Definition and measurement of rider-intrinsic physical attributes influencing all-terrain vehicle safety

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Object. All-terrain vehicle (ATV) usage has grown tremendously over the years, reaching 9.5 million vehicles in use in 2007. Accompanying this growth has been a concomitant increase in rider morbidity (including traumatic brain and spine injuries) and death, especially in children. The purpose of this study was to define and measure, through field testing, those physical attributes intrinsic to riders, such as height, weight, and wingspan, which may have implications for ATV riders’ safety.

Methods. Three field tests (J-hook, brake, and bump) were developed and performed to allow direct measurement of the lateral, longitudinal, and vertical dynamics in 5 riders of varying heights, weights, and wingspans. Two ATVs, a utility and a sport model, were tested for further comparisons. Data were acquired using a comprehensive data acquisition system attached to the ATVs. Assignment of individual rider/ATV test safety ratings and a rider/ATV Total Safety Rating were made from the results of these field tests.

Results. The J-hook test results demonstrated that larger rider wingspans positively influence ATV rider safety and mitigate against lateral instability. From the brake test it was determined that a 10-in (25.4-cm) longitudinal displacement, such as that experienced during a sharp deceleration, for a rider of any height or weight, breached the level of defined safety. As rider weight increased, displacement decreased. The bump test provided evidence that increased rider weight also mitigates against vertical displacement.

Conclusions. Individuals with light weights and small wingspans, such as those in the pediatric population, are under considerable risk of injury when operating an ATV due to lateral, longitudinal, and vertical operational instability. (DOI: 10.3171/2011.9.FOCUS1176)

Key Words • all-terrain vehicle • safety legislation • wingspan • pediatric traumatic brain injury
With only 2 exceptions, in each successive year between 1991 and 2007 an increase was witnessed in the US in the number of injuries derived from ATV operation or usage that required hospital emergency department medical treatment—from 58,100 to 150,900 injuries. Moreover, a minimum of 8,995 riders have lost their lives in ATV-associated accidents between 1982 and 2007. Of this total, 28% (2,497) were children < 16 years of age, and 12% (1,062) were < 12 years of age.

According to a US CPSC study on ATV-related injuries and frequency of use (Table 1), from 1997 to 2001 the number of ATV riders increased from 12 to 16.3 million (36%), the total number of riding hours went from 1.575 to 2.364 billion (50%), and the number of ATVs in use rose from 4 to 5.6 million (40%). However, revised CPSC data show an incongruent rise in the number of ATV-related injuries treated in hospital emergency departments over this 5-year period: from 52,800 to 110,100 (an increase of 109%).

TABLE 1: Frequency of use and ATV-related injury data in the US for 1997 and 2001

<table>
<thead>
<tr>
<th>Parameter</th>
<th>1997</th>
<th>2001</th>
<th>% Increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>no. of ATV riders</td>
<td>12 million</td>
<td>16.3 million</td>
<td>36</td>
</tr>
<tr>
<td>hrs of ATV riding</td>
<td>1.575 billion</td>
<td>2.364 billion</td>
<td>50</td>
</tr>
<tr>
<td>no. of ATVs in use</td>
<td>4 million</td>
<td>5.6 million</td>
<td>40</td>
</tr>
<tr>
<td>ATV-related injuries*</td>
<td>52,800</td>
<td>110,100</td>
<td>109</td>
</tr>
</tbody>
</table>

* Based on revised CPSC data not available during original study.

To conduct these tests it was necessary to design a data acquisition system capable of dynamically locating the center of gravity of both the ATV and rider while in the field simulating riding events. The center of gravity is the point at which gravity can be said to act. On a dynamic vehicle, the roll moment acts through this point. However, the location of the center of gravity of an ATV shifts as the vehicle bounces, tilts, and deflects its shocks and tires through riding events. Moreover, unlike in an automobile, the shifting of rider weight to maintain balance on an ATV is necessary. Therefore, the data acquisition system needed to be capable of deriving the position of the rider in relation to the ATV. By tracking the center of gravity of the rider, the movement of the rider’s weight force can be traced. Knowing the center of gravity of both the ATV and rider then allows for the determination of weight distribution, lateral, longitudinal, and vertical displacements, and an estimation of rollover risk.

