THE AVALANCHE DUMMY – DEVELOPMENT AND TESTING OF A SYSTEM TO MEASURE LOADS AND FORCES EXPERIENCED BY AN AVALANCHE VICTIM, USING AN AUTOMOTIVE CRASH TEST DUMMY.

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ABSTRACT: Avalanche injury data has generally been derived from medical evaluation of victims, or in the worst case, by autopsy. These post-event examinations evaluate injuries sustained, but cannot directly determine the forces or impact loads experienced by the victim. If an individual is caught in a slide, what forces and accelerations are experienced, and what injuries might result? The MSU Avalanche Dummy project was undertaken to directly investigate the forces imparted to a snow avalanche victim. During initial testing, a full-sized, instrumented crash dummy was entrained in avalanches at the Bridger Bowl Ski area. A portable battery-powered digital data acquisition system was developed and utilized to record multi-axis force data from load cells in the upper and lower leg, and knee. It also recorded head impacts sensed by accelerometers in the bio-fidelic ~200-pound dummy. Test sequences were recorded with both video and still images from setup through explosive-induced avalanche to recovery. This yielded a good visual record of entire test events, for research use and possibly for public avalanche awareness education purposes. Equipment, setup, test protocol and logistics, data correlation, test results, and future test scenarios are discussed.

KEYWORDS**:** Avalanche, Crash Dummy, Human Injury, Force Measurement

1. INTRODUCTION

Numerous formal studies, historical and verbal records, and common sense support the premise that injuries are likely if an individual is caught in a snow avalanche. An Austrian study [Hohlrieder, et. al., 2007] found that of 105 avalanche victims admitted to the University Hospital of Innsbruck between 1996 and 2005, 49 victims had significant injuries, including 20 victims with injuries of extremities, 18 with chest injuries, and 7 with spinal injuries. Utah Avalanche Forecasting Center records reviewed by Grossman, et. al. [1989] showed that evidence of major blunt trauma was present in nineteen cases of the 91 individuals caught in avalanches between 1982 and 1987.

Despite this injury data, targeted studies measuring the magnitude of forces, loads and accelerations *as experienced by humans entrained in avalanches* have been rare. The goal of this ongoing project is to develop a system to measure the forces, accelerations and impacts experienced by an individual caught in a snow avalanche, and to correlate those load measurements with the injuries that could result.

At the core of the system under development is an automotive-type crash test dummy. Signals from the dummy's sensors are gathered using portable computerized data logging equipment, developed and programmed for this application. The project also involves design and testing of portable prototype systems to measure the velocity, density and depth of a passing slide, in order to correlate slide magnitude with recorded dummy loads. The logistics of on-mountain testing were addressed during the initial field testing of the system during winter 2007/2008. Further testing is planned for the winter of 2008/2009 and beyond.

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A secondary goal of the avalanche dummy project is to continue to develop unique cold-regions research capability at Montana State University - in this case with an emphasis on human factors topics. Many possible studies – in the lab or in-situ - in cold-regions human factors research are now within reach based on progress made so far. Similar studies in diverse topics such as sports injuries, accident victim treatment and recovery, and other industrial & medical applications can also be envisioned.

2. BACKGROUND

2.1 Crash Dummy Development

Crash dummies have been utilized in testing since as early as 1949, in efforts to make vehicles safer. Several generations of dummies were utilized prior to development of the "Hybrid III-50th Percentile Male" dummy by General Motors Corporation beginning in 1973. The development program that created this dummy version was undertaken under auspices of the United States National Highway Safety Transportation Administration (NHTSA) to improve dummy bio-fidelity. The Hybrid III dummy is fabricated with numerous features that mimic human biomechanical response. Parameters of weight, height, mass distribution, scaling, and most other features are controlled by specification, and several manufacturers produce the model to these specs. The H-III 50th Dummy is the federally-mandated industry standard in front-impact passenger car crash-worthiness testing in the United States and abroad, and has found applications in other research areas.

