

Biomechanics of Occupant Responses during Recreational Off-Highway Vehicle (ROV) Riding and 90-degree Tip-overs

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ABSTRACT

Recently, side-by-side Recreational Off-Highway Vehicles (ROVs) have brought elements of the on-road vehicle occupant environment to the off-road trail-riding world. In general, ROV occupant protection during normal operation and in accident scenarios is provided predominately by a roll cage, seatbelts, contoured seats with seat backs, handholds, and other components. Typical occupant responses include both passive (inertial) and active (muscular) components. The objective of the current study was to evaluate and quantify these passive and active occupant responses during belted operation of an ROV on a closed course, as well as during 90-degree tip-over events. Passive occupant responses were evaluated using anthropomorphic test devices (ATDs) in 90-degree tip-overs simulated on a deceleration sled. Active occupant responses were evaluated using instrumented vehicles and volunteer occupants, wherein vehicle dynamics and gross occupant kinematics, muscle activity, occupant-to-vehicle pressure distributions and forces were quantified during riding on a closed course and during 90-degree tip-overs in a roll-spit fixture. For comparison, each test subject also performed a series of common physical activities while instrumented. Results indicated that the seatbelt was a critical component to the occupant protection system and that belted occupants were passively maintained within the occupant compartment during 90-degree tip-over events. Results also demonstrated that the active responses of the occupants further contributed to occupant stability and correlated significantly with the vehicle's lateral acceleration. Changes in patterns of muscle activation occurred approximate with the vehicle's change in turn direction and indicated a clear push-pull strategy of the occupant during left and right turns, respectively. Roll-spit testing demonstrated that the majority of lateral restraint was provided by the bucket seat, wherein modest lap belt forces constrained the pelvis within the seat contour and facilitated the generation of lateral contact forces. Forces exerted by occupants' extremities on the vehicle during a 90-degree tip-over were comparable to, or less than, the forces resulting from common physical activities.

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INTRODUCTION

In recent years, there has been growth in the sale and use of Recreational Off-Highway Vehicles (ROVs). Sometimes referred to as UTVs (utility terrain vehicles) or side-by-sides, ROVs are motorized off-road vehicles with four (or more) off-road tires, a bucket type seat (unlike a motorcycle or ATV seat), a steering wheel, seatbelts and some type of occupant protection structure. These ROVs generally have a driver and one or more passenger occupants. In general, ROV occupants interact with the occupant compartment in two ways, firstly "passively" as a result of their inertia and the vehicle dynamics, and secondly as a result of their "active" and volitional movements and posturing. In the current study, "active" refers to response features of awake and oriented

human occupants that are generated by active muscular contractions.

In general, awake and oriented humans possess passive muscular tone that allows for maintenance of a desired posture under the influence of gravity (1 g), during activities of daily living (ADL), and as they navigate their environment. This includes simple activities such as sitting upright and standing, as well as activities specific to transportation such as riding in/driving a car, riding in a bus, or riding a motorcycle. Aspects of an occupant's response to a dynamic environment that are related to body segment inertial properties and a level of muscle tone and passive joint stiffness associated with an awake and oriented occupant can be referred to as "passive" occupant responses. Due to this level of passive muscle tone or stiffness, relevant aspects of

occupant responses can be evaluated utilizing anthropomorphic test devices (ATDs), like the Hybrid III ATD. The Hybrid III ATD has been previously demonstrated as an appropriate occupant surrogate for the evaluation of kinematic responses during the lateral acceleration, tip-up, and airborne phases of a rollover event [Yamaguchi, et al., 2005; Lai, et al., 2005]. These studies have focused on a comparison of the responses of human volunteer occupants to those of the Hybrid III ATD. For example, Yamaguchi, et al. (2005) found that, except for differences in neck lateral bending, the Hybrid III ATD reasonably reflects occupant kinematics during the pre-trip phase of on-road rollovers. The ATD torso and head moved laterally in the same directions as the inertial forces during on-road steering maneuvers leading to a rollover. The ATD excursions were near the outer ranges of the human excursions throughout the tip-up phase, outrigger contact, and when the vehicle fell back onto its wheels. In addition, Lai, et al. (2005) further evaluated multiple occupant surrogate models versus human volunteer kinematics during rollover and found “... the Hybrid III ATD provides the best prediction of occupant motion when compared to the available human volunteer data.” The responses of awake and oriented human occupants and the Hybrid III ATD differ appreciably in low-g-force environments from those of limp post-mortem human subjects (PMHS) or similar occupant models. The latter are not intended or validated for use in evaluating occupant kinematics under such conditions.