The data acquisition system we designed was developed for direct attachment to the ATVs. It comprised an AiM Sports EVO3 data logger (with 2 internal accelerometers, 3 linear potentiometers, 1 magnetic pick-up speed sensor, and 2 inclinometers); a Bumblebee2 Stereoscopic Vision Camera (Point Grey Research, Inc.) for tracking rider movements and location with respect to the ATV; and custom MATLAB software code for translating the camera data into coordinates and combining all of the collected data from the EVO3 (that is, shock displacements, lateral and longitudinal accelerations, ATV speed, longitudinal and lateral inclination angles, and ATV and rider centers of gravity) for evaluation.

The EVO3 data logger was placed atop the ATV so the sensors could be easily plugged in. The 3 linear potentiometers were placed parallel to the ATV’s suspension by attaching them to metal brackets connected to the vehicle. The magnetic speed sensor was attached to one of the ATV’s wheels by using silicone caulk on the wheel and a metal bracket attached to the frame. The Bumblebee2’s specifications required the camera to be located 3 ft (91 cm) away from the target it was tracking. An angled boom and bracket was designed, stress analyzed, built, and attached to the back of the ATV so that it positioned the camera at least 3 ft (91 cm) from the rider’s back. The 2 inclinometers were attached to this boom and bracket. Additionally, to pull images from the camera it was necessary to place a laptop on the ATV during testing. A padded box was fabricated that allowed the safe attachment of a laptop to the back of the ATV during testing.

For field testing, 2 ATVs were ridden through identical events within the parameters of the 3 tests developed to measure and compare the dynamics of 5 adult riders of varying heights, weights, and wingspans. To ensure that comparable speeds were used by each rider during testing, and thus that reliable evaluations could be drawn, speed data were captured throughout each riding event. The ATVs used were a Polaris Trailblazer 250 (a sport ATV) and a Honda FourTrax 250 (a utility ATV). Both ATVs had 250 cm³ displacement engines and weights of approximately 480 lbs. However, each had a very different suspension design; the Polaris used a MacPherson strut front suspension, whereas the Honda had a typical...
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4-bar-linkage front suspension. Both ATVs had a solid rear axle.

After all field testing was concluded and the results were analyzed, a test safety rating was assigned to each individual rider/ATV combination in each of the 3 tests. Based on these results, a TSR was calculated for each rider/ATV combination. These ratings allowed for further evaluation and comparison of factors affecting ATV rider safety.

In relation to the different baseline driving capabilities of the participants, which might have significantly influenced the results, all 5 drivers were matched for such confounding factors as follow: 1) none of them had ever driven an ATV vehicle before the instructions and training that were provided in the laboratory; and 2) all 5 participants were grossly matched regarding their driving skills. All riders were students at Bradley University in Peoria, Illinois, who were > 18 years of age and had no professional driving training; although all of them reported having the general skills for car driving expected for the adult population at such an age.

The J-Hook Test

The J-hook test concept is used by the National Highway Traffic and Safety Administration to measure a vehicle’s dynamic movements in sharp turning. From this performance, a rating of resistance to rollover is assigned. We adapted this test, which involved the rider turning to the left and then suddenly veering to the right (Fig. 1), to gauge the lateral movement of an ATV rider under centrifugal forces. The results of this test are important because a common mechanism of ATV injury for younger riders is the rolling over of their ATV onto its side while on level terrain.7

A few assumptions had to be made to enable calculations predicting rider movement during a turn. First, it was assumed that the dimension of the rider’s arm segments and the distance between the shoulder joints were equal, and that the rider’s torso alignment was always perpendicular to the seat (Fig. 2A). This assumption was supported by the arm dimensions of the 5 riders. Second, it was assumed that the rider’s arm was fully extended, aligning the 2 arm segments (Fig. 2B). Third, the system was said to be a 4-bar linkage comprising the shoulder-to-shoulder distance, the distance between the rider’s center of gravity and the fulcrum of the handlebars, and the fully extended arm (Fig. 2C). Last, it was assumed that the rider shifted his or her weight a fixed distance into the J-hook to compensate for the centrifugal force (Fig. 2D). This fixed value was derived from examining the J-hook test data and finding the average inward lateral shift of the riders, which was approximately 3 in.

