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Publication Date
2023-02-01

DOI
10.1016/j.jsr.2022.11.010

Journal of Safety Research 84 (2023) 353–363

Contents lists available at ScienceDirect

Journal of Safety Research

journal homepage: www.elsevier.com/locate/jsr

Ability of youth operators to reach agricultural all-terrain vehicles controls

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ARTICLE INFO

Article history:
Received 7 September 2022
Received in revised form 12 September 2022
Accepted 21 November 2022
Available online 30 November 2022

Keywords:
Anthropometry
ATV
Children
Farm
Quadbike

ABSTRACT

Problem: Utility All-Terrain Vehicles (ATVs) are one major cause of youth injuries and fatalities on farms. Utility ATVs have heavy weights and fast speeds that require complex maneuvering. Youth's physical capabilities may not be sufficient to perform those complex maneuvers correctly. Therefore, it is hypothesized that most youth engage in ATV-related incidents because they ride vehicles unfit for them. There is a need to assess ATV-youth fit based on youth anthropometry. *Method:* This study focused on evaluating potential inconsistencies between the operational requirements of utility ATVs and the anthropometric measures of youth through virtual simulations. Virtual simulations were performed to assess 11 youth-ATV fit guidelines proposed by several ATV safety advocacy organizations (National 4-H council, CPSC, IPCH, and FReSH). In total, 17 utility ATVs along with male-and-female-youth of nine ages (8 to 16 years old) and three height percentiles (5th, 50th, and 95th) were evaluated. *Results:* The results demonstrated a physical mismatch between ATVs' operational requirements and youth's anthropometry. For example, male-youth aged 16 of the 95th height percentile failed to pass at least 1 out of the 11 fit guidelines for 35 % of all vehicles evaluated. The results were even more concerning for females. Female youth 10 years old and younger (from all height percentiles) failed to pass at least one fit guideline for all ATVs evaluated. *Discussion:* Youth are not recommended to ride utility ATVs. *Practical Applications:* This study provides quantitative and systematic evidence to modify current ATV safety guidelines. Furthermore, youth occupational health professionals could use the present findings to prevent ATV-related incidents in agricultural settings.

1. Problem

The use of utility All-Terrain Vehicles (ATVs) as working machines adds a heavy burden to the American public health system (Helmkamp, Marsh, & Aitken, 2011). According to data from the 2019 National Electronic Injury Surveillance System, over 95,000 emergency department (ED) visits were due to an ATV-related incident. Around 36.8 % of those ED visits involved youth younger than 18 years old, and 15.3 % of the incidents happened on farms or ranches (Wiener, Waters, Harper, Shockey, & Bhandari, 2022). Indeed, using utility ATVs in the farm setting is extremely dangerous for youth; ATVs are one of the most frequently cited causes of incidents among farm youth (Hendricks & Hard, 2014; Weichelt & Gorucu, 2018).

ATVs have three or four low-pressure tires, narrow wheelbase, and high center of gravity (Ayers, Conger, Comer, & Troutt, 2018; Chou, Khorsandi, Vougioukas, & Fathallah, 2022; House, Schwebel, Mullins, Sutton, Swearingen, Bai, & Aitken, 2016). Due to safety concerns, the production of three-wheelers ceased in the United States in 1987 (Voreacos, 1987). Three-wheelers were known to be even more prone to rollovers than four-wheeled ATVs (David, 1998).

Utility ATVs and sport models (which include youth ATV models) have several design differences. Utility models have higher ground clearance, stronger torque for hauling and towing, rear and front racks for carrying loads or mounting equipment, a hitch to pull implements, and heavyer weights (Khorsandi et al., 2021). Accordingly, utility ATVs are more suitable and more commonly used for tasks in agricultural settings. Therefore, in this study, agricultural ATVs are defined as utility ATVs used on farms and ranches.

Agricultural ATVs have heavy weights and fast speeds that require complex maneuvering. Youth's physical capabilities may not be sufficient to perform those complex maneuvers correctly. In fact, many studies have shown that youth are more vulnerable to injuries than adults because of their less developed physical

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https://doi.org/10.1016/j.jsr.2022.11.010
0022-4375/

Nomenclature

Name Abbreviation
4-Wheel-Drive 4WD
All-terrain vehicle ATV
American Academy of Pediatrics AAP
American National Standards Institute ANSI
ATV Safety Institute ASI
Cohen's Kappa Coefficient K
Computer-Aided Design CAD
Crush Protection Device CPD
Cubic Capacity cc
Department of Trade Industry DTI
Electric Power Steering EPS
Emergency Department ED
Farm and Ranch eXtension in Safety and Health FReSH
General Accounting Office GAO
Intermountain Primary Children's Hospital IPCH
Loss of Control Event LCE
National 4-H Council N4-HC
National Children's Center for Rural and Agricultural Health and Safety NCCRAHS
National Safe Tractor and Machinery Operation Program NSTMOP
Seat Reference Point SRP
Specialty Vehicle Institute of America SVIA
Three-dimensional 3-D
U.S. Consumer Product Safety Commission CPSC
Virtual Reality VR

capabilities and psychological and behavioral characteristics (Brison et al., 2006; Hard & Myers, 2006; Hendricks, Myers, Layne, & Goldcamp, 2005; Marlenga, Pickett, & Berg, 2001; Pollack-Nelson, Vredenburgh, Zackowitz, Kalsher, & Miller, 2017; Reed, Ebert-Hamilton, Manary, Klinich, & Schneider, 2005; Serre et al., 2010; Towner & Mytton, 2009), which likely affect their ability to safely operate agricultural vehicles (Bernard et al., 2010; Chang, Fathallah, Pickett, Miller, & Marlenga, 2010; Fathallah, Chang, Berg, Pickett, & Marlenga, 2008; Fathallah, Chang, Pickett, & Marlenga, 2009). Furthermore, previous studies have shown that ATV-rider misfit is another important risk factor (Bernard et al., 2010; Jennissen, Miller, Tang, & Denning, 2014).