In addition to the passive occupant response, prior research analyzing the motion of human volunteer occupants during the cornering and tip-up phase of motor vehicle rollover demonstrates that occupants actively contract their muscles so as to control their body posture, including the orientation of their head and neck [Yamaguchi et al. 2005]. Specifically, human occupants generate muscular forces in opposition to the inertial forces of cornering and tip-up events, and counter-posture in opposition to the lateral accelerations. This active muscular response of awake and oriented human occupants results in an effectively stiffer response in the lateral direction. An independent set of experiments produced similar results for front and rear seat volunteer occupants during critical yaw maneuvers [European Community - R&TD-Project, 2005].

The purpose of the current study was to evaluate the responses of recreational off-highway vehicle (ROV) occupants during riding and during 90-degree tip-overs, and to evaluate the performance of the occupant protection system. To evaluate passive occupant responses, we utilized an indoor deceleration sled facility and sled braking system to produce repeatable 90-degree tip-overs in an ROV with Hybrid III 50th-percentile ATD occupants. To evaluate active occupant responses, we conducted instrumented riding tests and controlled 90-degree tip-overs using volunteer occupants. This testing was performed with an instrumented test vehicle and utilized volunteers for the driver (approximate 50th-

percentile male) and passenger occupants. Three different sized passengers were evaluated, with heights, weights, and genders consistent with a 5th-percentile female, a 50th-percentile male, and a 95th-percentile male.

METHODS - PASSIVE RESPONSE

Passive occupant responses were evaluated using ATDs in 90-degree tip-overs simulated on a deceleration sled. To generate a 90-degree tip-over event, a 2004 Yamaha Rhino 660 side-by-side was placed laterally on the deceleration sled, which was accelerated to a constant speed, released to coast, and then decelerated at a controlled rate of 0.7 - 0.8 g with the leading side tires up against a 1.5-inch trip lip. For more information on the deceleration sled rollover test methodology, see section 3.5 Deceleration Rollover Sleds of SAE J2926 “Rollover Test Methods”. In response, the vehicle rolled about the trip lip, with the roll cage coming in contact with aluminum honeycomb blocks on the surface of the sled as it tipped to 90 degrees. The honeycomb blocks were used to provide a compliant contact that would help to avoid vehicle damage, allowing it to be used in repeated tests. To prevent the vehicle from traveling off the decelerating sled, straps were installed between the sled and the bottom of the vehicle. The deceleration was created with a pneumatic braking system with calipers mounted to the sled that came in contact with a linear fin mounted to the ground, i.e. a “roller-coaster-type” brake (although in a roller-coaster setup, the calipers are typically mounted to the track and the fin is mounted to the cars). A pre-defined pressure was set to generate a 0.7 - 0.8 g steady-state deceleration. The sled was instrumented with accelerometers to record deceleration and contact sensors to record the wheel lift timing. A roll rate sensor was installed on the vehicle chassis to obtain roll rate and roll angle during the tip-over event. Each run was documented with high-speed video (500 fps) installed on the sled and on the ground, as well as with ground-based real-time video.

The initial test series was with a driver-side-leading configuration (Figure 1). A 50th-percentile male Hybrid-III ATD was seatbelted into the driver position. The seatbelt system for the test ROV consists of a cinching latch-plate assembly, an end-release buckle, a B-pillar mounted turning loop (D-ring), and a web-sensitive retractor mounted near the base of the B-pillar. The ATD was configured with a pedestrian pelvis and all joints were adjusted to the standard 1-g setting except for the pelvis hip joints, which were set to be completely loose, allowing unrestricted rotation of the leg at the hip joint. This approach was taken to maximize the influence of inertial forces on ATD leg movement relative to the occupant compartment. The driver's right foot was placed on the accelerator pedal, and test runs were made with the left foot flat on the floor pan and also with the foot forward, partially on the floor and partially on the vertical footrest. Test runs were made with the ATD's hands lightly taped to the steering wheel and then with the hands affixed to the



Figure 1. Deceleration sled test configuration for driver-side-leading tip-over simulation.



Figure 2. Photographs of unbelted ATD occupant in ROV with (left) and without (right) a sculpted door present.

steering wheel, simulating a driver that releases the steering wheel and a driver than holds on tight during the tip-over event, respectively. With the hands lightly taped, it was found that they would release with an approximately 35 to 75 lb of force, which was within typical adult grip strength [Massy-Westropp NM, *et al.*, 2011]. A test run was also conducted with a deceleration rate of approximately 1.3 g, to investigate whether the occupant response changed at significantly higher acceleration levels, such as those associated with furrowing or tripped tip-over events.

