

Wearable Technology for Design and Safety Evaluation of Rider Acceleration Exposure on Aerial Adventure Attractions

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Abstract: Aerial adventure attractions are intended to produce exhilarating sensations at significant elevation, speed, and acceleration, all while maintaining the safety of the participant. While zipline designers and owners can refer to international standards addressing many safety requirements, the measurement and assessment of acceleration exposures of the zipline rider has not been standardized. This paper considers the design and validation protocol for wearable sensor technology to collect acceleration and g-force exposure of a zipline rider.

Introducing the combination of systematic design and quantitative analysis to wearable technology architectures requires considerable thought taking into account existing ride standards, biomechanics, ergonomics and the need for data accuracy. We first evaluate our state of knowledge and determine where there are gaps in safety standards. We then determine a design requirement outline for measuring acceleration utilizing wearable architecture. With the combination of complex processing requirements, the necessity of placing sensors and input/output modules at different locations on the rider's body, and stringent limits on size, weight, and sensor signal, the design of such systems is an inherently challenging problem. We contribute a test protocol that will evaluate the reliability and validity of the proposed system.

Keywords: design evaluation; wearable technology; computational public safety; aerial adventures; ziplines; accelerometers; requirements; test protocol.

1. Introduction

From exhilarating heights soaring across the mountains or complex terrains, ziplines are a popular activity choice for adrenaline seekers. Starting at heights of over 30 ft, and traveling well over 1,000 ft, a rider glides to the bottom at speeds averaging 100 km/h (Schilling, 2016). Securely contained within a properly fitted harness, riders wear a helmet but are otherwise unconfined, allowing them to experience a sensation of free flying in various postures, specific to each zipline. As a method to discover new vantage points within the rainforest to an activity commercialized for public leisure, there now exists hundreds of ziplines in many countries with a variety of intriguing features (Schilling, 2016). An increase of exposure presents more opportunities for occurrence of even rare events such as malfunction and other injury mechanisms.

As a rider would be physically exposed to grave injury in the event of structural or equipment failure, international standards establish requirements for safe operation (notably ASTM F2959 Standard Practice for Aerial Adventure Courses and Association of Challenge Course Technology standards). An estimated 16,850 nonfatal zipline injuries were treated in U.S. emergency departments between 1997 and 2012, and nearly 70 per cent of those injuries occurred during the last four years of that span (Edwards et al., 2015). The majority have been falls (77 per cent) and collisions (13 per cent), including those with trees and other structures used to anchor ziplines (Edwards et al., 2015).

An additional potential mechanism of injury is associated with abrupt deceleration on arrival at the braking system at the end of the zipline. Upon encountering the brake system, the free body of the harnessed rider suspended from the trolley typically behaves like a pendulum due to momentum and gravity, with some amount of flailing of the whole body or segments of the body upon abrupt deceleration, potentially compounded by the posture or movement of the rider. Although standards have established limits for acceleration exposure for amusement device riders (ASTM F2291), the Standard

Amusement Ride Characterization (SARC) test described in ASTM F2137 (and its counterparts in other standards systems) is based on a rider seated in a ride vehicle. The SARC test protocol describes the specifications of testing ballast weight, transducer location, gravity consideration, and test documentation practices. Little is known about the levels of acceleration experienced by zipline riders, nor is there a standard practice for acquiring acceleration measurements in a reliable manner.

This paper describes a design requirements model for measurement of zipline acceleration using wearable technology. Wearable devices integrating accelerometer sensors are commonly used for analyzing sport and health performance (Chambers et al., 2015; Beanland et al., 2013; 2014; Yamamoto et al., 2017; Kwee-Meier et al., 2016). Wearable computing has evolved greatly over recent years, with emerging systems that are active, intuitive, and virtually invisible (Adapa et al., 2018; Anliker et al., 2004). The method of developing wearable architecture enables users to discover beyond human capability, visualizing data from a pulse sensor or detecting movement as we currently see in fitness monitors. However, wearable technology to capture acceleration of zipline users is a novel application.