Despite compelling evidence showing that utility ATVs are unsuitable for youth, the most popular guidelines for ATV-youth fit disregard the rider's physical capabilities. Instead, those recommendations are based on the rider's age (Academy, 2018), vehicle's maximum speed (ANSI/SVIA, 2017), vehicle's engine size (CPSC, 2006), or farm machinery training certificate (Garvey, Murphy, Yoder, & Hilton, 2008). For instance, youth as young as 14 can operate utility ATVs while employed on non-family-owned farms if they receive training through an accredited farm machinery safety program, such as the National Safe Tractor and Machinery Operation Program (NSTMOP) (Garvey et al., 2008). The NSTMOP training includes tractor and ATV education, where students must pass a written knowledge exam and a functional skills test to receive a certificate (Murphy, 2020). Nevertheless, programs such as the NSTMOP lack appropriate coverage of specific ATV-related subjects, such as active riding and physical matches of ATVs and youth.

If the ATV is not fit to the rider, they will likely be unable to properly operate the ATV's controls, which increases their chance of incidents and consequently may lead to injuries and fatalities. In addition, the traditional guidelines adopted to fit ATVs for youth are inconsistent in evaluating their preparedness to ride. The suggested fitting criteria are subject to variances in state law and lack scientifically-based evidence. While some recommendations based upon the riders' physical capabilities exist (CPSC, 2006; FReSH, 2012; IPCH, 2018; National 4-H Council, 2005), the adoption of these recommendations has not gained attention because they are not comprehensive and lack quantitative and systematic data.

Recommendations based on riders' physical capabilities appear to provide a better foundation to determine if the machine is suitable for the rider (Bernard et al., 2010). Therefore, there is a need to evaluate youth-ATV fit based on the riders' physical capabilities (e.g., anthropometry, strength, and field of vision).

Since 95 % of all ATV-related fatalities involving youth between 1985 and 2009 included agricultural ATVs (Denning, Harland, & Jennissen, 2014), the purpose of this study is to evaluate the mismatches between the operational requirements of utility ATVs and the anthropometric characteristics of youth.

It has been hypothesized that youth are mainly involved in ATV incidents because they ride vehicles unfit for them. This study evaluated ergonomic inconsistencies between youth's anthropometric measures and utility ATVs' operational requirements. The ability of youth to safely operate ATVs was evaluated through computer simulations that comprised 11 fit criteria and male-and-female youth of varying ages (8–16 years old) and height percentiles (5th, 50th, and 95th) operating 17 utility ATV models.

2. Methods

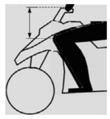
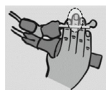
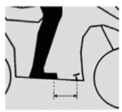
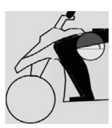
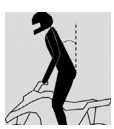
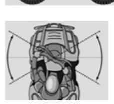
Youth-ATV fit was analyzed through virtual simulations and was carried out in five steps. First, 11 guidelines were identified for the fit of youth and ATVs. The second step consisted of identifying a database containing anthropometric measures of youth of various ages (8–16 years old), genders (males and females), and height percentiles (5th, 50th, and 95th). The third step consisted of collecting the dimensions of 17 ATV models to create a three-dimensional (3-D) representation of them. The fourth step consisted of using SAMMIE CAD (SAMMIE CAD Inc., Leics., UK) and Matlab (Matlab, v2021a; Mathworks, Natick, MA) to evaluate if the youth's anthropometric measures conform to the guidelines identified in step one. Lastly, the results of the virtual simulations were validated in field tests with actual riders and ATVs.

2.1. Fit criteria

The fit criteria provide movement-restraint thresholds that check if the rider can safely reach all controls and perform active riding, which requires the operator to shift their center of gravity to maintain the vehicle's stability, especially when turning or traveling on slopes (Thorbole, Aitken, Graham, Miller, & Mullins, 2012). Maintaining a correct posture is essential because, otherwise, the rider's ability to control the vehicle is compromised, which puts them and potential bystanders at risk.

The reach criteria considered in this study were selected based on the recommendations of the following institutions: (a) National 4-H Council (2005), (b) U.S. Consumer Product Safety Commission (CPSC) (2006), (c) Intermountain Primary Children's Hospital (IPCH) (2018), and (d) Farm and Ranch eXtension in Safety and Health (FReSH) Community of Practice (2012). Disregarding overlaps, these guidelines consisted of 11 anthropometric measures of fit, which are presented in Table 1.

Table 1
ATV-rider fit criteria.

ID	Criterion		Institution(s)	"Fit success" and reasoning for each criterion
1	Handlebar-knee distance		National 4-H Council, CPSC	Handlebar–knee distance > 200 mm. This is necessary to ensure the rider can reach the handlebar and steer around obstacles.
2	Hand size compared to ATV handlebar reach		National 4-H Council, IPCH	With hand placed in the normal operating position and fingers straight out, the first joint from the tip of the middle finger extends beyond the brake lever. This is important to guarantee that the rider can activate the brake lever.
3	Brake-foot position		National 4-H Council	Distance from the "ball" of the foot (at its most rearward position in the ATV's foot well) to the brake pedal divided by the length of the foot < 105 %. A disproportional rate indicates a risk for ineffective foot–brake operation.
4	Standing-seat clearance		National 4-H Council, CPSC, FReSH	Clearance zone between rider's crotch and ATV seat > 150 mm. This is important to guarantee that the rider can rise the torso up from the ATV seat to maintain balance and avoid distracting longitudinal torso impacts that occur while traversing rough terrains.
5	Elbow angle		National 4-H Council, IPCH	A narrow elbow angle (<90°) indicates excessive arm flexion, while an angle too wide (>135°) indicates the arms are excessively straight due to the grips being too far apart, which forces the rider to lean the torso to the outside of the turn to achieve an adequate range of handlebar turning
6	Upper leg		National 4-H Council	Upper leg within 10° of parallel to the ground. An upper leg too far off from parallel to the ground can compromise the rider's ability to activate the foot brake and keep balance.
7	Angle of lean from vertical		CPSC	Angle of lean from vertical < 30°. This is important to guarantee a correct posture while riding the ATV. Leaning forward significantly over the handlebars to steer when raised off the seat, can shift the system's center of gravity, increasing the likelihood of the ATV tipping forward.
8	Control reach		CPSC	Riders must be able to reach all ATV controls while seated upright.
9	Footrest reach		CPSC	Riders must keep their feet firmly on the footrests when not activating the foot-brakes. This is important to ensure the rider can maintain balance and not lose control of the ATV.
10	Knee angle		CPSC	Knee angle at least 45° while sitting and with the feet flat on the footrest. An angle wider than 45° indicates a risk for ineffective foot-brake operation.
11	Control grip		CPSC, FReSH	Riders must keep a grip on the handlebar and maintain throttle and brake control when turning the handlebar from lock to lock position. This is especially important while performing a sharp turn or a swerve.