The rider/ATV geometry was modeled as a 4-bar linkage. The loop closure equation for this system is

$$\vec{r}_M + \frac{1}{2} \cdot \vec{r}_4 - \vec{r}_5 - r_6 - \frac{1}{2} \cdot \vec{r}_1 = 0$$  [Eq. 1],

where $r_M$ is the vector between the rider’s center of gravity and the fulcrum of the handlebars; $r_4$ is the vector between the 2 handlebar grips (hands); $r_5$ is the vector...
between a handlebar grip (hand) and corresponding elbow joint; 
\( r_6 \) is the vector between an elbow joint and corresponding shoulder joint; and 
\( r_1 \) is the vector between the 2 shoulder joints.

Equation 1 can be simplified using the above-listed assumptions, as follows:

\[
 l_M \leq \theta_M + \frac{1}{2} \cdot l_H \leq \theta_4 - 2 \cdot l_s \leq \theta_5 - \frac{1}{2} \cdot l_4 \leq \theta_1 = 0 \quad [\text{Eq. 2}],
\]

where \( l_M \) is the magnitude of the vector between the rider’s center of gravity and the fulcrum of the handlebars; \( \theta_M \) is the direction of the vector between the rider’s center of gravity and the fulcrum of the handlebars; \( l_H \) is the length of the vector between the 2 handlebar grips (hands); \( \theta_4 \) is the direction of the vector between the 2 handlebar grips (hands); \( l_s \) is the magnitude of the vector between the rider’s center of gravity and the fulcrum of the handlebars; \( \theta_5 \) is the direction of the vector between the handlebar grip (hand) and the shoulder joint; and \( \theta_1 \) is the direction of the vector between the 2 shoulder joints.

For the Polaris ATV, the grip-to-grip distance and the distance between the rider’s center of gravity and the fulcrum of the handlebars were measured to be 25 in (63.5 cm) and 20.5 in (52.1 cm), respectively. For the Honda ATV, the analogous values were 26 in (66 cm) and 20.5 in (52.1 cm).

\[ \text{DistFromSeatToNavel} = \frac{1}{12} \cdot \text{RiderHeight} \quad [\text{Eq. 3}] \]

\[ \text{GoldenRatio} = \frac{\text{RiderHeight}}{\text{HeightToNavel}} = \frac{1 + \sqrt{5}}{2} \quad [\text{Eq. 4}] \]

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**The Brake Test**

The brake test was developed and performed to measure the longitudinal displacement of a rider experiencing sudden deceleration (Fig. 1). Starting from a stop, the rider accelerated along a linear path, reaching a certain minimum speed. On reaching a preset location, the rider would immediately apply the brakes as if in an emergency braking situation. The longitudinal displacement of the rider during the deceleration event was measured.

Without seat belts, which are used to control occupants in an automobile, an ATV rider can easily be thrown forward and sustain injuries in cases of sharp deceleration.

**The Bump Test**

The bump test was conducted to observe and measure a rider’s vertical bounce when driving over a 3.5 in (8.9 cm) high bump (Fig. 1). This test is based on the premise that riders’ safety is severely compromised once they are in a position in which their legs are completely extended. Any displacement beyond this boundary could cause their feet to leave the foot pegs—a condition conducive to ATV/rider separation. Similarly to longitudinal displacement, without restraint, excessive vertical displacement from the ATV seat can easily lead to rider injury.