The second test series was conducted to simulate a passenger-side-leading tip-over (Figure 2). The test setup was similar to the driver-side-leading tests except that ATDs were belted into both the driver and passenger seating locations. The passenger-side ATD was again configured with the pedestrian pelvis, all joints were adjusted to the standard 1-g setting except for the pelvis hip joint, which was again set to be completely loose to allow unrestricted rotation of the leg at the hip joint. Test runs were conducted with both the passenger-side ATD's hands at its side, and then with the right hand taped tightly to the outboard A-pillar-mounted handhold. The feet were either flat with the lower legs

vertical, flat and forward with the shoes touching the firewall, or forward with the balls of the feet against the firewall.

A third series of sled tests was conducted to: (i) evaluate the effect of an inboard handhold, comprised of a post with a looped strap, on the kinematic response of a belted passenger, and (ii) examine the influence of a sculpted door on the kinematics of a restrained and unrestrained passenger occupant in the same tip-over scenario (Figure 2).

METHODS - ACTIVE RESPONSE

SURROGATES

Active occupant responses were evaluated using instrumented vehicles and human volunteers, and testing was performed in accordance with procedures approved following review by an Institutional Review Board (IRB) for testing with human subjects. Four human subjects were selected to participate in the active response testing - three passengers and one driver. The three passengers were selected to approximate a 5th-percentile female, a 50th-percentile male, and a 95th-percentile male, and the driver's size approximated

Table 1. Surrogate Information

Surrogate	Standing Height (inches)	Seated Height (inches)	Weight (pounds)
5 th -percentile female passenger	61-3/8	33-9/16	95.2
50 th -percentile male passenger	67-7/16	35-1/8	173.4
95 th -percentile male passenger	70-7/8	37-9/16	236.4
50 th -percentile male driver	68-15/16	37-5/16	169.8

a 50th-percentile male (Table 1). The driver was experienced in the operation of off-road vehicles, including considerable experience with the test vehicle. The passenger occupants had various levels of off-roading experience, but did not have experience with the test ROV. Data was recorded during the passenger occupants' initial ride through the off-road course.

The driver and passengers were clothed in long pants, long-sleeved shirts, over-the-ankles boots, and gloves, and wore helmets and goggles as described in the ROV manual. Surrogates were instructed to read the warnings in the product manual and on-vehicle warning labels in order to familiarize themselves with the occupant protection system prior to testing. They were asked to follow these warnings, including use of the seatbelt, during all tests.

INSTRUMENTATION

A 2006 Yamaha Rhino 660 side-by-side (without doors) was used for testing (Figure 3). The vehicle was equipped with steel wheels and MAXXIS tires, the springs were set to stock settings (setting B), tire pressure was set to 10 psi and 14 psi for front and rear, respectively, and the vehicle was run in two-wheel drive on the off-road course.

The vehicle was instrumented to record vehicle data, and data acquisition and conditioning units were mounted in the cargo bed of the vehicle. Vehicle parameters were monitored using an OXTS RT3003 inertial and GPS navigation system mounted in the vehicle. Data was transformed to the vehicle center of gravity (CG). Transducers were used to measure steering wheel angle and torque, and vehicle brake and throttle. Modifications were made to mechanically isolate each passenger handhold and the occupant seat mount, so that instrumentation could be installed at those locations to record occupant handhold and seat forces. Six-axis load cells were mounted on each passenger handhold, and a multi-axis load cell (lateral and vertical loads) was mounted beneath the seat. Additionally, load cells were used to record seatbelt-webbing loads across the lap and torso.

Occupant-to-vehicle pressure distributions and forces were recorded using a TekScan portable pressure mapping system, comprised of flexible seat pan and seatback sensor mats (CONFORMat model 5330) and flexible sensors affixed to the insoles of the surrogate's boots (F-scan model 3001E). Pressure data was acquired using TekScan Versatek Edge cuffs. Surface electromyography (EMG) was used to evaluate muscle activity using a Noraxon Telemyo 2400T V2 (8-channel) telemetry system. Each subject was prepared for EMG electrode placement by scrubbing placement sites with alcohol, and lightly abrading the skin with 220 grit emery

paper. Dual contact, saline-gel-interfaced Ag/AgCl disposable electrodes with 1 cm² conductive area and 2 cm spacing (Noraxon, Scottsdale, AZ) were placed over the left and right biceps, left and right triceps, left and right obliques and right gastrocnemius.

All instrumentation was calibrated, and data was acquired in accordance with recommended practices and controls. All data collection was synchronized and initiated using a common trigger, and data was acquired using a 16-bit multifunctional I/O DAQ module. The vehicle and occupant signals acquired are summarized in Table 2. In addition, on-board, off-board, and helmet-mounted video cameras were used to document vehicle and occupant motion.