2.2. Human mockups

Human mockups were developed in SAMMIE CAD. This computer program allows users to create customized virtual humans based on eight anthropometric dimensions, as shown in Fig. 1a. In total, 54 youth mockups were created, a combination of two genders, nine ages (8–16), and three body size percentiles in height (5th, 50th, and 95th). The age range was selected because most youth start operating farm machinery at 8 years old (Marlenga et al., 2001), and most ATV-related crashes occur with riders younger than 16 years old (Denning et al., 2014). Two adult mockups (male and female of the 50th body-size percentile) were also created to establish a baseline for comparisons. The anthropometric measures used as input to SAMMIE CAD were retrieved from the database of Snyder et al. (1977), which includes measurements from 3,900 subjects from 2 to 18 years of age for both genders. The adopted anthropometric measures were based on the mean values of groups of subjects with the same age, gender, and height.

One of the required inputs (seated shoulder height) was not available in the database used for this study. Therefore, the missing input was computed using the available data. The seated shoulder height was calculated by subtracting the head and neck length from the seated height (Fig. 1b).

2.3. ATV mockups

In total, 17 utility ATV models were evaluated. Selected models consisted of vehicles of varying engine sizes (200–700 cc) from the most common ATV manufacturers on U.S. farms (Apollo, Arctic Cat, CF Moto, Honda, Polaris, and Yamaha). General descriptive vari-

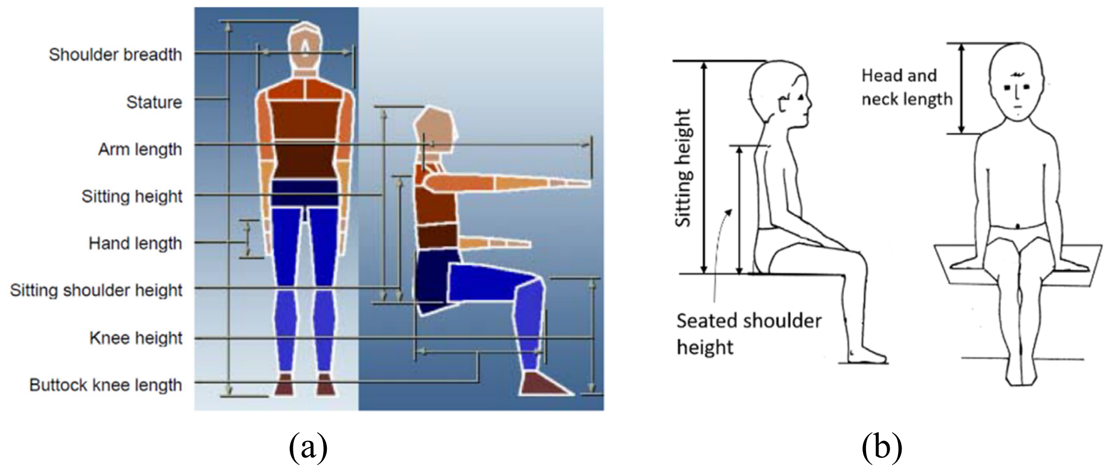


Fig. 1. SAMMIE CAD human creation. (a) Selected input variables (source: SAMMIE CAD Inc.); (b) Interpolation of missing variable (seated shoulder height) - Adapted from Snyder et al. (1977).

ables such as manufacturer, model, series, engine capacity (cc), drive terrain (4 W/2W), transmission, and suspension type were recorded.

ATV mockups were developed based on the spatial coordinates (X, Y, Z) of selected ATV features (e.g., ATV seat, chassis, handlebars, footrests, and controls). An original attempt to record spatial coordinates of ATV features consisted of using Photogrammetry, a technique in which several pictures of an object are taken from various angles and then processed to create a 3-D model. Nevertheless, this technique proved inefficient, as initial trials were time-consuming, and the results had unsatisfactory accuracy. A second attempt consisted of using a virtual reality (VR) tracking system. This alternative proved fast to implement with excellent accuracy (±1 mm); hence, this technique was selected and presented in the following section.

2.3.1. Data acquisition

The VR tracking system (Vive – HTC Corporation, China) utilized in this experiment consisted of two controllers and two infrared laser emitter units (lighthouses). The system allows the user to move in 3-D space and use motion-tracked handheld controllers to interact with the environment. The system uses the lighthouses to shoot horizontal and vertical infrared laser sweeps that are detected by photodiodes positioned in the surrounding of the controller's surface (Niehorster, Li, & Lappe, 2017). The position and orientation of the controllers are calculated by the difference in time at which each photodiode is hit by the laser (Kreylos, 2016). By placing the controller over selected vertices of ATV features, it was possible to record their spatial coordinates, which allowed the development of the 3-D ATV mockups.

A custom program was developed to calibrate the system, log, and manipulate data. This program was initially retrieved from Kreylos (2016) and then modified to meet the specific needs of the present study. The software runs in Linux operating systems and has several functionalities that are useful to the user. Examples of these functionalities are a 3-D grid, which allows for real-time visualization of labeled points, and a measuring tool (to verify the measurement scale).