The maximum allowable bounce for a particular rider was determined as his or her change in position from sitting to standing with legs at full extension. Figure 3 shows the basic geometry of a rider in the sitting position. Equations 3, 4, and 5 were used to calculate the inseam of the riders based on their height through the golden ratio and proportions presented by Leonardo da Vinci’s Vitruvian Man (http://en.wikipedia.org/wiki/Vitruvian_Man [Accessed October 7, 2011]).

\[ \text{DistFromSeatToNavel} = \frac{1}{12} \cdot \text{RiderHeight} \quad [\text{Eq. 3}] \]

\[ \text{GoldenRatio} = \frac{\text{RiderHeight}}{\text{HeightToNavel}} = \frac{1 + \sqrt{5}}{2} \quad [\text{Eq. 4}] \]
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\[ \text{Inseam} = \text{HeightToFront} - \text{DistFromSeatToFront} - \text{RiderHeight} \left( \frac{1}{12} - \frac{1}{6} \right) \]  [Eq. 5]

Figure 3 also shows a diagram of an ATV rider in a standing position, legs fully extended. The vertical change in the position of the pelvic area of the rider is equivalent to the change in position of the tracked target (center of gravity) on the rider. Therefore, defining the change in height from the sitting to standing position will define the maximum allowable bounce deemed safe.

Equations 6, 7, and 8 describe the derivation of the maximum allowable bounce through the measurable dimensions of rider height, distance between ATV foot pegs, and distance from the foot pegs to the seat of the ATV.

\[ H = \sqrt{\text{Inseam}^2 - \left( \frac{\text{DistFromSeatToFront}}{2} \right)^2} \]  [Eq. 6]

\[ \text{AllowableBounce} = H - \text{HeightFromPedalsToSeat} \]  [Eq. 7]

\[ \text{AllowableBounce} = \sqrt{\text{Inseam}^2 - \left( \frac{\text{DistFromSeatToFront}}{2} \right)^2} - \text{HeightFromPedalsToSeat} \]  [Eq. 8]

Although a rider at a given weight can be one of many heights, the bounce experienced by an ATV rider is dependent on his or her weight and the ATV’s suspension engineering. Therefore, the safety of a rider experiencing vertical displacement must be evaluated within the context of the weight variable. For the purposes of defining the safety of a rider, the typical height ranges corresponding to a particular weight were found using health insurance documentation from BlueCross BlueShield for juvenile and adult health underwriting guidelines. For the minimum and maximum heights at each weight, Equation 8 was used to calculate the maximum allowable bounce of the rider.

The TSR

The 5 riders chosen for field testing of the ATVs were selected based on desired variances in height, weight, and wingspan combinations. This allowed for the observation and examination of how each intrinsic physical attribute may be responsible for rider safety.

Table 2 outlines the key physical features of each test rider. Rider A simulates a child due to her short height and light weight. Rider B is nearly the same height as Rider A, but weighs considerably more. Riders C and D are of approximately the same height as Rider B, but with greater height and wingspan. Therefore, they were used to evaluate the effect of increased height on rider safety. Rider E is close in height to Riders C and D, but is > 90 lbs (40.8 kg) heavier than both.

The TSR was derived from the safety ratings of the individual tests, which were combined through the following equation:

\[ \text{TotalSafety} = 60\% \cdot \text{J-HookSafety} + 25\% \cdot \text{BumpSafety} + 15\% \cdot \text{BrakeSafety} \]  [Eq. 9]

Each test’s safety rating was weighted according to what rider movements were deemed most influential to rider safety.

Results

The J-Hook Test Results

With the aid of Equation 8 and the measured values for grip-to-grip distance, the distance between the rider’s center of gravity and the fulcrum of the handlebars, and the lateral rider shift, a plot was made using a range of wingspans from 24 in (61 cm) to 84 in (213.4 cm), in 0.5-in (1.3-cm) increments, for the 2 ATV models (Fig. 4).

Analysis of this plot allowed certain adjustments to be made. Because a rider must be able to shift his or her body into a turn to maintain balance, any handlebar angle < 0° was filtered out, on the assumption that if the rider is unable to shift at least 3 in (7.6 cm) into a turn and maintain a handlebar angle ≥ 0°, the rider is unsafe. Additionally, any handlebar angle > 60° was filtered out, on the assumption that if the rider is able to shift at least 3 in (7.6 cm) into a turn and maintain a handlebar angle ≥ 60°, any increase in wingspan is superfluous.