OFF-ROAD COURSE

Exponent's TEC off-road course was utilized to evaluate the driver and passenger occupant responses during off-road riding, since it includes a wide range of turns and terrain features over a distance of approximately 1 mile (Figure 4). Two tests were conducted for each passenger surrogate. The first test was conducted while the surrogate was using both the left and right handholds, and the second test was conducted while the surrogate was using only the right handhold. In addition, two test runs were conducted to capture the driver response. Each run was completed in approximately 3 minutes and 20 seconds at average speed of approximately 18 mph, with speeds exceeding 35 mph.

ROLL SPIT

A roll spit fixture was used to evaluate occupant responses, including quantification of the forces and muscle activations exerted by the occupants, during simulated quasi-static tip-overs to 90 degrees. The battery was removed, fluids were drained, and the vehicle was secured in the roll spit fixture. The vehicle was rolled to 90 degrees in 17 seconds, held at 90 degrees for approximately 5 seconds, and the returned to its upright position in 17 seconds (Figure 5).

A total of eight roll spit tests were conducted where the vehicle was rotated from upright to approximately 90 degrees. Each surrogate participated in two rotations in the fixture. Analogous to the off-road course, surrogate passenger tests were conducted passenger-side-leading with the surrogates using both handholds or using only the right handhold (Figure 6). In the driver tests, the surrogate was rolled driver-side leading while holding the steering wheel in a normal driving position.

Table 2. Vehicle and Occupant Data Acquisition and Filtering Information

Vehicle Instrumentation	Acquisition Frequency	Filtering Frequency
Speed	100 Hz	2 Hz
Distance	100 Hz	Unfiltered
Local GPS position	100 Hz	Unfiltered
Triaxial accelerations	100 Hz	2 Hz
Roll angle	100 Hz	2 Hz
Pitch angle	100 Hz	2 Hz
Slip angle	100 Hz	2 Hz
Yaw rate	100 Hz	2 Hz
Roll rate	100 Hz	10 Hz
Pitch rate	100 Hz	10 Hz
Steering wheel angle	100 Hz	10 Hz
Steering wheel torque	100 Hz	10 Hz
Throttle position	100 Hz	Unfiltered
Brake signal	100 Hz	Unfiltered
Restraint (lap and torso) webbing loads	100 Hz	10 Hz
Triaxial seat loads	100 Hz	10 Hz
Triaxial left and right handhold loads	100 Hz	10 Hz
Pressure sensor, seat pan	100 Hz	Unfiltered
Pressure sensor, seat back	100 Hz	Unfiltered
Occupant Instrumentation	Acquisition Frequency	Filtering Frequency
EMG, bilateral biceps	1500 Hz	Band-pass 20 to 500 Hz
EMG, bilateral triceps	1500 Hz	Band-pass 20 to 500 Hz
EMG, bilateral obliques	1500 Hz	Band-pass 20 to 500 Hz
EMG, gastrocnemius (outboard leg)	1500 Hz	Band-pass 20 to 500 Hz
Pressure sensors, bilateral boot insoles	100 Hz	Unfiltered

**Figure 3. Vehicle setup for active occupant response testing.**



Figure 4. Off-road riding course. Black line is actual GPS data from a representative run.

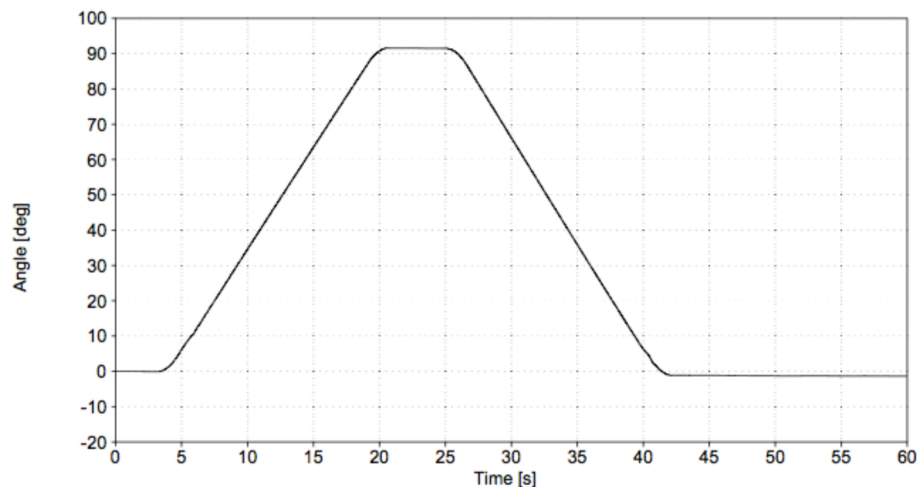


Figure 5. Representative roll angle versus time for quasi-static rolls to 90 degrees.