A probe was custom-manufactured and attached to the controllers to ease the calibration process and data collection. The probe was made of metal and had a rounded tip, which made it wear-resistant and prevented it from damaging the ATVs. The measurements were collected inside a tent covered by a white rooftop that reduces the interference of solar rays in the communication between the lighthouses and the photodiodes in the controllers. In total, 38 points were collected per ATV. The points were selected aiming to get an efficient representation of all selected ATV controls (hand brake lever, foot brake pedal, steering handlebar, throttle lever, hand gearshift lever, and foot gearshift pedal) and additional features that were used to assist the virtual simulations, such as the seat and the footrests. After data filtering, the data were processed in SAMMIE CAD for a 3-D representation of the evaluated vehicle, as shown in Fig. 2.

2.4. Data analysis

ATV-rider fit was evaluated through SAMMIE CAD and Matlab. Fit criteria 4, 5, 6, 7, 8, 9, and 10 (Table 1) were evaluated in SAMMIE CAD because their assessment involved complex interactions between riders and ATVs, such as measuring the angle of the rider's knee while riding. SAMMIE CAD provides a 3-D environment and full control of human mockups, which makes it possible to evaluate those complex interactions. The simulations performed in SAMMIECAD consisted of: (1) creating 3-D human mockups; (2) creating 3-D ATV mockups; and (3) integrating (1) and (2) in the virtual environment to simulate their interaction. For each simulation, the correct reach posture was achieved by positioning the human limbs according to the specific task's requirement. For example, a seated position was adopted when evaluating fit criterion 10 (knee angle), as shown in Fig. 3a. On the other hand, a standing straddling posture was selected when evaluating fit criterion 4 (clearance zone between the rider's crotch and ATV seat), as shown in Fig. 3b.

Some criteria involve the youth reaching a specific control (e.g., criteria 5, 7, 8, and 9). The feature "Reach" under the "Human" menu on SAMMIE CAD was used to evaluate the ability of the youth mockups to reach the selected controls. The "Reach" was set as "Absolute," and "Object Point" was set as "Control." When the selected control could be successfully reached, the software would display an animation of the human limb reaching the desired object (the rider was assigned a score of 1 – meaning that they fulfilled the requirements of that criterion). On the other hand, if the control was out of reach, SAMMIE CAD would show an error window and display the required distance for the human limb to reach the desired control (the rider was assigned a score of 0 – meaning that they failed to pass that specific criterion).

Simulations involving buttons and levers were performed with the fingertip of the index finger or the thumb, accordingly. Simulations involving levers or the handlebars were performed with palm-grip-hand postures. All controls on the right side of the

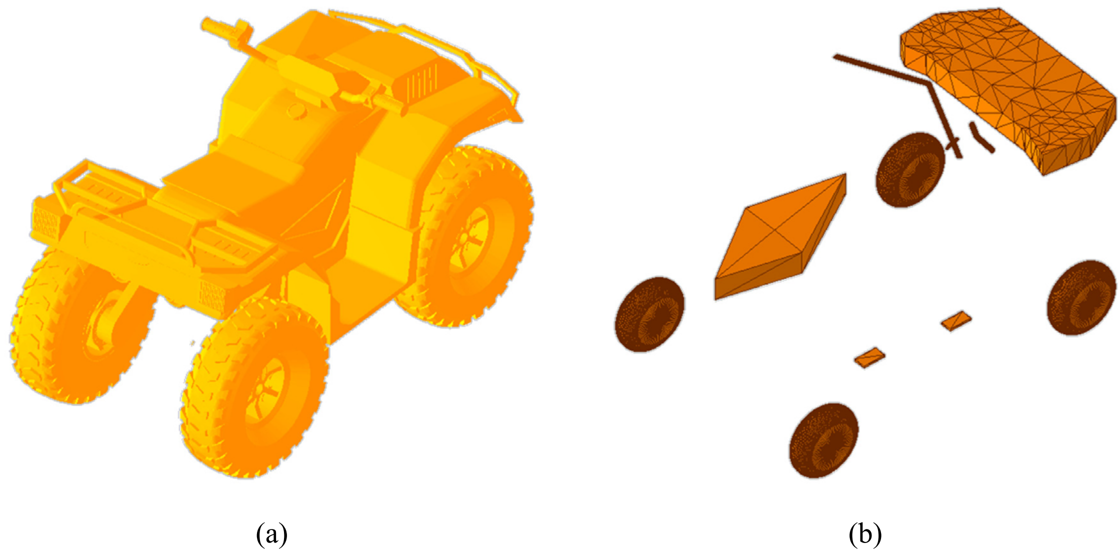


Fig. 2. 3-D representation of ATV mock-ups. (a) Fully assembled model – for visualization purposes only; (b) Example of a 3-D ATV mock-up used for the virtual simulations in SAMMIE CAD.

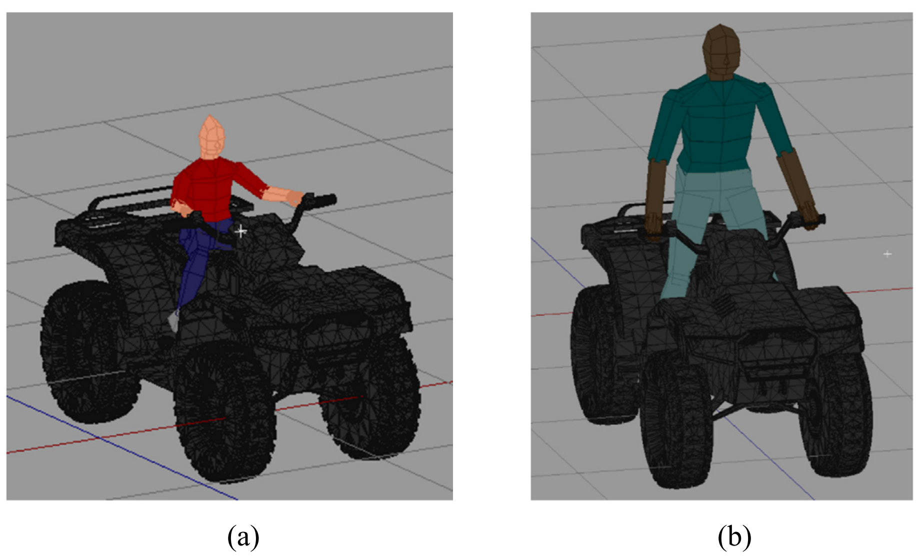


Fig. 3. Different reach postures. (a) Seated posture (9 yr. old – 5th percentile boy); (b) Standing straddling posture (16 yr. old – 95th percentile boy).