In studies that analyze acceleration, data acquired using a tri-axial accelerometer is often supplemented with a GPS sensor and concurrently recorded digital video footage. This way, data recorded from the sensors can be compared with a visual recording, to analyze the correlation or causation. The type of accelerometers used varied. Accelerometers on the market range in price, customization and specification, therefore, the appropriate sensors will depend on the zipline's acceleration magnitude and frequency recorded.

Despite the frequent use of body-worn accelerometers, some sources report challenges regarding sensor displacement, number of sensors and signal accuracy. For example, sensor deployments are subject to variations introduced by the normal use of the accessories into which they are embedded (Banos et al., 2014). Sensors may also change position dynamically due to loose attachments, e.g., when integrated into baggy clothes (Harms et al., 2008). As a consequence, data acquired can drastically drift from the intended activity observed (Banos et al., 2014). Methods to minimize sensor displacement often involve the use of multi-sensor configurations to counteract the variations (Banos et al., 2014; Davila et al., 2017). Placement of the sensors should consider the biomechanics required to perform the desired motion or activity for more accurate results (Amasay, 2010).

We envision the development of a method of acquiring acceleration data from garments worn by zipline riders which are capable of capturing the full nine degrees of freedom of movement as they encounter a zipline braking system. Data recorded in this way will inform the assessment of the zipline acceleration exposure. Furthermore, the development of the context-aware, proactive, and intelligent garment, may be used in real time by designer/engineers, owner/operators and regulatory inspectors in support of their roles in the future. This paper refers to a device that could be used in design analysis, testing during the commissioning stage to verify that the zipline as built has the intended characteristics, and periodically to verify that the characteristics have been maintained.

2. Related literature

2.1 Acceleration safety testing in amusement rides and devices

Impacts involving the human body are a common phenomenon of life. As Mckenney (1970) describes it, “from the buttock’s slap which is often used to start the breathing of a newborn baby, to the fatal fall, which may occur at practically any age, impact may be said to be part of human experience from birth to death”. However, with the adoption of mechanical devices within multiple industries such as the military, aerospace and amusement parks, impact hazards have increased both in number and magnitude (Mckenney, 1970; Pfister et al, 2009).

Amusement rides are unique in that they are deliberately designed to create the illusion of danger and expose users to a variety of motions (Eager et al., 2016; BIAA, 2003). For example, zipline riders are purposely subjected to elevated acceleration where the magnitude, duration and rate of change of the acceleration. These variables are increased to enhance the sensory stimulation but are also limited to ensure ride safety (Eager, 2013). Despite the intention to entertain and thrill, effects of elevated accelerations do not all lead to pleasure. If a ride was inadequately designed or faulty, it would result in discomfort or even harm to the health of its’ passengers (Eager et al., 2016).

With the progressive adoption of mechanized entertainment, safety standards are required to address acceleration limits. Safety testing is performed for different purposes throughout the design and use lifecycle of a product. The complexity of this process involves multiple parties - inspector/auditor, designer/manufacturer, owner/operator, and any authority having jurisdiction (ADJ) (Personal communication, Gonzales to Woodcock 27 April 2018). The dynamic structure allows for an evolution of solutions brought through collaboration between self-organizing, cross-functional teams to utilize appropriate practices for their context. Ultimately, each party works together to ensure safety regulations are met.

Acceleration experienced by the rider is determined not only by the speed and acceleration of the movement of the passenger carrying unit, but also by the seating position of the rider within it. Typically, tri-axial accelerometer measurements are made during a normal operating cycle with accelerometer placement and vehicle loading (BIAA, 2003). A SARC test is

used to specify a standard coordinate system to measure acceleration in terms of Gx (eyes front/back), Gy (eyes right/left) and Gz (eyes down/up) (ASTM F2137). Reference to the positive and negative acceleration limits help to analyze what is tolerable given the duration of the ride. As the duration increases, magnitude tolerance decreases. This is due to the fact that: a) blood flow in the body is time dependent and it takes a few seconds for the blood to be reduced or increased in the head and b) fatigue can become a factor (BIAA, 2003).