Applying these adjustments, a plot of the calculated J-hook test safety values (five-thirds of handlebar angle) as a function of wingspan was developed (Fig. 5). As shown, there are minimum and maximum values for each data set. These values represent the 0% and 100% values, respectively. Any wingspan that has a handlebar angle ≤ 0° will have a corresponding safety value of 0%. This safety value represents the range of wingspans that cannot shift and turn adequately on the ATV. In contrast, any wingspan that has a handlebar angle ≥ 60° will have a corresponding safety value of 100%. This safety value represents the range of wingspans that should not have difficulty shifting and turning adequately on the ATV. For example, an individual with a 60-in (152.4-cm) wingspan can turn the handlebars 7.27° and 5.96° on the Polaris and Honda, respectively, with corresponding safety values of 12.12% and 9.93%.

The J-hook test results clearly demonstrate that rider wingspan can have direct implications for ATV safety. Much of this effect is probably due to the need for the ATV rider to actively engage the vehicle to mitigate against rollovers. To maintain stability, a rider must coordinate the counterintuitive shifting of his or her body weight in the opposite direction of a turn. For these procedures, a large wingspan is certainly beneficial.

The Brake Test Results

Figure 6 shows the exponential curve fit for the experimental data collected from the brake test. Through measurements of the geometry of each ATV, it was determined that a 10-in (25.4-cm) position change for a rider of any height or weight would be unsafe. This 10-in value was true for both the Polaris and Honda. All rider weights that moved 10 in or more were given a safety rating of 0%. As rider weight increased, the change in position decreased, and the difference between the unsafe value of 10 in and actual rider displacement was used to find the safety rating. A diagram of the measured rider displacement is shown in Fig. 7, and a plot summarizing the safety ratings of various weighted riders is illustrated in Fig. 8. These results illustrate a key takeaway: heavier weights can significantly aid in ATV rider safety by effectively...
buffering longitudinal displacement experienced during sharp deceleration.

**The Bump Test Results**

The calculated maximum allowable bounce for riders of specific weights at minimum and maximum heights, as defined by the BlueCross BlueShield data, is shown in Fig. 9 upper for the Honda ATV. As shown, a rider weighing 100 lbs (45.3 kg) would be expected to bounce a distance of 9 in (22.9 cm) on the Honda when driving over a 3.75-in (9.5-cm) bump. However, a tall 100-lb (45.3-kg) rider is capable of bouncing 13 in (33 cm) before becoming unsafe, and a short 100-lb rider can bounce only 5 in (12.7 cm) before the same effect occurs. Therefore, not every 100-lb rider should be expected to be safe when riding under congruent conditions. Assuming the typical population has a height between the minimum and maximum values described by BlueCross BlueShield, only 45%–50% of 100-lb persons could be expected to withstand a 9-in (22.9-cm) vertical displacement without leaving the foot pegs. Figure 9 lower illustrates the bounce and bump test safety of a rider with respect to his or her weight on the Honda.

Maximum allowable bounce and safety rating profiles were also calculated for the Polaris (Fig. 10). Notable differences are evident between the 2 ATV bounce plots. The Honda, being a utility ATV, has a more stable design. It sits lower to the ground and has firmer suspension. The Polaris, a sport ATV, is made for rugged entertainment and sits higher off the ground, with more bounce in its suspension. In addition, the Polaris has a greater distance from its foot pegs to its seat than the Honda. As a result, riders’ legs are more extended in the sitting position. Consequently, a rider will have less allowable bounce before their legs will reach full extension on the Polaris. These stability factors influenced the location and shape of the “predicted bounce” lines of each bounce plot. Under equal conditions, a rider would bounce less on the Honda than on the Polaris. To illustrate, a weight of 75 lbs (34 kg) marks the weight value at which a rider becomes unsafe on the Honda when riding over a 3.75-in (9.5-cm) bump. On the Polaris, however, this weight value is 85 lbs (38.5 kg).