2.2 Previous Dummy Testing

Several published accounts of manikin or automotive crash dummy usage in avalanche safety equipment studies. Airbag systems designed to increase buoyancy in an avalanche were introduced by Josef W. Hohenester around 1970. These systems were tested (presumably using manikins) during the next several years as commercial avalanche safety products were introduced – primarily for the European market. During the winter of 1994 and 1995, dummies were used in an airbag study at the Swiss Federal Institute for Snow and Avalanche Research (SLF.) [Tschirky et. al. 1995.] Several of the 65 kg to 85 kg dummies used in that test sequence were equipped with ABS avalanche balloons, some with radio remote-control triggering of the balloon. The dummies were placed by helicopter, and slides were induced using explosives. (Fig. 1.) Study results were presented at the 1996 International Snow Science Workshop in Banff, AB.

Figure 1: Dummies used in avalanche airbag testing at SLF, in 1994, 2001. Photos courtesy of the Swiss Federal Institute for Snow and Avalanche Research, Davos, Switzerland.

The SLF subsequently reported results of testing of avalanche airbag systems, again using several dummies to facilitate the tests. [Kern, et. al., 2001.] One Hybrid III automotive crash-test dummy (supplied by an automotive manufacturer) and twelve un-instrumented manikins were employed during this sequence of field testing. A backpack-mounted Campbell datalogger provided a record of cervical vertebrae loads from the crash dummy. That test series focused on the effectiveness of different kinds of avalanche safety devices in burial avoidance, but by recording cervical turning moment and shear force the investigators introduced the concept of using instrumented automotive crash dummies to study human biomechanical response during snow avalanche entrainment.

More recent testing of avalanche flotation systems utilized dummies of various types, such as those entrained in slides in British Columbia during testing by JTW Associates during winter 2007/2008. (Fig. 2.) [Radwin, et. al., 2002.] This testing used human-form manikins as a test-bed for development their line of buoyancy products.

Figure 2: JTW Associates Dummy airbag testing in British Columbia during winter 2007/2008. Photo courtesy of JTW Associates.

Despite these and other instances of previous usage of manikins or dummies in avalanche gear testing, the documentation of these tests has provided relatively little information regarding forces and loads that are imparted to a human subject when entrained in a snow slide.

2.3 Injury Databases and Methodology

The key to using an instrumented human analog (dummy) in testing is a reliable database that ties dummy sensor output to injury. Transportation databases provide a good source for injury-to-load correlation due to the well-documented history of usage and extensive testing of instrumented dummies. In the US, the National Highway Transportation Safety Administration (NHTSA) coordinates the Human Injury Research Division (HIRD) and the Crash Injury Research and Engineering Network (CIREN) that deals with severe injuries involving level-1 trauma. The Cooperative Crash Injury Study (CCIS) in the UK, the Japan Automobile Research Institute, the US Insurance Institute for Highway Safety, and other agencies throughout the world provide similar incident database resources with information on automotive accidents and injuries.

The Abbreviated Injury Scale (AIS) has been adopted by all US Federal studies and is used internationally in ranking injury severity. The AIS evaluates nine regions of the body, utilizing rankings ranging from AIS 1, Mild Injury = 0% Risk of Death thru AIS 6, Maximum Injury = Virtually Un-survivable.

The Head Injury criterion (HIC) is an evaluation tool specific to head trauma that has been adopted by the NHTSA and US Federal government as the accepted standard for correlating measurements from Hybrid III dummy impacts in crash testing with (AIS) head injuries. The HIC relates the change of kinetic energy and linear acceleration over a time interval, for impacts with hard objects. Head injury risk curves correlate the HIC values with AIS rankings. For instance, an HIC value of 1000 is intended to ensure that 80% of the general population will not suffer serious or greater (AIS 3+) head injuries from crashes. While providing useful correlations indicating impact severity relating to injury, HIC evaluation is problematic since the HIC standard was developed initially to rate vehicle crashworthiness, not to assess individual injury probabilities. [Nordhoff, 2005.] The HIC also is defines only linear accelerations rather than more complex angular accelerations, but it is in common use as an indication of potential injury.

Athletic studies are another source for information relating head impact to injury. A study at Virginia Tech is presently underway, using football helmets instrumented with accelerometers and 900 MHz spread-spectrum transmitters for real-time monitoring of impacts and head trauma in football athletes. The system records data for subsequent analysis but also provides an alert to the team physician if impacts greater than 98 g’s occur. [Physorg.com, 2007.] This 98 g threshold of concern may provide a less complicated head trauma standard upon which to base avalanche dummy data evaluation than the HIC scale.

