Risk Assessment of Air Cannons at Sporting Events

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RISK ASSESSMENT OF AIR CANNONS AT SPORTING EVENTS

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ABSTRACT

This study looked to determine the safety of air cannons used at public events based on experimentally collected ballistic data. Specifically, the probable injuries to bystanders resulting from being hit by various projectiles launched from air cannons were investigated. Due to the rapid deceleration of projectiles fired from air cannons as they travel through the air, this study focuses on the worst case scenario: point blank impacts. Based on data collected using a chronograph and force plate, this study asserts that it is likely an air cannon operating under the conditions of this experiment can cause significant ocular, maxillofacial, laryngeal, and extremity injuries. To mitigate the risks posed by using air cannons, this study recommends the use of safety glasses for operators, mandatory operator training, automatic trigger locking mechanisms, frequent inspections of the cannon, regulations on the projectiles that can be fired, and the establishment of a minimum firing distance between the operator and bystanders.

INTRODUCTION

Air cannons (i.e. t-shirt launchers) are increasingly popular at sporting events and have become more advanced and powerful. Air cannon manufacturing companies are providing access to systems with increased ranges and higher muzzle velocities (the speed of the projectile as it exits the barrel). At the same time, there is sparse detail about the inherent risks these systems produce for spectators, other than information detailing the small risk of internal barrel explosions. There is also scarce literature detailing the potential hazards across the variety of projectiles that these cannons can effectively launch. This is important to the numerous stadiums and other venues that employ air cannons as their misuse is grounds for litigation seeking compensation. Legal precedent has been set that any object fired from air cannons at sporting events are not classified as incidental to the game and are thus additional hazards assumed by the stadium [1]. A detailed evaluation of the characteristics and potential damages of an air cannon would be of interest to promote spectator safety and reduce risk for officials who employ these systems at their events.

PROBLEM STATEMENT

This study sought to determine the safety of air cannons used at sporting events and other public venues based on experimentally collected ballistic data using a chronograph and a portable force plate. Specifically, the likely injuries to humans resulting from being hit by various projectiles launched from air cannons were investigated. These projectiles were chosen based on objects commonly found at sporting events: rolled up t-shirts, tennis balls, and miniature footballs, that can also often be associated with advertising or marketing activities.

To determine the hazards of each projectile, the kinetic energies, impact forces, and impact pressures were calculated from experimentally collected data. These results were then compared to human injury tolerance studies published in various medical and automotive journals to determine the likely effects of each projectile.

For the purposes of this experiment, only the worst case scenario was examined as it proves most valuable to organizations that employ these air cannons. Rolled up t-shirts can be modeled as right cylinders as they travel through the air, but in reality the t-shirt is not stable in flight. Tumbling, spinning, and partial unraveling during flight drastically increase the coefficient of drag and severely decrease the velocity of a t-shirt after it exits the barrel. As such, the worst case scenario for each projectile is determined to be a point blank impact, meaning that the target is less than a meter away from the muzzle.

To determine the potential damage these projectiles can cause to bystanders, four categorized injuries of interest were chosen. Nasal, ocular, throat, and extremity injuries were investigated in this experiment due to the relatively small force required to inflict damage, and their likelihood of being hit with a projectile. Spectators at public events being struck in the face and injured by air cannon projectiles have been documented [2], and extremity injuries are likely to occur in similar situations. In addition to unsuspecting bystanders sustaining injuries, observant bystanders attracted to air cannons and their projectiles may also be injured. Overly enthusiastic spectators may try to jump in front of air cannons or stick their hand in front of them in an attempt to prevent the souvenir from flying overhead to a different spectator, potentially resulting in injury.

EXPERIMENTAL METHODS

Projectiles

All projectiles were fired from a commercially available air cannon, whose identification is withheld for privacy purposes. The air cannon's barrel has an internal diameter of 8.0±0.1cm and was operated at pressures ranging from 138kPa to 552kPa (20-80psi). The compressed air was provided by a commercially available portable compressor.

In accordance with the scope of the experiment, the t-shirt folding technique was varied and tested to determine which configuration would produce the highest velocity and thus pose the greatest risk. The folding technique that produced the greatest velocities is a five step process that uses an adult large t-shirt and warps it into a tight cylinder with an aspect ratio (length: diameter) of approximately 2. First the sleeves were folded inward so that the outside edges of the t shirt were flush. Next, the outside edges of the t-shirt were folded to the vertical centerline and the resulting configuration was folded in half along the same vertical centerline. Finally, the shirt was tightly rolled from the base of the shirt to the collar and bound at both ends by a rubber band. The resulting cylinders measured on average 7.5±1cm (3.1in) in diameter and 16±1cm (6.3in) in length. The other folding techniques that did not produce the greatest velocities utilized larger aspect ratios, looser rolls, and varying amounts of tape.