ATV were simulated with the right hand/foot, and all controls on the left side of the ATV were simulated with the left hand/foot. Specific controls that required using both hands, such as the handlebars, were simulated with both hands.

Criteria 1, 2, 3, and 11 were evaluated through Matlab because their assessment required the computation of simpler calculations, such as the distance between the rider's knee and the ATV's handlebars. Matlab also provided the ability to automate the calculations for a more efficient data analysis. A code was generated based on conditional statements to assess whether riders' anthropometric measures conformed to the constraints imposed by the ATV design. For instance, when evaluating criterion 1, the distance between the ATV footrests and the handlebars minus the rider's knee height must be greater than 200 mm (Table 1).

For each reach criterion, riders received a binary score (1 if the rider fulfilled the requirements of that criterion; and 0 otherwise). Riders with a total score of 11 (adequate reach for all evaluated criteria) were classified as "capable of riding the ATV." On the other hand, riders with a total score below 11 (inadequate reach of at least one or more criteria) were classified as "not capable of riding the ATV."

2.5. Validation

In order to validate the results of the virtual simulations, an experiment including three adults (two males and one female) and one study ATV (model Yamaha Grizzly EPS – 700) was carried out. Each subject had completed an ATV safety riding course prior to the experiment and was awarded a certificate from the *ATV Safety Institute* (ATV-Safety-Institute, 2009). The capability of the subjects to fulfill each fit criterion was evaluated and recorded. For the field tests, a measuring tape graduated in mm was used to measure distances and a digital angle finder (General Tools & Instruments LLC., New York, NY, USA) to measure angles. To assist in some of the angle measurements, a straight edge 48″ ruler (model J48EM, Johnson level & Tool, Mequon, WI, USA) and a magnetic level (model 7500 M, Johnson level & Tool, Mequon, WI, USA) were used.

The anthropometric measures of the subjects were taken with a body-measuring tape and then used as input in SAMMIE CAD to create 3-D mockups. The results observed in the experimental setting were then compared to those observed in the virtual simulations through the Cohen's Kappa coefficient (K) (Landis & Koch, 1977), which is a statistic widely used to measure inter-rater reliability for qualitative (categorical) items (McHugh, 2012). A Z-test ($\alpha = 0.05$) was performed to evaluate whether the value of K was statistically different than zero, which would imply that the virtual simulations are reasonable.

3. Results

Seventeen ATV models were evaluated from eight different manufacturers. Engine capacity ranged from 174-686 cc, with most vehicles in 100–400 cc (35 %). Moreover, 58 % of the ATVs evaluated included electric power steering (EPS), 4 wheel-drive (58 %), solid suspension (88 %), and manual transmission (48 %).

Findings of individual reach criteria for the ATV models are presented in Tables 2 and 3, for males and females, respectively. The last column of those tables (Total) represents the percent of observations for which riders scored 11 points (i.e., they fulfilled the requirements of all 11 fit guidelines). Criterion 1 (Handlebar-knee distance) seemed difficult for 16-year-old-males of the 95th body-size percentile. This result may be attributed to the height of these subjects, which decreases the gap between their knee and the handlebars (Bernard et al., 2010).

Unlike criterion 1, criterion 2 (hand size compared to ATV handlebar reach) did not present any difficulty for the virtual youth (Tables 2 and 3). Indeed, virtual subjects of all ages, body-size percentiles, and genders succeeded in this criterion for all (100 %) evaluated vehicles.

Criteria 3, 4, 6, 7, 8, 9, 10, and 11 all presented a similar trend where young riders do not conform well to these criteria, but older riders do (Tables 2 and 3). The contrast in success rate among subjects of different ages and height percentiles are likely also attributed to the variations in height among the subjects. For example, virtual 8-year-old-female riders of the 95th percentile did not pass criterion 5 for any of the evaluated ATVs. In contrast, their 16-year-old-counterpart passed the same criterion for 75 % of the evaluated ATVs (Table 3), a surprising difference of 75 %.

The results from Tables 2 and 3 indicate that 8-year-old youth would probably not be able to control utility vehicles when traversing rough or uneven terrains (Criterion 4 – Standing seat clearance). This finding likely explains the fact that youth are more subject to loss of control events (LCEs) than adults (McBain-Rigg, Franklin, McDonald, & Knight, 2014).

The results of the simulations related to Criterion 7 (Angle of lean from vertical) indicated that youth 9 years old and younger are more likely to lean forward over 30° (safety threshold) when raised off the seat to reach the handlebars of agricultural ATVs. As a result, the center of gravity of the ATV can shift forward, thus increasing the chances of a tip over.

Lastly, some results of the simulations related to Criterion 5 (elbow angle) were concerning. Males up to 11 years old and females up to 13 of the 50th percentile passed this criterion for less than 50 % of the evaluated ATVs.

Table 2
Percent of observations (n = 17) for which reach criteria did not limit adult-sized ATV usage by males of various ages and percentiles.

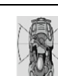
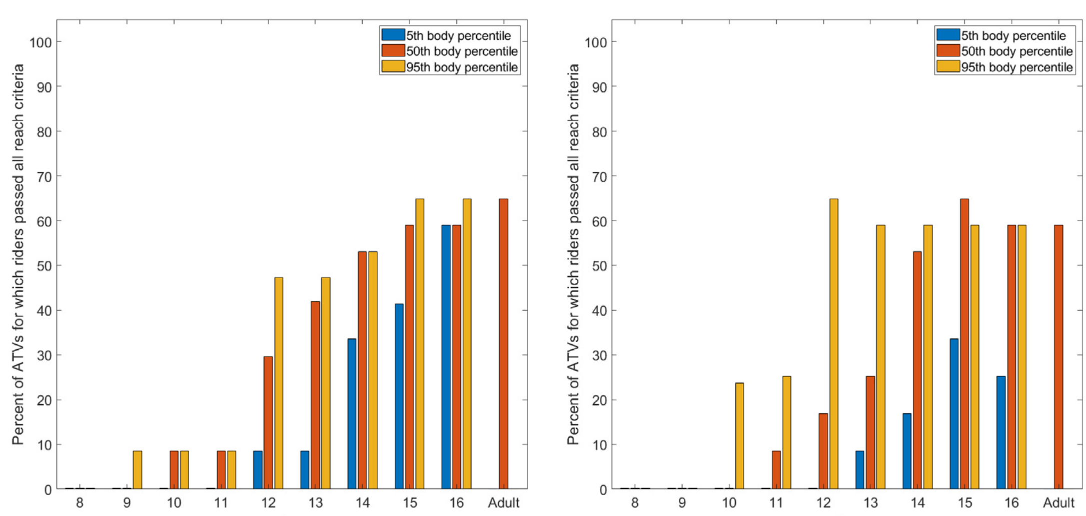
Age	Percentile	Criteria											
													
