

Case Report

Impact Forces and Injury Potential from Landing on Large Inflatable Airbags

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Abstract

This paper presents the impact forces associated with landing on a large inflatable airbag. A set of experiments was performed for a litigated case in which a man suffered injuries upon landing on a large airbag being used as an attraction/ride at a music festival. The man jumped off a 27-foot high platform, landed headfirst on the airbag and sustained a fracture to his cervical spine. To determine the impact forces involved, experiments were conducted by releasing instrumented kettlebells onto an exemplar airbag. Results demonstrated that the man's cervical spine was subjected to 1,100 lbs of compression, which exceeded published neck injury tolerance limits. In addition to neck injuries, landing on the airbag with an outstretched arm or leg has a high potential to cause injuries to the upper or lower extremities, respectively. These results are useful and offer a strong cautionary note for forensic experts and product designers dealing with similar large inflatable airbags.

Keywords: Biomechanics; Airbag; Amusement Park; Action Sports; Free Fall; Stunts

Introduction

Several manufacturers offer large inflatable airbags to attenuate the impact forces generated during falls from moderate heights. These airbags are often used instead of a foam pit for applications such as amusement park attractions, freestyle or action sports, training for ski and snowboard jumps, and practicing stunts at skateboard or bike parks, among others. Although the majority of landings on such airbags result in no serious injuries, the impact forces have not been extensively studied.

Moreover, there are currently no mandatory safety standards that apply to the design of these airbags. The ASTM (2017) Standard Practice for Design, Manufacture, Operation, and Maintenance of Inflatable Amusement Devices [1] specifically excludes "Inflatable devices that require a sudden loss of air to perform their intended function (for example, stunt bag style inflatable impact attenuation devices)". The biomechanical responses and injury potential of landing on such airbags are largely unknown.

The question of impact forces and injury potential arose in a case in which a 58-year-old man jumped off a 27-foot high platform at a music festival, landed headfirst on an airbag, and sustained a fracture to his cervical spine. The purpose of this analysis was to determine experimentally the impact forces associated with landing on a large inflatable airbag. To assess the potential for injury, these impact forces were then compared against published injury tolerance limits.

Methods

Case description

In June of 2013, a 58-year-old man (5'11", 200 lbs) attended a music festival with his friend. At this festival, an attraction/ride (Figure 1) was set up such that customers could pay to jump off a 27-foot high platform and land on a large inflatable airbag (50' by 50' square, and 9' high). The man testified that the subject incident was the first and only time he had ever jumped off a platform onto the airbag. He saw

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people jumping off a lot of different ways, doing flips off the platform, and landing every which way. Before jumping off the platform, he asked for instructions and whether it was okay to do a flip. He was told "you do whatever you want", and thus, the man did a flip. He did not take into account how he was going to land on the airbag. The man described what felt like hitting the ground very hard, and he could hear the bones in his neck crack upon impact. Before jumping off the platform, nobody specifically instructed him to land on his butt, nor did he hear anyone else being given that instruction. This incident was recorded on video by the man's friend, which shows him jumping forward off the platform, completing one-and-a-half forward flips (i.e., somersaults) and then landing headfirst on the airbag.



Figure 1: Photograph of the 27-foot high platform and large inflatable airbag.

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Airbag tests

A series of experiments was performed to determine the accelerations and forces generated during impact with the airbag. Two iron kettlebells (Rogue Fitness, Ohio, USA) were released from a crane basket positioned above an exemplar inflated airbag (Figure 2). Both kettlebells were spherical in shape with a handle on top. The smaller kettlebell had a diameter of 9.1" and weighed 106.5 lbs. The larger kettlebell had a diameter of 11.5" and weighed 204.5 lbs. The smaller and larger kettlebells were selected to represent the approximate weight of a small female and a large male, respectively. The kettlebells were appropriate for analyzing concentrated loading scenarios, i.e., landing on one's head or an outstretched arm or leg, as opposed to landing on one's back, buttocks or stomach. Similar metal, hemispherical "missiles" are also used in ASTM International Standards to test the impact attenuation properties of indoor wall padding [2] and playground surfaces [3].

The kettlebells were instrumented with a wireless tri-axial accelerometer (S3-1000G-HA, NexGen Ergonomics, Quebec, Canada) to measure the accelerations at the center-of-gravity. The laws of physics were then used to determine the forces applied to the kettlebell during impact. More specifically, Newton's second law of motion, which holds that the acceleration of a body is directly proportional to the net force acting on the body and inversely proportional to its mass (F=ma). Both kettlebells were dropped from two different heights above the ground: 27' (representative of the litigated case) and 40' (to analyze the trends associated with using a different height). For the tests using the smaller kettlebell, both centered and off-center impacts to the airbag were performed. For the off-center impacts, the smaller kettlebell impacted approximately halfway between the center and edge of the airbag. For the tests using the larger kettlebell, only centered impacts to the airbag were performed. Each combination of kettlebell size/drop height/ impact location was repeated three times, for a total of 18 tests.