This folding technique was repeated for all of the following measurement tests to maintain consistency. All t-shirts used were adult large short sleeve cotton shirts. One standard tennis ball was used for all trials as well, measuring 6.7±0.1cm (2.7in) in diameter. Furthermore, one miniature foam football measuring 8.5±0.1cm (3.3in) in diameter was used in all trials for consistency.

For each variable of interest, velocity and impact force, ten trials were conducted to produce an average value for the calculations. This experiment focused on determining kinetic energy, impact force, and impact pressure for each projectile as these are the measurements referenced in medical journals when providing standards for various injuries.

Kinetic Energy

The kinetic energy (KE) of a projectile was calculated using equation (1) by measuring its mass (m) with an electronic scale, and its velocity (v) with a commercially available ballistic chronograph.

$$KE = \frac{1}{2}mv^2 \tag{1}$$

The velocity was measured with a chronograph placed 20cm in front of the muzzle as depicted in figure (1). Additionally, the air cannon's internal pressure was set to 550±10kPa (80psi), the manufacturer's highest recommended setting in order to achieve the highest velocities. Because the velocity was measured a short distance from the muzzle, the calculated kinetic energies are referred to as the muzzle energy, allowing for easier comparisons with other projectiles.

The projectiles' flights directly before impact were recorded using a high-speed camera sampling at 1000 frames per second. The videos were used to investigate the impact orientation, displaying the pitch, yaw, and roll of each projectile. To highlight changes in the orientation of the projectiles, a black and white striped "piano board" was used as a backdrop for the high-speed camera.

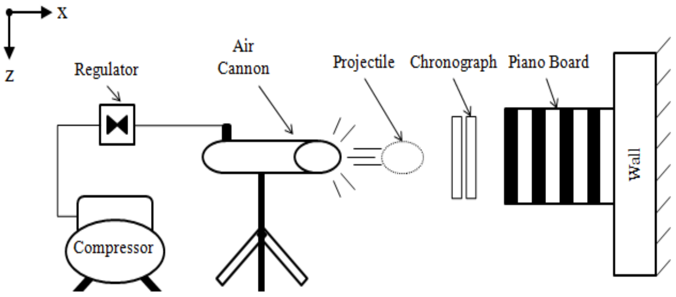

FIGURE 1. KINETIC ENERGY TEST SETUP

Initial Force

The maximum force of a projectile occurs while it is still in the barrel, shortly after the pressurized air is released. Therefore its initial force is

$$F = PA \tag{2}$$

where P is the pressure inside the barrel (fixed at 550±10kPa) acting over A, the cross-sectional area of the projectile.

This measure represents the maximum theoretical force that can be imparted on the projectile. For this experiment, the t-shirts were modeled as idealized cylinders with flat homogeneous ends. Although no measuring device was used to record the initial force of the t-shirt, the value is likely lower than the idealized value due to the irregularity of t-shirts.

The theorized initial force of the projectiles was then compared to the impact force recorded by the force plate. A comparison of the two demonstrates how much force is dissipated over the projectile's flight.

Impact Force

Due to the size of the force plate used, and its inability to rotate, all tests were conducted vertically (see figure 2). The air cannon was fixed in a tripod and oriented downward (z-direction) orthogonal to the surface of the force plate. The chronograph was placed directly below the muzzle recording the velocity before impact, and the force plate below the chronograph to record the impact force. The muzzle of the launcher was positioned 97±1cm (38in) from the force plate, providing ample room for the projectiles to rebound off of the force plate without impacting the backside of the chronograph.

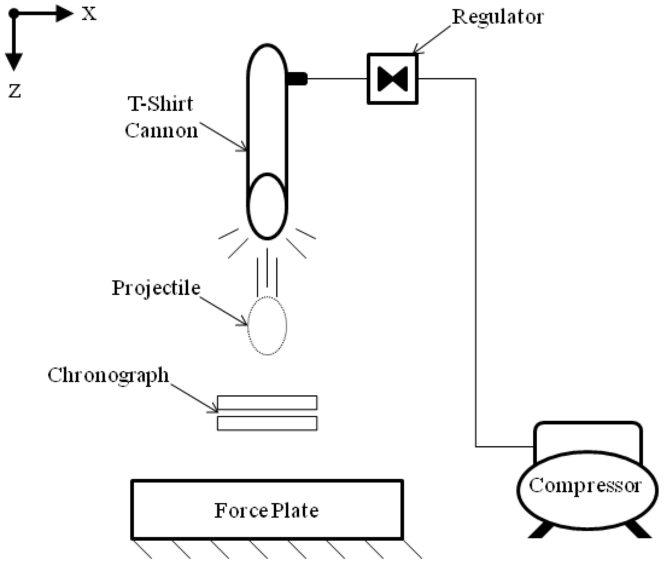

FIGURE 2. IMPACT FORCE TEST SETUP

Because the air cannon fired the projectiles downward along earth's gravitation pull, the projectiles experienced an additional acceleration equal to if it were simply dropped from that height. The recorded impact force, a function of mass and acceleration would display a slight increase in the measured value. However, this slight increase in acceleration is negligible in comparison to the larger acceleration generated by the air cannon.