Specific measurement placement include cases for which riders ride while seated, standing or lying down. For example, “for a ride or device in which riders ride while seated, the accelerometer shall be mounted at a location between 12 and 16 in above the seat level and between 2.5 and 5 in. fore of the upper torso” (ASTM 2137). A minimum of two consecutive test data records from one transducer mounting location is required to establish a repeatable measure for test configuration and the acquired test data. Test documentation for all rides or devices that incorporate significant random, non-repeatable, motion is excepted from this requirement. The raw data recorded is then required to be post-processed, with a 4-pole, single-pass, Butterworth low-pass filter using a corner frequency (Fn) of 5 Hz (ASTM 2137). Such requirements serve to eliminate noise and impact accelerations less than 200 ms.

While we may presume that the acceleration limits of F2291 are valid for maximum tolerable exposure of a rider from his or her frame of reference, we have no method of reliably determining what the actual exposure is for a rider on a zipline. For example, to suspend a SARC-instrumented dummy within a harness is unlikely to indicate the acceleration experienced by a rider in different foreseeable postures achievable through voluntary/involuntary body movements. Consequences of avoiding analysis of acceleration limits may result in serious injuries, e.g., brain injury/aneurysm, or aggravating blood pressure/cardiac, etc (BIAA, 2003). This gap informs the goal of the project, to measure the acceleration experienced in a realistic zipline exposure.

2.2 Human behaviour on amusement rides

In addition to prevention of rider ejection due to the acceleration of the ride, many amusement rides limit human posture and behaviour through user instructions and various restraint and containment systems particularly where self-extraction could lead to serious injuries. Additional positioning devices, such as handrails, may be provided to increase subjective sense of security and a structure that can be used to brace against the ride’s forces. Despite these provisions, most sources report that the majority of rider injuries on amusement rides involve situationally inappropriate rider behaviour (Stenzler, 2016; Woodcock, 2007). While most attractions provide posted safety information, riders may not perceive the information as personally applicable (Sarkisian, 2008). In addition, inappropriate actions may be intuitive reactions to sudden stimuli, rather than risk-taking decisions. Each rider has his or her own risk tolerance, and individual risk tolerance, as well as risk perception, affects behaviour (Wilde, 1989).

Unsafe actions may be produced by an effort to reduce sensation and increase security and comfort, e.g., grabbing for something to hold, and grasping the zipline cable instead of the trolley, as easily as by intentions to increase sensation and sense of thrill, e.g., twisting into a posture that increases disorientation and conceals view of safety equipment. Each of these postures could affect the acceleration of the body torso in relation to the point of attachment upon braking, as well as the acceleration of the head and extremities in relation to the torso. While the acceleration on a roller coaster is predominantly determined by the acceleration of the ride vehicle, this is not the case on a zipline. The approach to measuring effective acceleration of the rider’s body must allow foreseeable variety of voluntary/involuntary postures and unconscious movement as well as swinging and flailing movement produced by momentum of unrestrained body segments.

3. System requirements

To measure acceleration during use of a zipline that accounts for a realistic range of foreseeable postures and voluntary/involuntary body movements, the accelerometers must be mounted on a body that will be exposed to the movement profile of the zipline. Anthropomorphic manikins (“crash test dummies”) or ballast containers (torso-shaped water bottles) or sandbags are often used in the SARC test. However, the object’s speed and hence the momentum to be counteracted by the brake deceleration is affected by the aerodynamics of the dummy shape and material. Static objects such as manikins, containers, and sandbags have limited positioning. Although a human rider can introduce difficulties in achieve repeatability and consistency due to differences in the way humans respond to changing forces (BIAA, 2003), in the case of ziplines, capturing the effect on acceleration of these different responses is of the utmost relevance. Therefore, the design must be wearable by a human rider, as well as attachable to a static object.