**The TSR**

Table 2 documents the TSRs derived for each rider on the Polaris and Honda ATVs. As can be seen in relation to Rider A, the greater weight of Rider B produced a significant increase in the TSR: approximately 35 percentage points for the Polaris and 30 percentage points for the Honda. However, due to the relatively short wingspans of Riders A and B, they were still both rated considerably less safe than the other riders.

The greater heights and wingspans of Riders C and D contributed to a TSR increase of approximately 20 percentage points over Rider B on both machines. The heavier weight of Rider E led to a 7–8 percentage point TSR increase over Riders C and D. This underwhelming increase illustrates 2 key points: short height, light weight, and small wingspan traits dramatically and detrimentally influence rider safety. In addition, there are physical attribute thresholds whereupon the TSR begins to taper, and further increases do not significantly augment rider safety.

**Discussion**

The implications of this study are enormous, especially for the pediatric population, because they have been found to be 4–12 times more likely to be injured riding an...
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ATV than adult riders. In 2001, there were 2.8 million ATV riders < 16 years old, of whom only 1% received any formal ATV rider training. Despite having made up only 17% of all ATV riders, children < 16 years of age disproportionately accounted for 31% of ATV-associated injuries and 26% of ATV-associated fatalities in 2001. Within this pediatric population, 85% rode adult-sized ATVs (> 90 cm³ displacement) and, not surprisingly, 87% of those injured were riding on such a vehicle. An analysis of ATV fatalities from 1999 to 2000 by the CPSC noted that 93% of ATV-related fatalities in children < 16 years old occurred on adult-sized machines. Moreover, an analysis of the hazard patterns associated with these fatalities demonstrates that many were due to the vehicle overturning (40%) and ejection from the vehicle (15%). Compounding matters, children have a high incidence of trauma to the CNS, defined as intracranial or spinal cord injury, when involved in ATV crashes. In fact, adolescent ATV riders have more head injuries than other age groups, and these injuries tend to be more severe in nature.

For all age groups, head trauma is the leading cause of death from ATV-associated injuries. It has been reported that 80% of all ATV-associated deaths involved a CNS injury. Despite this fact, the helmet usage rate among ATV riders is dismal. Only 35% of riders reported always wearing a helmet, whereas 32% reported never wearing one. A recent survey of typical ATV usage patterns in rural Illinois youth revealed that most never used safety gear, including helmets (61.4%), and few (14.6%) had received safety education. A statistical analysis revealed that helmet usage among all ATV riders would reduce the risk of death by 42% and nonfatal head injuries by 64%. In Ireland, for example, where helmet usage is required and compliance is quoted at 78%, head injuries are rare, and most injuries are orthopedic in nature. Moreover, by extrapolating motorcycle-associated health care costs to ATVs, the cost of care for unhelmeted ATV patients could be 23%–60% greater than for helmeted patients.
Helmed or unhelmed, ATV-associated injuries are not without considerable financial consequences. Expenses related to ATV injury can include medical and legal bills, disability payments, and lost economic productivity. The American Academy of Orthopedic Surgeons estimated that in the year 2000 alone, ATV-related injuries in the US cost society $6.5 billion. The bulk of these expenses are borne by private insurers.

Between 1988 and 1998, the CPSC instituted federal marketing and manufacturing requirements for ATV usage in children. Integral to these requirements was the stratification of ATV engine size (and thus vehicle size and power) for riders at specific ages (< 70 cm³ for riders < 12 years old, 70–90 cm³ for those 12–16 years old, and > 90 cm³ for operators > 16 years old). After the consent decree expired, the major ATV manufacturers agreed to continue the program voluntarily. In 2008, due to public outcry over rising ATV injuries and fatalities in children, the CPSC published a new and final rule adopting the ATV industry standard, ANSI/SVIA-1–2007, as a man-

Conclusions
Injuries related to ATVs continue to be a great concern for public health as well as safety regulatory agencies. Through our comprehensive field testing and safety rating assignments, we were able to provide substantial evidence supporting the belief that individuals with short wingspans and light weights are under considerable risk while operating an ATV.

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