The force exerted by each projectile during impact was measured by a commercially available force plate. The force plate recorded force exerted in all three directions at a 200Hz sampling rate.

To determine the impact force of the projectile, the resultant force was calculated from the three force vectors (F_x, F_y, F_z) provided by the force plate using the equation below.

$$F_{net} = \sqrt{{F_x}^2 + {F_y}^2 + {F_z}^2} \tag{2}$$

Ideally, the impact would be perfectly orthogonal, meaning the projectile would contact the force plate perpendicularly, distributing the force evenly over its entire cross sectional area, exerting no forces in the x or y directions. But due the rolled up t-shirts' inability to maintain stable flight, the idealized situation did not present itself and equation (2) was used to calculate the net impact force.

With values for the impact force being recorded over time, the impulse (J_{impact}) of the impact was also calculated by taking an integral of the imparted forces over the duration of the impact.

$$J_{impact} = \int \vec{F}\, dt \tag{3}$$

The time differential (dt) is the time over which the impact force acts on the force plate. Due to the 200Hz sampling setting of the force plate, the time differentials used are in increments of 5ms.

Medical Comparison

The calculated values for kinetic energy, impact force, and impact pressure were compared to those in medical and automotive journals that outline human tolerances to various injuries. The journals consulted include: the Archives of Ophthalmology [7], the British Journal of Ophthalmology [8], the Journal of Maxillofacial and Oral Surgery [10], the Annals of Advances in Automotive Medicine [11], proceedings from the Stapp Car Crash Conferences [3] [12], and the Journal of Hand Surgery [13],

Each journal provided benchmarks for the kinetic energies, forces, and pressures required to cause ocular, maxillofacial, throat, and extremity injuries. This study focuses on the face, throat and fingers, as they are regions susceptible to injury from non-penetrating compressible projectiles. These injuries can manifest when a spectator is unaware of an incoming projectile, or when an overly enthusiastic spectator reaches their hand in front of the muzzle in an attempt to catch the projectile.

Specifically, the air cannon's ability to cause nasal and midfacial fractures, global ruptures (bursting of the eyeball), orbital penetrations (breaching the eye socket), laryngeal cartilage fracture, and impact induced mallet finger (tearing of the extensor tendon) were examined.

When comparing the recorded impact forces to those listed as human tolerance levels, the peak force was used. Previously, Nahum et al. has shown that peak forces recorded during blunt impact can accurately be used when determining tolerance levels [3].

RESULTS

Kinetic Energy

A seen in Table 1, the large-sized folded t-shirt had the largest muzzle energy (233±10J), whereas the miniature foam football had the greatest muzzle velocity (82±5m/s). The football lacked the muzzle energy of the t-shirt due to its lower mass (47.5±0.5g compared to 143.0±0.5g) characterized by equation (1).

TABLE 1. KINETIC ENERGIES

Projectile	Average Velocity [m/s]	Average Kinetic Energy [J]
T-Shirt	57±5	233±10
Tennis Ball	60±5	105±10
Mini Foam Football	82±5	160±10

The variability of each shot through the chronograph introduced the largest amount of uncertainty (±5m/s) into the kinetic energy calculation, resulting in an uncertainty of ±10J for each value. Due to inconsistencies in the behavior and flight of some projectiles, the chronograph would not register the projectile or would display unrealistic values on various occasions. The chronograph had difficulties measuring the velocity of the rolled t-shirts especially as the rubber bands would occasionally disconnect from the t-shirt prematurely triggering the sensor. Additionally, small variability in the rolled t-shirts produced slightly altered geometries because of the pressure within the barrel and air resistance during their flight, which further increased uncertainty.

Video results from the high-speed camera show that the rolled up t-shirts did not fly ideally. Within 20cm of the barrel, some t-shirts began to either tumble end over end, or spin about the z-axis and continue to do so until impacting the target. Figures 3and 4 are screenshots showing a t-shirt in front of the piano board immediately before impact.