Second, the accelerometers must be capable of capturing the swing (pitch-X and roll-Y) and rotation (yaw-Z) as well as the deceleration of the trolley. The body parts close to the trolley will decelerate similarly to the trolley, but the more remote body parts will experience different acceleration as momentum causes them to continue to travel, and swing. To address sensor displacement, a well-fitted structured garment with fixed pockets will further secure placement.

To collect data to describe this movement pattern, accelerometers must be positioned at critical points. The preliminary proposal is to capture acceleration at head, base of the neck, shoulder, centre of mass (COM), and heart. The most damaging injuries occur in the head and upper extremities (Pfister, 2005; Pieles, 2017). Therefore, placement on the head and the base of the neck can help analyze the *pitch (rotation around Y)*. As the rider can turn freely over the duration, *yaw (rotation around Z)* can then be detected by placing accelerometers on the shoulder. This will determine the angle of the rider as they approach the braking mechanism, indicating the appropriate accelerometer-duration limit to compare results with. To analyze the pendulum effect, namely at the COM placement, will be dependent on the type of harness used. The position with respect to the rider's body will vary as the adult harness has the connection point located at the navel and for children it is located closer to the chest. Finally, the heart level placement will be used for comparability with exposure limits based on the SARC test. Each individual accelerometer indicates the acceleration at its corresponding point. Deriving motion capture by the synchronized system of accelerometers will describe the degree of whole-body swing (X-Y) and rotation (Z). Different acceleration at different points on the body presents potential for strain and soft-tissue injury or concussion.

Additionally, we will use digital camera video footage to supplement data obtained from the instrumented garment. The use of four cameras, two at the top platform and two at the bottom platform will observe the rider's initial and final position. Data recorded from the sensors can be compared with the visual recording, to further observing the correlation or causation between the two.

Although these requirements describe the overall concept of the wearable, an iterative design approach will be required.

4. Test Protocol

A test instrument and sensor placement must produce reliable data for commissioning tests and periodic inspections. While the proposed device design has incorporated several performance requirements, a prototype must be tested to evaluate the reliability and validity of its data. This test protocol will collect acceleration data with a variety of different human participants, equipment, structure and methods. By analyzing the results, we will report a method to determine the most appropriate setup for analyzing the task.

4.1 Venue description

Since the dynamic characteristics may be affected by local attributes of the venue, descriptive data will be collected about the structures and operational practices. Each zipline resort has unique features and structures. Obtaining the specifications of the rides, information about current safety inspection processes and understanding the challenges faced during said processes should be noted as shown in Table 1.

Table 1. Venue description data

Topic	Data to be collected
Customers	Attendance and seasonality of operation
Zipline(s) at venue	Tabulation of each zipline and its parameters: elevation, length, intended speed and duration of transit.
Safety procedures, general	Description of nature and frequency of safety inspection
Safety procedures, specific to acceleration	Description of current process/practice/equipment used, if any, to measure acceleration.
Subjective assessment of acceleration	Operator perception of circumstances of variation in acceleration, if any, for each zipline.
Objective assessment of acceleration (if available)	Typical and maximum acceleration recorded, if available, for each zipline.

4.2 Procedure for data capture, filters and analysis

The test procedure is described in the next paragraph. When we refer to the “test participant” we mean either human rider or a stimulant. We refer to a “test administrator” who is a qualified individual who is responsible for conducting a safe, effective and meaningful test using the instruments previously described.