For body areas other than the head, the NHTSA compiles data from many available sources A series of Injury Assessment Reference Values have been developed by the NHTSA, for each of nine body regions, using cadaver testing [Rupp, 2003] and other methodologies to correlate load levels with resulting injury. These reference values define units of axial compressive or tensile force, extension bending moment or flexion bending moment, shear, or translation, as appropriate ‘not to exceed’ threshold values for the body areas in question, and are one of the critical elements in successful interpretation of crash dummy sensor output magnitudes.

Other available injury databases include compilations of injury complaints or incidents versus activity - without specific load information. The loading history that induced the noted trauma can sometimes be estimated or calculated through the use of computer-based reconstructions or models, but the resulting load information is subject to a high degree of uncertainty.

It should be emphasized that relating impact, force or acceleration to specific injury is an imprecise art, despite the resources available. Wide variations exist in the ability of individuals to withstand various levels of loading. Age, fitness, body mass and composition, and other factors play a role. And the complex interaction of the human skeletal structure with the infinite loading variations possible in this particular situation complicates the relationship between load and injury.

3. PROJECT TEST EQUIPMENT

A variety of specialized equipment was purchased, developed, or adapted for use during this project. With the exception of the actual dummy, much of the equipment was designed with the assistance of undergraduate engineering students as part of their coursework or during a summer internship. Cost and manpower was an over-riding concern throughout, resulting in the need for numerous creative solutions by researchers and students.

3.1. Dummy

An early consideration was “what measurements should be incorporated into the dummy system?” A fully-equipped HIII-50th dummy can be ordered with sensors installed to obtain up to 44 response measurements, but the cost of this complete sensor packages far exceeded the budget available. Increased channel count drives up complexity and cost of data acquisition apparatus needed to capture the signals, and requires increased processing speed and larger data storage capacity.

It was determined that for initial testing, one complete leg including lower and upper tibia, knee, and femur would be instrumented: Additionally, two 3-axis accelerometers would monitor possible head trauma. This configuration resulted in 20 channels of data, with options for future expansion as the project matured.

With funding assistance from the MSU College of Engineering, an R.A. Denton, Inc. Hybrid III-50th percentile crash dummy was purchased as the primary test sequence “victim”. (Fig. 3.)

Figure 3. Hybrid III-50th Percentile Crash Dummy standard configuration. Photo courtesy R.A. Denton, Inc.

In addition to the basic HIII-50th dummy, a ‘pedestrian kit’ straight pelvis adapter was purchased to replicate the posture of a skier, and load cells and accelerometers were purchased and installed. The dummy was equipped with a ski parka and ski pants, ski boots, 165-cm skis with bindings set at DIN14, and a ski helmet. These peripheral components provided a more lifelike and less obtrusive appearance for on-mountain logistics exercises, while helping to minimize snow and melt-water problems with electronics. (Fig. 4.)

Figure 4. Dressed dummy en-route to testing.

3.2. Data Acquisition System

Considerations during data acquisition system selection included size, weight, channel count, expandability, ease of use, cost, performance, data storage and data accessibility, and system durability. The determination of sampling rates necessary to characterize dummy “injuries” was based primarily on the need to capture head impact accelerations, but the desire to maximize sampling rates had to be balanced against the capabilities and cost of data acquisition apparatus that would support channel counts. A sample rate of 1 to 2 KHz was determined to be achievable and adequate given these boundary conditions.

Project budget limitations did not permit purchase of existing crash-dummy specific data acquisition equipment, or commercial custom-built units. A student project to develop a custom system for the dummy was initiated, but fell behind schedule and short on performance due to unforeseen student problems. As a fall-back, two generic National Instruments 4-slot Compact Reconfigurable Input/Output (CompactRIO, or C-RIO) modules were purchased, one each for the dummy and for the velocity/density sensing apparatus. The C-RIO systems use a small real-time controller to communicate with a reconfigurable field-programmable gate array (FPGA) backplane in a rugged, compact chassis with options for various input/output modules. The real-time controller is connected through an Ethernet port to a desktop PC for programming, which is accomplished using LabVIEW software. The selection of this system took advantage of existing university software site licensing agreements and hardware educational discounts, for a relatively affordable, flexible, robust, high-speed data acquisition capability. Once programmed the C-RIO units operated in a stand-alone battery-powered mode.