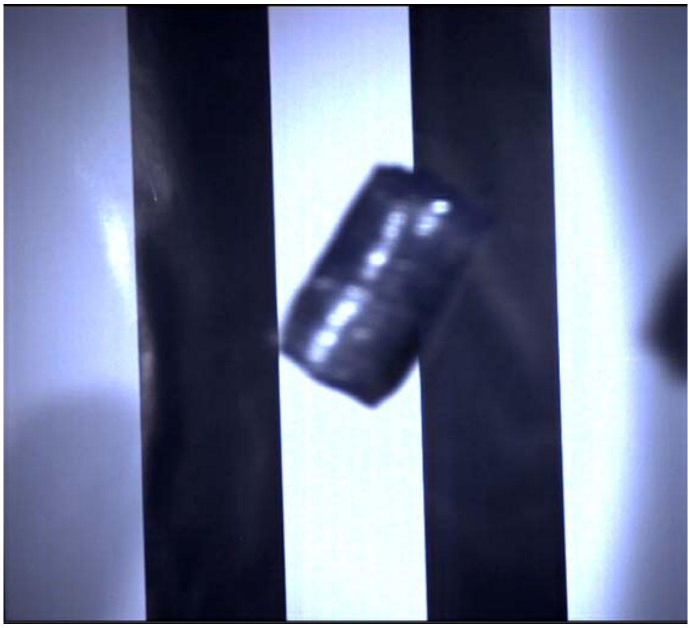

FIGURE 3. PRE-IMPACT PITCH

The t-shirts' continuous tumbling and spinning during flight likely results from a poor aerodynamic shape. As a result of the rolling technique, the t-shirts had blunt profiles with helical crevices that did not direct air around the body as a rounded nose would. Additionally, the air cannon barrel does not have rifling, which would induce roll into the system while decreasing the pitch and yaw.

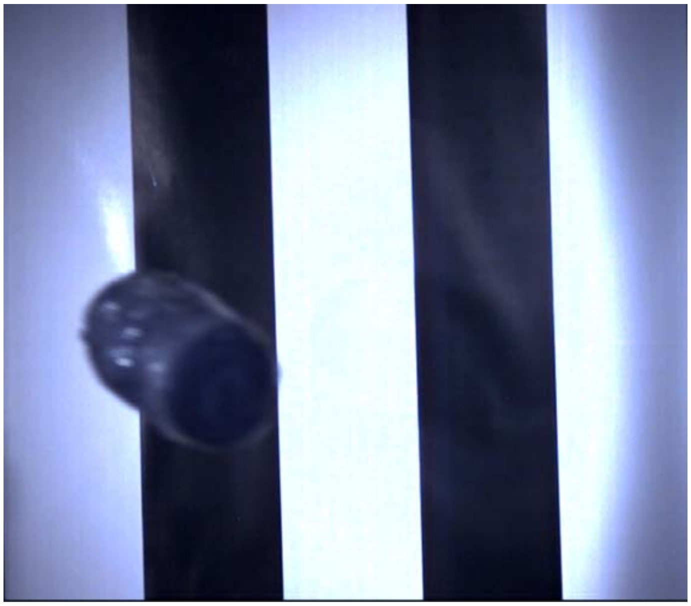

FIGURE 4. PRE-IMPACT YAW

Furthermore, differences in the obturation of the rolled t-shirt likely contribute to its unstable flight. Obturation is the amount of space a projectile occupies in the barrel, and since all t-shirts were hand rolled, their levels of obturation varied. Because the t-shirts never had perfectly circular profiles, the loaded t-shirt contacted the inner diameter of the barrel unevenly. Therefore the pressure was not applied uniformly over the cross-sectional area of the t-shirt and instead escaped through small gaps between the t-shirt and the barrel. This non-uniform application of force likely produced different instantaneous velocities along the cross-section of the t-shirt. The combination of these irregularities likely caused the undesired rotations about the y and z axis.

Initial Force

With an internal pressure set by the regulator to 550±10kPa (80psi), the initial force and thus maximum force of the projectiles are displayed below.

TABLE 2. INITIAL FORCES

Projectile	Cross Sectional Area [cm^2]	Force [N]
T-Shirt	44±2	2,439±1
Tennis Ball	35.3±0.2	1,976±1
Mini Foam Football	56.7±0.2	2,771±1

Due to the fixed 550±10kPa setting and small differences in the cross sectional areas in the projectiles, their resulting maximum forces are similar. Nevertheless, the miniature foam football experienced the greatest force of 2.77kN, as it had the largest cross-sectional area.

Also important to note is that because the barrel has an internal diameter of 8.0±0.1cm, each projectile had a varying degree of obturation. The tennis ball (diameter of 6.7±0.1cm) was small enough that it only contacted the lower half of the barrel, whereas the miniature football had an initial diameter larger than the barrel and was compressed by the inner walls of the barrel, maintaining complete obturation. For the calculation, the internal diameter of the barrel (8.0±0.1cm) was used instead of the football's initial diameter. The t-shirt (diameter of 7.5±1cm) was mostly obturated as it had a diameter similar to the barrel. Due to imperfections in the folding technique, the rolled t-shirt was not perfectly circular and did not contact the barrel evenly at every point.

Impact Force

The impact force of the rolled t-shirt recorded by the force plate can be seen below in Table 3. The average resultant force was 1,481±1N, roughly 61% of the theorized maximum force the projectile experienced in the barrel. Additionally, non-negligible forces were recorded in the x and y directions. Although these forces were on average 9% and 3% of the vertical impact force respectively, they increased the net force by 9N.