		1	2	3	4	5	6	7	8	9	10	11	Total
8	5th	94	100	65	25	0	0	42	42	0	0	6	0
	50th	94	100	77	33	0	8	50	58	8	8	12	0
	95th	94	100	94	67	0	8	83	83	8	8	35	0
9	5th	94	100	77	50	0	0	42	42	0	0	12	0
	50th	94	100	94	83	0	8	58	67	8	8	29	0
	95th	94	100	94	92	8	50	83	92	50	50	41	8
10	5th	94	100	77	42	0	8	58	67	8	8	12	0
	50th	94	100	94	92	8	25	92	100	25	25	35	8
	95th	94	100	94	100	8	58	92	100	58	58	65	8
11	5th	94	100	94	92	0	8	92	100	8	8	29	0
	50th	94	100	94	100	8	50	92	100	50	50	41	8
	95th	94	100	94	100	8	58	92	100	58	58	71	8
12	5th	94	100	94	92	8	42	92	100	42	42	41	8
	50th	94	100	94	100	33	58	92	100	58	58	65	29
	95th	88	100	94	100	58	92	92	100	92	92	88	47
13	5th	94	100	94	100	8	50	92	100	50	50	35	8
	50th	94	100	94	100	42	92	92	100	92	92	71	42
	95th	82	100	94	100	67	92	92	100	92	92	88	47
14	5th	94	100	94	100	33	58	92	100	58	58	71	33
	50th	94	100	94	100	58	92	92	100	92	92	88	53
	95th	82	100	94	100	92	92	92	100	92	92	88	53
15	5th	94	100	94	100	42	58	92	100	58	58	71	41
	50th	88	100	94	100	83	92	92	100	92	92	88	59
	95th	82	100	94	100	100	100	92	100	100	100	88	65
16	5th	88	100	94	100	67	92	100	100	92	92	88	59
	50th	82	100	94	100	92	92	100	100	92	92	88	59
	95th	71	100	94	100	92	100	100	100	100	100	88	65
Adult	50th	82	100	94	100	100	92	100	100	92	92	88	65

Table 3
Percent of observations (n = 17) for which reach criteria did not limit adult-sized ATV usage by females of various ages and percentiles.

Age	Percentile	Criteria 1	2	3	4	5	6	7	8	9	10	11	Total
8	5th	94	100	53	17	0	0	8	8	0	0	6	0
	50th	94	100	77	25	0	0	25	25	0	0	12	0
	95th	94	100	94	75	0	8	83	83	8	8	12	0
9	5th	94	100	77	42	0	0	58	58	0	0	12	0
	50th	94	100	88	75	0	8	83	83	8	8	12	0
	95th	94	100	94	83	0	33	92	92	33	33	41	0
10	5th	94	100	82	58	0	0	67	67	0	0	12	0
	50th	94	100	94	75	0	25	92	92	25	25	35	0
	95th	94	100	94	100	25	67	100	100	67	67	65	24
11	5th	94	100	88	75	0	8	100	100	8	8	18	0
	50th	94	100	94	92	8	42	100	100	42	42	41	8
	95th	94	100	94	100	25	75	100	100	75	75	77	25
12	5th	94	100	94	83	0	33	100	100	33	33	29	0
	50th	94	100	94	100	17	58	100	100	58	58	65	17
	95th	94	100	94	100	67	92	100	100	92	92	88	65
13	5th	94	100	94	92	8	33	100	100	33	33	41	8
	50th	94	100	94	100	25	67	100	100	67	67	77	25
	95th	88	100	94	100	67	92	100	100	92	92	88	59
14	5th	94	100	94	92	17	33	100	100	33	33	65	17
	50th	94	100	94	100	58	83	100	100	83	83	77	53
	95th	88	100	94	100	67	92	100	100	92	92	88	59
15	5th	94	100	94	100	33	58	100	100	58	58	71	33
	50th	94	100	94	100	67	92	100	100	92	92	88	65
	95th	82	100	94	100	75	92	100	100	92	92	88	59
16	5th	94	100	94	100	25	67	100	100	67	67	77	25
	50th	94	100	94	100	67	83	100	100	83	83	88	59
	95th	82	100	94	100	75	92	100	100	92	92	88	59
Adult	50th	94	100	94	100	67	75	100	100	75	75	77	59

The percent of ATVs in which riders passed all criteria is presented in Fig. 4. The main finding is that certain youth should not ride most utility ATVs. For instance, the average (50th percentile) male operator aged 16 passed all 11 safety criteria for less than 60 % of the evaluated vehicles. That number decreases sharply for younger youth or youth of the same age but smaller height percentile. A similar trend was also observed for female operators.



(a)   (b)

Fig. 4. Percent of observations for which riders passed all 11 fit criteria. (a) Males and (b) Females.

3.1. Validation

The results of the validation tests are presented in Table 4 and summarized in a confusion matrix (Table 5). In the confusion matrix, the outcome of the test (pass/no pass) is labeled in both horizontal and vertical axes. The horizontal axis represents the number of outcomes predicted by the virtual simulations, and the vertical axis represents the ground truth data (field experiments). The results of the virtual simulations were very close to those of the field tests, with a total accuracy of 88 %.