COMMON PHYSICAL ACTIVITIES

In order to provide quantitative reference to the magnitude of the occupants' responses during off-road course and roll spit testing, each test subject also performed a series of activities during which EMG and insole pressure data was collected. Additionally, left and right ground reaction force plates and a hanging load cell were used for a select number of activities. Activities included lifting water bottles (weighing 28.2 lb), lifting a 29.8-lb weight, stepping up on a stool, sitting down on a stool, push-ups, climbing a ladder,

pull-ups, applying a downward load, jumping, running in place, standing on their toes, and performing jumping jacks.

DATA ANALYSIS

The pressure sensors are comprised of individual sensing elements arranged into an array of rows and columns. The center-of-pressure and total force were computed for both the seat pan and seatback sensor arrays using TekScan CONFORMat software (version 7.02).

EMG signals from the bilateral triceps, bilateral biceps, bilateral abdominal obliques, and right gastrocnemius were digitally sampled at 1500 Hz and band-pass filtered from 20



Figure 6. Video frame from passenger roll spit during quasi-static roll to 90-degrees. This is the 95th-percentile male volunteer in the one-handhold configuration.

Hz to 500 Hz using bi-directional 0-phase digital filters. The band-passed signals were then rectified and low-passed filtered to form linear envelopes, which have been shown to correlate to muscle tension during isometric contractions [Winter, 2005]. The amplitude of each processed signal channel during maximum voluntary contractions (MVCs) was used for amplitude normalization.

The occupant forces and muscle activity were compared for each occupant individually during the off-road course riding, 90-degree roll spit tip-overs, and common physical activities.

To quantify the relationship between vehicle and occupant dynamics, cross correlation analysis was performed for vehicle and occupant measures in the lateral direction. In signal processing, cross-correlation is a measure of similarity of two waveforms as a function of a time-lag applied to one of them. This is also known as a sliding dot product or inner-product [Orfanidis, S.J., *et al.*, 1996]. This analysis can be used to identify the correlation, r , (also known as the correlation coefficient, product-moment correlation or Pearson's correlation) between two time-varying signals, along with the time lag at which the correlation between the signals is greatest.

RESULTS AND DISCUSSION

To confirm that the simulated tip-over generated on the sled fixture was representative of actual 90-degree tip-overs, the roll angle and roll rate responses in the sled tests were compared to that measured in documented steering-induced tip-over tests (Figure 7). Warner and Bready [SAE 2011-01-1117] reported a series of passenger-side-leading full-lock steer-induced tip-up tests on grass and dirt, and SEAL Corp has produced results from a full-lock steer-induced tip-up test on grass [unpublished, public-domain

documentation]. The roll behavior (roll angle and roll velocity versus time) in each of the passenger-side-leading sled tests of the current study fell within the range of that observed in the available steering-induced tip-over tests.

PASSIVE RESPONSE

Evaluation of the high-speed video of the belted sled tests demonstrates that the ATD's pelvis is maintained in the seat as the occupant's head and upper body initially move outboard in response to the ROV lateral acceleration; the ATD's torso interacts with the shoulder belt; and, there is subsequent restraint of lateral motion associated with locking of the web-sensitive seatbelt retractor. Figure 8 illustrates the occupant position just before ground impact in the driver-side-leading tests, and Figure 9 illustrates the same for the passenger-side-leading tests. As shown, the ATD's lower extremities, pelvis, torso, and head are restrained relative to the vehicle such that the ATD enters a shoulder-leading orientation at ground contact. The ATD's lower extremities are passively maintained completely within the occupant compartment until ground contact, and the ATD's limbs do not move into a position where they could be interposed between the vehicle structure and the contact surface. Based on review of the video, the foot does not tend to move at all, relative to the vehicle, until the side of the vehicle impacts the contact surface (honeycomb blocks). As the foot and lower leg do not move significantly relative to the vehicle during tip-over, it is apparent that the inertial forces acting on the ATD and its lower extremities are less than the restraint and constraint forces (e.g. contact forces and friction between the foot and the floor, thigh and seat, thigh and hip restraint) which act to maintain the lower extremities inside the ROV.

The belted ATD kinematics with the door and inboard handhold were very similar to the previously described belted passenger-side-leading tests without the door (Figure 10).