TABLE 3. T-SHIRT IMPACT FORCE DATA

Trial	F_x [N]	F_y [N]	F_z [N]	F_{net} [N]
1	93	4	1,428	1,431
2	129	18	1,539	1,545
3	89	147	992	1,007
4	191	4	1,432	1,445
5	165	44	1,971	1,978
Average:	133±1	44±1	1,472±1	1,481±1

Ideally, the impact would be perfectly orthogonal, meaning that the values for F_x and F_y would both be zero and the only recorded force would be along the z-axis. The nonzero values recorded along both the x and y-axis therefore suggest that the impact was not perfectly orthogonal. Perfectly orthogonal impacts were likely not achieved due to the unstable flight of the t-shirts portrayed in Figures 3 and 4. With inconsistent rotations about the x and y-axis during flight (different from kinetic energy tests due to change in firing orientation), each t-shirt impacted the force plate with a slightly different orientation. A t-shirt that experienced rotation predominantly about the x-axis would produce a large F_y value compared to its F_x value (trial 3). Conversely, a t-shirt that experienced rotation predominantly about the y-axis would produce a large F_x value compared to its F_y value (trials 1, 2, 4, and 5).

Table 4 presents the three primary measures used to investigate non-penetrating impacts: impact force, impact pressure, and impulse. Although the relatively small forces exerted along the x and y-axis indicate that the impact may not have been perfectly orthogonal, the impact force was assumed to act evenly over the entire cross-sectional area. The time difference between the leading edge and trailing edge on the same face of the cylindrical t-shirt roll upon impact is negligible. This simplifies the pressure calculation and results in an average impact pressure of 335±5kPa.

TABLE 4: IMPACT CALCULATIONS

Trial	F_{net} [N]	P_{net} [kPa]	J_{impact} [N·s]
1	1,431	324	7.15
2	1,545	350	7.72
3	1,007	228	5.03
4	1,445	327	7.23
5	1,978	448	9.89
Average:	1,481±1	335±5	7.41±0.01

The forces recorded by the force plate were highly ephemeral, existing only in one time step. As such, the minimum time differential fixed by the force plate (5ms) was used for all impulse calculations. The average impulse imparted by a folded t-shirt was 7.41±0.01N•s.

Medical Comparisons

Table 5 compares the muzzle energies of the folded t-shirts, tennis ball, and miniature football calculated in this experiment, to the known muzzle velocities of other projectiles in similar apparatuses.

TABLE 5: COMPARING KINETIC ENERGIES

Apparatus	Projectile	Kinetic Energy [J]
Air Cannon	T-Shirt	233±10
Air Cannon	Tennis Ball	105±10
Air Cannon	Mini Foam Football	160±10
Paintball Gun	3.5g Paintball	14
Pellet Gun	0.51g Pellet	26
9mm Pistol	7.5g Bullet	465

The folded t-shirts achieved kinetic energies fifteen times larger than that of a paintball gun, nine times larger than that of a pellet gun and nearly half that of a 9mm handgun. The projectiles in this study generated kinetic energies much higher when compared to a paintball and pellet gun due to the mass of the projectiles. Paintballs and pellets have higher average velocities at 90m/s and 320m/s respectively, but much smaller masses than the air cannon projectiles, measuring on average 3.5g and 0.51g respectively [4] [5]. The muzzle energy calculated for the 9mm pistol projectile was based on a 7.5g bullet that travels on average 1,349ft/s [6].

According to a 1999 study, a baseball traveling 24.6m/s (55mph) generating approximately 88J can rupture the human globe [7]. Interestingly to note, of the projectiles tested, all of them exceeded the 88J benchmark. The diameter of a baseball is 7.27cm equating to a cross-sectional area to 41.5cm^2, which is similar to the cross-sectional areas of the projectiles used in this experiment detailed in Table 2.

Moreover, a separate study comparing the velocities of various projectiles found at sporting events to the degree of ocular damage found that a tennis ball traveling at 40m/s penetrated 18.6mm into the human orbit (i.e. the eye socket), and a size 3 soccer ball traveling at 18m/s penetrated the orbital 8.1mm [8]. As seen in Table 1, the velocities of all projectiles tested in this experiment achieved velocities 20m/s to 54m/s higher than those measured in the previous study. Additionally, a size 3 soccer ball has a diameter of 18-19cm, roughly 2.5 times larger than the diameter of the rolled up t-shirt in this experiment [9].

The average impact force exerted by a rolled up t-shirt in this experiment was measured at 1481±1N. For comparison, Table 6 lists facial structures and their respective fracture tolerance range as functions of impact force [10].