The Z-test determined that the Cohen's Kappa coefficient (K = 0.45) was significantly greater than zero (p = 0.036), indicating that the virtual simulations are reasonable. This approach to evaluate ergonomic inconsistencies between youth's anthropometry and the operational requirements of ATVs proved to be an effective and accurate technique.

Not all results of the virtual simulations matched those of the field tests. One unexpected result is related to criterion 6 (upper leg angle). It was observed that the mean angle between the riders' upper leg and the horizontal plane (parallel to the ground) was 16.7°, slightly above the recommended threshold (10°). Similarly, two subjects failed to pass criterion 5 (elbow angle) in the actual field tests but passed it in the virtual simulation.

During the field tests, riders were asked to sit comfortably as if they were just about to start riding the ATV. We argue that it would be possible for riders to adjust their way of sitting so they would pass both fit criteria; however, it would not result in the most ergonomic posture from the rider's standpoint. On the other hand, in the virtual simulations, our ultimate goal was to place the 3-D subjects' mockups to physically conform to the proposed fit criteria. Thus, it was impossible to predict whether the final adopted postures in the simulations would match those selected by the riders in the validation tests. Therefore, we argue that despite some outcomes of the virtual simulations did not match those of the field tests, the results of the virtual simulations are still reasonable. One just has to be cognizant that the outcomes of the virtual simulations represent a hypothetical scenario where the rider is able to attain a posture based on their anthropometric measures relative to the ATV, not on their preferences.

5. Discussion

This study evaluated limitations in youth's anthropometric dimensions when riding commonly used ATVs. Using a combination of actual field measurements and a novel digital simulation approach, the present study evaluated 11 ATV fit criteria for youth. The major finding was that youth are not recommended to ride adult-sized ATV models, which is a common practice in the United States (Bernard et al., 2010; Office (GAO), 2010; Jennissen et al., 2014). This finding raises serious concern regarding youth's ability to ride ATVs, especially when unsupervised.

Table 5
Confusion matrix based on the validation tests.

Actual outcome (field tests)		Pass	No Pass
	Pass	27	0
	No pass	4	2
		Predicted outcome (virtual simulations)	

5.1. Limitations of youth

The present findings outlined that some youth are too small, which makes them incapable of properly reaching the vehicle's hand/foot brakes, resting their feet on the footrests, or having to lean forward beyond 30° to reach the handlebars when rising off the seat. Failing to activate the ATV brakes limits the youth's ability to reduce the speed or to stop the vehicle, which likely prevents them from avoiding unexpected hazards, such as obstacles or bystanders (Fathallah et al., 2008). In fact, previous research has shown that a significant number of ATV incidents include hitting a stationary object (Balthrop et al., 2007; Concannon et al., 2012; Helmkamp et al., 2011; Jennissen, Wetjen, Hoogerwerf, O'Donnell, & Denning, 2018; Lower & Herde, 2012).

In addition, the inability to place the feet on the footrests when not breaking the ATV entails a functional loss of control of the vehicle. ATV LCEs occur frequently and are a significant cause of injury and death in agriculture (Carman et al., 2010; Clay, Treharne, Hay-Smith, & Milosavljevic, 2014; Milosavljevic et al., 2011). This finding indicates an opportunity for manufacturers to consider changing the design of their machines, allowing riders to adjust the ATV's seat height, which would likely reduce longitudinal torso impact while traversing rough and uneven terrains. Furthermore, leaning beyond 30° can cause the ATV to tip forward, resulting in a rollover. Most ATV-related crashes on farms and ranches, especially those resulting in deaths, involve rollovers (Cavallo, Gorucu, & Murphy, 2015; Chou et al., 2022; Khorsandi, Ayers, & Fong, 2019; Lower & Herde, 2012; Lower, Monaghan, & Rolfe, 2016; McIntosh, Patton, Rechnitzer, & Grzebieta, 2016).

On the other hand, some youth are too tall, which decreases the clearance zone between their legs and the handlebars. A clearance zone smaller than 200 mm makes it difficult for the rider to properly reach and steer the handlebars (CPSC, 2006; National 4-H Council, 2005). Consequently, riders may lose control of the vehicle (Clay, Hay-Smith, Treharne, & Milosavljevic, 2015; McIntosh et al., 2016) or have difficulty keeping it at a safe speed. As mentioned before, these series of events can lead to injuries and deaths.

Table 4
Validation tests separated by subject and specific fit criterion.

Subject	**Subject 1 (male)**		**Subject 2 (male)**		**Subject 3 (female)**	
Criterion	Real	Virtual	Real	Virtual	Real	Virtual
1	1	1	1	1	1	1
2	1	1	1	1	1	1
3	1	1	1	1	1	1
4	0	0	1	1	1	1
5	1	1	0	1	0	1
6	0	1	0	1	0	0
7	1	1	1	1	1	1
8	1	1	1	1	1	1
9	1	1	1	1	1	1
10	1	1	1	1	1	1
11	1	1	1	1	1	1

Furthermore, despite some results showing that youth are capable of riding many of the ATVs evaluated in this study, other risk factors such as experience, psychological, and cognitive development cannot be overlooked (FReSH, 2012; NCCRAHS, 2018). Youth who are high in thrill-seeking are more likely to engage in risky ATV riding behaviors, regardless of their safety awareness (Jinnah & Stoneman, 2016). Those cases require external interventions, such as changes in legislation, improved ATV design, and use of crush protection devices (Jinnah & Stoneman, 2016).

5.2. Lack of inclusive designs

The results indicated that most utility ATV models are unfit for youth. As such, there is an increased chance of incidents when youth ride these vehicles. There is a need to design ATVs that better accommodate riders of various sizes.

5.3. Assessment of ATV-youth fit guidelines

The results of this validation experiment showed that some riders failed criteria 5 and 6 even though they seemed able to operate the study vehicle comfortably and safely according to our ATV safety research team. Particularly, subjects 1, 2 and 3 presented elbow angles of 129°, 170° and 172.5°, respectively. While fit criterion 5 recommends an elbow angle between 90 ° and 135°, it is not uncommon to see motorcycle riders reporting comfortable elbow angle values up to 168° (Arunachalam, Singh, & Karmakar, 2021).