Injury potential

As an indicator of injury potential, the measured impact forces were directly compared against published injury tolerance limits for the cervical spine, and the upper and lower extremities. To assess the likelihood of injury, the Factor of Risk [4] was calculated, which is defined as the ratio (Φ) of each predicted load to the respective injury tolerance limit. When this ratio exceeds 1.0, injury is more likely than not (i.e., at least 51% probable). This metric is the simplest, and most intuitively obvious, approach to predicting injury risk and is useful in forensic settings since it meets the burden of proof for civil cases, i.e., a preponderance of the evidence or "more likely than not"[5].

Results

Airbag tests

Each combination of kettlebell size/drop height/impact location was repeated three times, for a total of 18 tests. However, one of the tests using the 106.5 lb kettlebell at the 40' drop height (centered impact) was



Figure 2: Photo of experimental test setup. Instrumented kettlebells were released from a crane basket positioned above an exemplar inflated airbag.

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not recorded properly. Therefore, the test results were only processed for the remaining 17 drop tests. On average, across all test configurations, peak kettlebell accelerations (Figure 3) and impact forces (Figure 4) were between 4.7 and 10.1 g, and 639 and 1,370 lbs, respectively. For the test configuration representative of the litigated case (204.5 lb kettlebell, 27' drop height, centered impact), the peak kettlebell acceleration was 4.7 ± 0.4 g with a peak impact force of 961 ± 82 lbs.

Several trends were observed when further analyzing the test results. First, for a given kettlebell and drop height, there was little difference between the centered and off-centre impacts. Second, as would be expected, increasing either the kettlebell mass or its drop height resulted in greater impact forces. Thus, the greatest impact forces were measured with the 204.5 lb kettlebell at the 40' drop height. The third trend was less intuitive. When analyzing the acceleration results, increasing the drop height resulted in greater accelerations, whereas increasing the kettlebell mass resulted in lesser accelerations. This trend can be explained by Equation 1:

$$a = v \sqrt{\frac{k}{m}}$$
(Equation 1)

where, a=acceleration, v=impact velocity, k=airbag stiffness, and m=kettlebell mass. Equation 1 is derived from the Conservation of Energy Principle and demonstrates that acceleration is proportional to impact velocity (which is proportional to drop height) but inversely proportional to mass.

Injury potential

For the test configuration representative of the litigated case, on average, the peak kettlebell acceleration was 4.7 g. Based on Equation 2:

F = ma + W.....(Equation 2)

where F=force on the neck, m=body mass, a=kettlebell acceleration, and W=body weight (i.e., the man's body weight of 200 lbs minus the approximate 10 lb mass of an adult human head), the man's cervical spine was subjected to 1,100 lbs of compression upon impact with the airbag. In comparison, for a male his age, approximately 860 ± 220 lbs of compression [6,7] is necessary to fracture a pre-flexed neck (i.e., his neck was bent forward when he landed on the top of his head). Thus, with respect to his neck injuries, the Factor of Risk value was 1.3, meaning that, on a more likely than not basis, the impact to the man's head should have been expected to, and did cause his neck injuries.

Furthermore, the airbag was found to be defective in two ways. First, the airbag failed to properly attenuate the impact forces sustained by the man's cervical spine. Second, as the airbag deflated and deformed upon impact, the man's head became pocketed or trapped, making it more difficult for his neck to escape the weight of his following torso as the weight of his body crushed his cervical spine. This pocketing injury mechanism also occurs when gymnasts land headfirst on the gym mat or when people dive headfirst into a shallow lake and strike their head on the soft bottom of the lake [8].

In addition to neck injuries such as those suffered by the man in this litigated case, unintentionally landing on the airbag with an outstretched arm or leg (with an approximately vertical orientation of the body at impact) has a high potential to cause injuries to the upper or lower extremity, respectively. On average, for the 40' drop height (centered impact), the measured peak acceleration was 9.8 g for the 106.5 lb kettlebell (i.e., small female), and 6.7 g for the 204.5 lb kettlebell (i.e., large male). Thus, based on the laws of physics described above, for a 40' drop height, unintentionally landing on the airbag with an outstretched arm or leg would subject the extremity to approximately 1,200 lbs of compressive force for a 5th percentile female, and 1,700 lbs of compressive force for a 95th percentile male. In comparison, for females, to produce wrist [9] and foot/ankle fractures [10], approximately 600 lbs and 800 lbs are required, respectively. For males, approximately 800 lbs and 1,400 lbs are required, respectively.

Conclusion

A set of experiments was performed to determine the impact forces associated with landing on a large inflatable airbag. These results are useful for forensic experts and product designers dealing with similar large inflatable airbags. For the specific case being analyzed, the high impact forces on the man's cervical spine were consistent with the neck fracture that he actually suffered. More generally, these data demonstrate that, in addition to neck injuries, landing on the airbag

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with an outstretched arm or leg has a high potential to cause injuries to the upper or lower extremities, respectively.

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