TABLE 6. FACIAL STRUCTURES FRACTURE TOLERANCES

Facial Structure	Fracture Tolerance
Nasal Bones	111-334N
Maxilla	623-1979N
Zygomatic Body	890-2002N
Zygomatic Arch	925-2113N
Mandible	1890-4115N
Frontal Bone	3559-7117N

The impact force measured in this study exceeds by over four times the maximum fracture tolerance of the nasal bones determined by Pappachan and Alexander [10]. The folded t-shirts' impact force exists within the range of fracture tolerances of the midface bones. The midface bones are those between the mouth and eyes, namely the maxilla, zygomatic body, and zygomatic arch. Bones outside of the midface region (mandible and frontal bone) are considerably stronger and have higher resistances to fracture [10]. The minimum fracture tolerance of these bones both exceeded the average impact force generated by the folded t-shirts in this experiment.

In a similar study, Cormier et al. determined that subjecting a human nose to forces of 450N-850N with a steel tipped aluminum impactor produced a 50% risk of fracture [11]. The impactor weighed 3.2kg and had a cross-sectional area of 2.54cm^2 (1in^2). The minimum corresponding pressure associated with this range is 698kPa-1,318kPa assuming the force acts over the entire cross-sectional area. However, in all of the tests conducted, the entire available area was not engaged. The contact area of each test ranged greatly from approximately 0.5cm^2 to 4.0cm^2 with an average of 2.0cm^2. With smaller contact areas, the resulting impact pressures range from at minimum conditions 1,125kPa to at maximum conditions 17,000kPa, with an average of 3,250kPa (using 650kN and 2.0cm^2).

The average impact force of the folded t-shirts in this study was 1,481±1N; however it was distributed over a larger contact area. The t-shirt's 44.2cm^2 cross-sectional area lowers its average impact pressure to 335±5kPa; two to three times lower than the calculated impact pressures that produced the fracture results by Cormier et al.

Tests conducted on unembalmed cadavers by Gadd et al. revealed that the tolerance of the laryngeal cartilages ranged from 400N-445N (90-100lbf) [12]. These tests were performed using a scaffold that dropped an adjustable weight with a 2.54cm^2 (1in^2) metal impacting tip [3]. The forces that produced marginal fractures in both the thyroid and cricoid cartilage were roughly three and a half times lower than those produced by the folded t-shirts, the characteristic difference being the size and material of the impacting surface.

DISCUSSION

The comparisons of the muzzle energies between a 9mm pistol, a paintball gun, a pellet gun, and the projectiles in this experiment demonstrate the energy produced from an air cannon. However, the effects of an air cannon cannot solely be determined based on its muzzle energy alone. The relatively large mass of the t-shirts or football that the cannon fires increases the projectile's kinetic energy without producing the same results as the other, more documented projectiles. A bullet's ability to penetrate the human body with a large velocity undoubtedly produces severe if not lethal damage. Moreover, the metallic nature of a bullet prevents it from crumpling and dissipating its kinetic energy upon impact. The force of a paintball and pellet also act over a much smaller area increasing impact pressure and producing more damage than the projectiles used in this experiment. But the comparisons call to attention the amount of muzzle energy air cannons produce, further emphasizing the need to demonstrate care when utilizing them.

When compared to the results from the two studies testing projectiles' abilities to rupture the human globe and penetrate the orbit, the air cannon in this experiment would likely achieve similar results. Assuming the same settings used during testing to achieve velocities of 57m/s, 60m/s, and 82m/s, it is likely that each projectile has the potential to rupture the globe, and penetrate the orbit.

The obvious difference between most the medical research experiments that are referenced in this paper and the tests conducted is the characteristic difference of the projectiles. Most notably, the hardness of a t-shirt is substantially lower than that of a baseball, steel impactor, or metal contact tip. For example, the rolled up t-shirt achieved 233J of kinetic energy, nearly three times more than the baseball that achieved 88J rupturing a human globe. It is unlikely a rolled t-shirt will produce as severe of a rupture due to its soft and easily compressible characteristics when compared to a baseball. However, this may introduce complications because of its tendency to tumble in flight. Tumbling during flight can result in the preceding edge of the cylindrically shaped t-shirt roll to strike the globe first. Applying the same force over a smaller contact area would increase localized stress and may increase the severity of the rupture. The pointed end on a miniature football can also produce this phenomenon, adding to its ability to rupture the globe.

In addition to its hardness, the size of the projectile and its ability to maintain its shape differ greatly between a t-shirt and the projectiles tested in previous experiments. The t-shirt would more likely resemble the soccer ball used to test orbital penetration due to its size and compressibility. Although no definitive conclusions can be made, the t-shirts attained a larger muzzle velocity than the soccer balls suggesting that the damaging effects of a t-shirt impacting an orbit immediately after exiting the muzzle would probably produce penetration. Furthermore, the soccer balls tested remained in the orbital space longer than any other projectile due to its inability to transfer energy quickly [6]. Because a t-shirt compresses further than a soccer ball and does not rebound quickly, a t-shirt would likely stay in the orbital space longer than the soccer balls did. Remaining in the orbital space for extended periods of time, regardless of projectile, is a medical hazard to be avoided.

