tottori	13.2
6. Chiba	860	6. Wakayama	11.8
7. Aichi	825	7. Nara	11.69
8. Kanagawa	794	5. Nagano	11.67
9. Hiroshima	544	9. Hiroshima	11.4
10. Shizuoka	454	10. Kyoto	10.8

Local governments have responded in various ways to the issue of whether and how to limit gymnastic formations. Some, like Nagareyama city in Chiba prefecture, have abolished all use of gymnastic formations. Osaka has forbidden the formation of pyramids and towers, while Nagoya has limited pyramids to four tiers, and towers to three. Hyogo prefecture has only issued a warning, leaving specific limits to the discretion of individual schools.

8. The need for a scientific view

An accident occurred during the formation of a four-tier tower at an elementary school in Tokyo's Kita ward. The tower was constructed as shown in Fig. 5,[9] with 15 students forming tiers of 6, 5, 3, and 1 students. A four-tier tower is normally created using 16 students (with 6 in the second tier), and when 15 are used there is an uneven distribution of force.

The formation in which an accident occurred

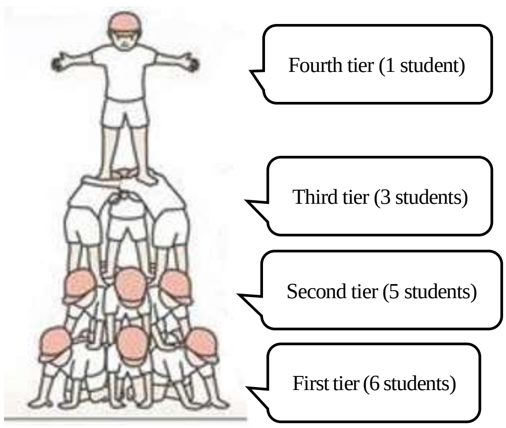
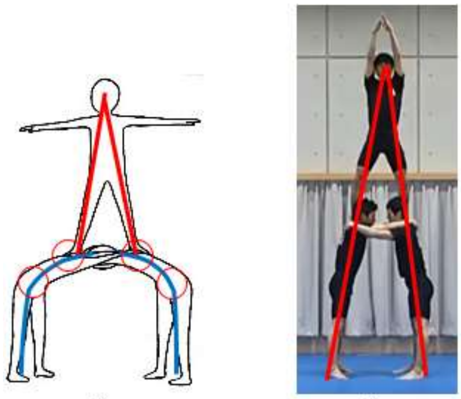


Fig. 5: A faulty four-tier tower[9)]

In this case, a four-tier tower was created using 15 students for a very poor reason: there were 96 students at this school, so the original plan was to create six four-tier towers of 16 students each, but one student was absent that day. Tower formation proceeded, regardless.

Another common formation is a two-tier tower called the “antenna,” in which two students generally bend forward to create a base (Fig. 6.1). However, Professor Ryosuke Miyake of Nippon Sport Science University has noted a problem with this common form: it is supposed to be performed with the persons forming the base standing straight, so that force is transmitted along the body axis (Fig. 6.2).

The fact that there are over 8,000 accidents annually shows the necessity for educators to use mathematics and science to calculate loads so that they can differentiate between safe and dangerous activities. I also hope that scientists will take an interest in this problem, and fulfill their social responsibility of providing appropriate advice.



(1) (2)

Fig. 6: Two-tier towers[12]

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