For testing the C-RIO dummy data acquisition system computer was packaged tightly into a well-padded army-surplus steel ammunition canister, which also contained a 12 Volt sealed gel cell battery for dummy sensor and computer power, a 6 volt lantern battery for servo-controlled remote start, a power bus bar with 12-5 volt transformer, a radio receiver with servo actuated power switch, hand warmer packets, and cables. (Fig. 5.) The assembly was secured to the dummy in a padded backpack. The system was activated using a radio control unit and booted directly into data acquisition mode. Data was stored on a 2GB USB drive.

Figure 5. Surplus ammunition container enclosure containing data acquisition system.

3.3. Peripheral and support equipment designs

Another consideration in testing was how to characterize the slide magnitude. Two separate prototype systems were developed to measure slide density and velocity, each utilizing more data acquisition capability. A third means, involving manual density measurement and video-based velocity measurement was also pursued, and utilized in the first test sequences.

3.3.1. Portable Load Plate with Depth and Velocity Sensor

Specifications to be used with this system included the ability to accurately determine average density from dynamically-measured snow weight, vertical height from a known datum (running surface) and velocity under dynamic conditions. Low cost, portability, and tolerance for expected environments were also considered. The unit was to be used with a portable, battery-powered high-speed data acquisition system.

Two versions of this load plate were designed and fabricated. The first used piezo-resistive sensor elements (change in resistance with pressure) mounted on a folding load plate assembly. Calibration and repeatability of this unit proved unsatisfactory, so a new design using fluid-filled tubing was created. Fluid pressure variations were monitored with an electronic pressure transducer. (Fig. 6.)

Figure 6. Portable fluid pressure load plate.

A companion device was fabricated to measure both slide velocity and depth. That design consisting of a 2.5 meter aluminum beam, anchored into the snowpack in the slide path using pickets and cable. Velocity sensing modules were incorporated at various heights on the beam, each unit consisting of two infrared emitter/photo-optical diode pairs. Cross-correlation of signals from photo-transistor output has been used successfully for velocity determination in a number of studies. [Dent, et. al., 1998.] A rotary potentiometer mounted at the upper end of beam, with an adjustable swing-arm attached to the axis of the potentiometer. Potentiometer resistance change as a function of the angle measured was used to indicate slide depth.

Output signals from the pressure transducer in the load plate, potentiometer, and velocity sensors were connected to a desktop PC for all laboratory testing and to a laptop PC with a PCM-CIA Data Acquisition card for initial field tests. In actual avalanche testing the signals were to be directed to a battery-powered remotely activated C-RIO computer sampling at 2 KHz, anchored to the slope.

After acceptable laboratory testing, limited small-scale field testing of the prototype load plate unit occurred in August 2006 in wet snow conditions at a high-altitude Southwest Montana location. (Fig. 7.)

Figure 7. Portable fluid pressure load plate initial field testing. Photo by A. Yudell.

While systems functioned approximately as anticipated, lingering operational concerns regarding the need for avalanche track preparation, erosion of the slide running surface, load plate and depth/velocity sensor anchoring challenges, and other placement issues remained. Design modifications that addressed these issues seemed to violate the desire for a high level of portability in the completed units. As a result, further field testing of this system was delayed while alternative devices were investigated.

3.3.2. The Snow Bullet

A new density/velocity measurement system was conceived to address the placement difficulties encountered and anticipated with the load plate system. Deemed the “snow bullet”, this system is intended to take advantage of the ridge/chute terrain familiar to Montana researchers, with a safe zone above a slide path. The device consists of a tethered projectile-shaped housing with an internally-mounted S-beam load cell, power supply, C-RIO data acquisition storage computer, and transceiver for recovery in the event of a tether failure. Redundant optical velocity sensors were embedded in the housing. (Fig. 8.) External dimensions were chosen based upon mass balance and volume calculations, to ensure that the density of the device approximated expected nominal avalanche snow densities. The hemispherical nose cone and cylindrical shell shapes were selected for their well-characterized fluid flow drag coefficient values.