Regarding the penetration of the orbit, the tennis ball and miniature football tested in this experiment traveled 20m/s to 42m/s faster than the tennis balls tested in the Vinger study. Due to the standardization of tennis balls, an air cannon firing tennis balls could likely produce similar orbital penetration of 18.6mm. Based on the velocity data, it is reasonable to assert that the miniature football would also be able to penetrate the globe a similar distance, if not further due to its smaller contact area.

As seen in Table 6, the impact force generated by the folded t-shirt exceeded the required force to fracture the nasal bones, and existed within the range of fracture tolerances for the bones of the midface. The maxilla, zygomatic arch, and zygomatic body may be vulnerable to fracture from air cannon projectiles, but definitive conclusions cannot be made. Although the t-shirts achieved forces larger than the minimum fracture inducing forces detailed in the Pappachan and Alexander study, a t-shirt's softness and compressibility introduce uncertainty as to whether or not it could replicate the injuries mentioned.

The Cromier et al. study suggested that higher forces are required to fracture the nasal bones, but this range also falls below the forces produced in this experiment. That study also provided the impact pressures of the projectiles which varied from trial to trial based on the contact area that impacted the target. Because the t-shirts in this study impacted a large force plate, the entirety of the t-shirts' cross-section was considered to have been the contact area. When impacting a nose however, the t-shirt would have the same impact force acting over a smaller area which in turn would produce higher impact pressures based on the geometry of the nose. Because the t-shirt achieves more impact force than given tolerance levels, and would act over a smaller area, it is likely that a folded t-shirt has the ability to fracture nasal bones immediately after exiting the muzzle.

Similarly, the t-shirts' impact forces exceeded the nominal forces listed as tolerance values for the laryngeal cartilages in the Gadd et al. study. Moreover, the projectile used in the cadaver experiments had a contact area less than the t-shirts (2.54cm^2 at a maximum). Correspondingly, it is still likely that a folded t-shirt fired under the circumstances in this experiment could cause marginal fractures in the thyroid or cricoid cartilage due to the geometry of the larynx. Because the larynx does not have the cross-sectional area of a folded t-shirt (44.2cm^2), a direct impact to the laryngeal cartilages would decrease the contact area of the t-shirt closer to that of the metal impacting tip Gadd et al. used to achieve marginal fractures.

The final area of interest for this experiment is the small joints located on outer extremities, namely fingers. Mallet finger, an injury characterized by tendon disruption or distal phalangeal fracture due to the rapid bending of the finger needs to be considered in regards to air cannon risk [13]. Mallet finger is usually caused by a blunt impact from a projectile that axially loads a single digit. The commonality of this injury in ball sports has been well document [13], and the t-shirts used in this experiment can be considered a ball like projectile immediately after it exits the muzzle. Because of their large muzzle energies, the t-shirts, tennis balls, and miniature footballs tested can likely produce a mallet finger injury, if the impact conditions are conducive. While it is improbable that any of these projectiles can produce this injury at the end of their flight because of the velocity lost due to drag, all projectiles have the potential to cause mallet finger upon exiting the muzzle. Fans seated near an air cannon launching memorabilia at sporting events may try to intercept a projectile immediately after it leaves the barrel with their hand. In this type of scenario, it is possible that if the fan's finger is oriented collinear with the muzzle, a mallet finger injury can occur.

CONCLUSION

The advancements in air cannon technology have produced devices that can endanger the safety of those located near its muzzle. Although no definitive assertions can be made about the exact degree in which an air cannon can injure a bystander, the potential injuries can be speculated. Of the regions of the body examined in this experiment, the eye is most at risk to the damaging capabilities of an air cannon. The injuries an air cannon can inflict on the eye do not vary greatly with the projectile it fires due to the eye's sensitivity and exposed nature. However the type of projectile used does affect the severity of the injury because of their different impact velocities, contact areas, and tendencies to deform. As described in this experiment, it is likely that being shot in the eye by an air cannon located directly next to the victim will result in a ruptured globe or penetrated orbit.

The nasal bones are also susceptible to injury from an air cannon fired at point blank ranges, as the t-shirts in this experiment produced forces that greatly exceed the listed fracture tolerance level. The peak forces and pressures exerted by projectiles fired from air cannons, specifically t-shirts as they relate to this study could potentially damage the midfacial bones (maxilla, zygomatic arch, and zygomatic body). Because the peak force exerted by the t-shirts in this study fall within the range of fracture tolerances for these bones, the likelihood of a resulting fracture varies case by case.

Similar to the nasal bones, the laryngeal cartilages' fracture tolerances exist below the average recorded t-shirt impact force, suggesting nontrivial injury may occur if a bystander is struck in the throat at close range. The smaller geometry of both the nose and throat reduce the contact area of large projectiles, and thus increase the impact pressure and probability of injury.