The test participant will be fitted with the instrumented garment and typical harness and helmet involved for safety protection. The garment will be tested to ensure that its’ instruments are in order. Subjects will don the garment before the beginning of the ride. A check for sensor placement will be conducted once the garment is being worn. The test administrator

will prepare the test participant to ride the zipline, latching the harness onto the trolley. Before departing, the test administrator will take note of the initial position of the test participant and the tri-axial accelerometers. More specifically, addressing the direction of the three axes involved. Two cameras placed at the starting position of the ride will capture the test participant's initial position for additional reference. The test participant will then ride the zipline, approach the end of the ride, encounter the zipline braking system and stop. The test administrator will observe the final position of sensors before unlatching the test participant. Two cameras at the end of the ride will capture the final position of the test participant for additional reference. Data will be filtered and analyzed following the recommended procedure noted in ASTM F2137.

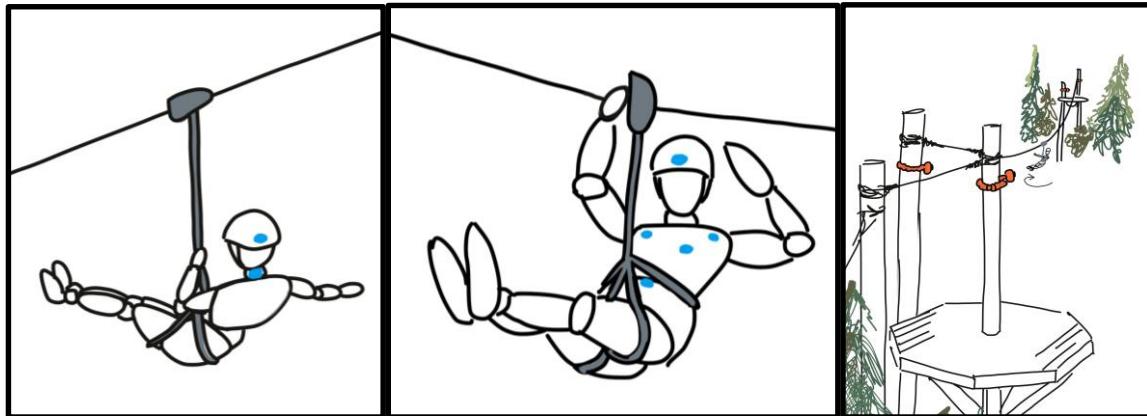


Figure 1. Wearable architecture setup. Blue indicates accelerometer placement. Orange indicates camera placement.

5. Discussion

Summarized, we contribute a test protocol that will evaluate the reliability and validity of a wearable architecture system used to measure acceleration of a zipline rider. Although this study provides a model for exploration, there exists a number of assumptions which require investigation in future research.

First, our design is intended to be wearable by a human rider, as well as attachable to a static object. Based on existing injury reports and perceived biomechanics used during this activity, we assume that the accelerometer placements chosen is the most ideal. However, as we start to collect data and investigate the acceleration recorded, the initial placements may or may not suffice. Additional sensors to detect the rider's position may be an avenue to explore.

Secondly, we assume that the acceleration recorded will begin with a gradual increase, plateau as speed is maintained, and complete with a sudden spike as the rider encounters the brake device. We assume that the most force will be experienced at the brake mechanism. Voluntary/involuntary movement of the subjects will affect the direction of the rider's position. The direction in which the rider is positioned will then affect which axis the set of events described will exist.

Thirdly, we do not consider a camera placement on the rider. Reasons for avoiding this placement are based on added safety, e.g. the use of a selfie-stick may put the rider at risk if abrupt acceleration causes them to whip themselves in the face. However, we are aware that use of such video footage would be beneficial to observe the comparison between data recorded from the instrumented garment, similar to that of our top and bottom platform setup.

In terms of our iterative exploration, it is our goal to perform an extensive study on the dynamic range of subjects, and venue architectures. Such an exploration will provide a systematic quantitative basis for the development of our proposed wearable system. Conclusively, the exploration will serve to predict if the novel application can accurately observe acceleration on rides.

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