Figure 8. Snow Bullet prototype.

Other components of this direct density measurement include a 12-to-5 volt transformer, power switch, wiring harness, transceiver for recovery in case of lanyard failure, a nylon and aluminum housing, foam padding, and lanyard attachment. A spectra rope and a shear-pinned anchor block were included to facilitate safe deployment and testing.

The theory of operation of this device was relatively straightforward: The device would be cast into a slide path and anchored from a safe zone above the path. Force on an obstruction in fluid flow is a function of the shape, the fluid velocity, and fluid density. Solving the fluid drag force equation

$$F_d=(1/2) * C_d*A*\rho*V^2$$

for density yields the relation

$$\rho =2* F_d /(V^2* C_d *A)$$

where
ρ = (snow) density
F_d = drag force of the object
C_d = Drag coefficient
V = (Snow) velocity

Initial drag coefficient C_d can be estimated from published fluid dynamic relations. Difficulties in drag coefficient determination are expected due to changes of C_d with flow regime, as reported by Gauer (2005) and others. If a successful C_d calibration is achieved for given snow type, the system would then directly reveal snow density. Classification of slide intensity could then be made using the kinetic energy relationship $\rho *v^2$ from the measured values.

Potential advantages of the concept must be weighted and tested against anticipated operational issues. Initial laboratory testing of the device occurred but field testing is required to see if further development work is warranted.

3.3.3. Video Measurement

Due to the state of development of portable automated velocity and density sensing devices it was determined that field testing in 2008 would rely on simpler methods: Video-based velocity measurement and manual snow density measurement. Field testing to-date has utilized bamboo poles placed at known distances and a review of test video with known frame rate to determine slide velocity and depth

4. DUMMY LOGISTICS AND TESTING

Logistics and operational scenarios evolved during the project to rely heavily on the Bridger Bowl Ski Area and Patrol for in-bounds testing. (Fig. 9.) The advantages - primarily chairlift access and manpower availability - were partially offset by expectations of relatively smaller slides. The use of the historic Montana State University “Revolving Door” test site [Miller, et. al., 2002] was considered, but that site was decommissioned in 2008 for safety reasons, due to increased back-country usage and a new open-boundary policy.

Figure 9. Chair lift transport

To support in-bounds testing a logistics plan was developed. In summary, the plan involved these steps:

1. Transport dummy and support equipment to upper mountain staging area. Watch weather.
2. Setup on afternoon of predicted snowfall event in active slide path. Install all equipment.
3. Morning safe zone: Activate dummy power remotely. Set up video. Patrol detonates charge.
4. Compile video and photo avalanche record. Recover, data dump, transport back to staging area.

5. PRELIMINARY RESULTS

Two tests were completed during 2008, exercising all systems and forcing some modifications of the dummy systems and the operational plan. (Fig. 10.) During the first

Figure 10. Testing location at Bridger Bowl Ski Area. Photo by C. McCammon.

functional test the slide impacted and tumbled the dummy approximately 50 m. It came to rest partially buried with skis still on. Recovery was uneventful with no transceiver search necessary and only minor excavation required. Unfortunately a power connector failed at some point during setup or test, resulting in loss of data integrity during the slide event. A video record permitted velocity and depth estimates to be obtained using frame analysis. (Fig. 11.)

Figure 11. Video capture image of test 1.

A second test in late April 2008 appeared to yield more promising results, as a 250+ MB data file was successfully recorded to the usb drive during the event. (Fig. 12.)

Figure 12. Dummy recovery after test 2.

However, subsequent data analysis revealed that once again the electronic record was imperfect: Accelerometer channels failed to record data properly, and some scaling issues with fluctuating power supply voltage reduced confidence in signals acquired from the remaining sensors. Future data recovery efforts may reveal usable data from this second test but no conclusive load results or injury correlations can be claimed at the present time.

6. SUMMARY

The project has made good strides towards the goals of creating a system that can be utilized to correlate avalanche-induced forces and accelerations with human injury. Equipment has been field-tested, computer systems and data reduction techniques have been exercised, and many problems solved. The entire system is functional and ready to be utilized for testing during the winter of 2008/2009. Faculty researchers and the undergraduate student research team are enthused about getting back into the field.

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