Additionally, air cannons can likely produce injuries in the extremities, namely the finger if certain criteria are met. To induce injuries such as mallet finger, the bystander must be located in close proximity to the air cannon's muzzle, as the energy of the projectile decreases exponentially over increased distances, and have their fingers outstretched in the flight path of the projectile. Although finger injuries vary case by case and depend on the orientation of the finger with respect to the projectile, the muzzle energies attained by the projectiles in this experiment suggest that a finger immediately in front of the muzzle would likely be injured upon being struck.

FUTURE RESEARCH

For future experiments, projectiles' imparted forces should be determined as a function of distance. Now that various injuries have been speculated as likely to occur at point blank range, the distance at which these injuries are no longer likely to occur should be investigated. Determining at what distance a bystander is likely to be injured at contributes to the safety procedures of firing an air cannon at sporting events. Ensuring an air cannon operator maintains an established minimum firing distance between himself/herself and their target increases bystander safety. This test could be conducted using a series of force plates at incremented distances. The recordings from each force plate could then be compiled to create an equation that models an air cannon's impact force as a function of distance from its barrel.

In addition to measuring the force of a projectile as a function of distance, the change in velocity over distance can be recorded with the use of a radar based chronograph. Additional velocity measurements would allow for the kinetic energy of projectiles to be presented as a function of its distance from the muzzle of the launcher.

To increase the accuracy of future testing, additional measuring devices should be incorporated. An accelerometer placed within the projectile itself would be able to calculate its deceleration and velocity at impact, allowing for a coefficient of restitution to be calculated. This coefficient is a numerical representation of a projectile's ability to transfer energy to its target. Additionally, force plates capable of higher sampling rates should be used to capture the imparted force as a function of time over numerous time steps. The increased sampling rate improves the accuracy of the impulse measurement to be used in later comparisons.

Furthermore, additional types of projectiles should be tested. With the growing popularity of air cannons, and the ability to fire any object that can fit within the barrel, there is a myriad of potential projectiles that could be used at public venues that pose additional safety hazards. By testing more projectiles, operators can be educated on the options in projectiles they have when deciding which projectile they can safety use in specific situations.

This experiment was limited to testing the impact force of only t-shirts because of the vertical firing orientation. When attempting to fire other projectiles from the cannon, they rolled or slid out of the barrel due to a lack of obturation. The addition of a force plate that can be secured to a wall would allow for a horizontal testing configuration enabling other, projectiles to be tested.

Finally, the use of unembalmed cadavers as targets would allow for immediate conclusions to be drawn regarding the injuries an air cannon can cause. Comparing t-shirt impact data collected from a force plate against human tolerances experimentally determined using metal projectiles, is an indirect method that introduces uncertainty on any inference made because of the inherent differences in the projectiles.

RECOMMENDATIONS

To mitigate the risks associated with using an air cannon at a stadium event, organizational precautionary measures need to be taken. Before air cannon operators are able to fire the device, they need to have been trained on proper usage of the cannon. Knowing that the most severe injuries will likely occur close to the muzzle, stadium directors must ensure the operator has a space to fire the air cannon free of all personnel.

The worst injuries speculated on in this experiment were those involving penetration and rupture of the eye. Although it is not feasible to ensure bystanders continually wear eye protection, the cannon operators should wear it to protect themselves in case of a misfire while handling or loading the launcher. To further reduce the risk of ocular injuries, all operators should be instructed to avoid aiming at bystander's faces regardless of the distance between them.

To achieve the same safety oriented outcomes, mechanical modifications to air cannons can be made. To prevent the operator from firing the air cannon while it is parallel to the ground (i.e. firing it directly at someone) a gyroscopic sensor or inclinometer can be utilized. Locking the trigger when the barrel is positioned at a low angle, this sensor would prevent operators from targeting individuals. Moreover, a proximity gauge mounted on the air cannon could be used to prevent it from firing, should a bystander place their hand in front of the muzzle.

Additionally, this experiment only examined the hazards of t-shirts and sporting balls, all of which are relatively soft and blunt. As such, the hazards of hard or sharp objects cannot be determined and should thus not be used when firing the air cannon into crowds of bystanders. Objects with these characteristics, such as promotional pencils, "back-scratchers", or similar products, have the potential to penetrate bystanders, greatly increasing the hazard of the air cannon.

Furthermore, proper maintenance and regular inspections before every use are vital to ensuring the safety of these launchers. In addition to an overall inspection that looks for deformities or loosening of any moving parts, the barrel must be examined before usage. Operators must ensure before firing any projectile that the barrel is free of any foreign debris or internal parts that may have fallen into it. Firing hazardous objects (e.g. screws, nuts, rocks) that have unknowingly entered the barrel poses the greatest risk to bystanders.

Using the safety measures prescribed, the risk associated with operating air cannons in densely populated gatherings can likely be reduced to acceptable levels. This study does not suggest that air cannons should not be used at public venues, but rather it asserts that air cannons are powerful devices capable of inflicting damage unless reasonable control measures are utilized to prevent unnecessary risks.

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