Moreover, subjects 1, 2, and 3 presented upper leg angles of 14°, 14.7°, and 21.4°, respectively (above the recommended threshold of 10°). A previous survey regarding motorcycle riders' perceived comfortable posture reported optimum upper leg angles as high as 23° (Arunachalam et al., 2021). It is our understanding that fit guidelines 5 and 6 are rather conservative, and their proposed thresholds may rule out riders that are perfectly able to ride utility ATVs safely and comfortably. As such, we propose some modifications to those fit guidelines.

First, we recommend that the rider's elbow angle should be between 90° and 170° as long as the rider feels comfortable steering the handlebars and is able to pass fit criteria 8 (control reach) and 11 (control grip). Moreover, we recommend that the rider's upper leg angle should be within 23° of parallel to the ground as long as the rider is able to pass criteria 3 (brake-foot position), 8 (control reach), and 9 (footrest reach). These new thresholds were selected based on the empirical results of our validation experiments and the angle values reported in the previously mentioned survey (Arunachalam et al., 2021).

Lastly, we stress that the fit guidelines are essential to assess whether the machine is suitable to the rider. We strongly recommend that stakeholders consider the fit criteria when evaluating youth's readiness to ride a utility ATV.

5.4. Changes in guidelines and policies for youth operating ATVs

Current guidelines for ATV-youth fit are mainly based on the rider's age (Academy, 2018) and vehicle's engine size (CPSC, 2006) and maximum speed (ANSI/SVIA, 2017). However, these recommendations are not supported by the present findings, which clearly showed that some fit criteria favor smaller youth while some benefit taller youth, regardless of the rider's age and vehicle's engine size or maximum speed. Furthermore, previous studies have also demonstrated that only rider's age and ATV characteristics are insufficient to evaluate youth-ATV fit (Bernard et al., 2010; De Moura Araujo and Khorsandi, 2020; De Moura Araujo, Khorsandi, Kabakibo, & Kreylos, 2021). As such, we strongly recommend that parents, dealerships, youth occupational health professionals, and policy makers adopt fit guidelines based on the reach ability of youth for the assessment of youth-ATV fit.

5.5. Study limitations

There are noteworthy limitations of this study that need to be considered when interpreting the results. First, one may argue that the database selected for this study (Snyder et al., 1977) is outdated. Nevertheless, to the best of our knowledge, this is the only available source that includes enough parameters to create youth mockups on SAMMIE CAD. In addition, there is no clear evidence of the secular trend in anthropometry over U.S. youth over the past 40 years (Fathallah et al., 2009). For instance, when investigating other sources (CHILDATA – DTI (1995)), we did not observe any significant differences (p-value < 0.05) in the mean values of shoulder breadth and hand length for youth aged 5 or 10 years old. However, it is reasonable to assume that there might be differences in the sizes of the youth population of 2022 and their counterparts of 1977. This potential difference should be considered in the interpretation and generalizability of the present findings.

Second, although we used a systematic approach to identify common ATVs used in the United States, the sample is subject to sampling error and may not be necessarily representative of the models ridden specifically by youth. Moreover, safe and effective riding of utility ATVs involves consideration of factors other than the ability of youth to reach its controls or attain a specific posture. ATVs are rider-active vehicles, which means that riders must be able to shift their body weight to safely perform maneuvers such as turning, negotiating hills, and crossing obstacles (Jennissen et al., 2014; National 4-H Council, 2005). These circumstances warrant further investigation.

Third, we had to determine the absolute location of each control due to feasibility issues. The further-most position was used as the standard position for all controls with gradual adjustment such as the hand gearshift, while pedals were set to resting position.

Fourth, all the human mockups were placed at the ATVs' seat reference point (SRP). This may not be the "best-case" scenario from a reach standpoint since many riders, especially small youth, tend to sit closer to the handlebars (ahead of the SRP) to allow control reaching. However, the SRP is a standardized expected seat position, which allowed for a consistent evaluation approach among the various conditions. The effect of seating adaption to reach controls while riding requires further assessment.

Finally, the reach simulations were performed with static mockups (i.e., we did not evaluate any trunk or hip movement). In real riding situations, riders may shift their hips forward and/or bend their trunks to reach an otherwise unreachable control and perform active riding. However, while active riding can increase the ATV's stability by 10–30 % (Shortland, 2013), there is no clear evidence that active riding and rider separation reduces the risk of rollover for agricultural ATVs specifically (Grzebieta, Rechnitzer, & McIntosh, 2015).This warrants further investigation.

6. Summary

This study evaluated the potential mismatches between youth's anthropometric measures and operational requirements of 17 ATV models. The study's main findings/receommendations were: (1) Most riders failed to pass at least 1 out of the 11 fit criteria for the evaluated vehicles; (2) Youth are not recommended to ride utility ATVs; and (3) Only engine size, maximum speed, and rider's age are insufficient indicators of youth-ATV fit.

The present findings, along with the results of a recent study regarding the forces required for effective ATV operation (De Moura Araujo & Khorsandi, 2020), raise serious questions about the ability of youth to safely operate utility ATVs in common use on U.S. farms and about the validity of current youth-ATV fit guidelines. Therefore, we recommend that the readiness of youth to ride ATVs, especially for occupational purposes, should be carefully evaluated by their parents/guardians. Moreover, we argue that current youth-ATV fit guidelines should be reviewed and updated based on quantitative and systematic data comparing the physical ability of youth and the operational requirements of ATVs.

7. Practical applications

The present study provides such quantitative and systematic data comparing the physical ability of youth and the operational requirements of ATVs. These data support manufacturers in considering design changes or manufacturing new machines and provides critical evidence contributing to the scientific basis for modifying regulatory/advisory guidelines for youth operating utility ATVs.

Acknowledgments

This work was supported by the National Children's Center for Rural and Agricultural Health and Safety (NCCRAHS) under grant No NIOSH 5U54 OH009568. In addition, the Western Center for Agricultural Health and Safety provided a seed grant for conducting preliminary studies.

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