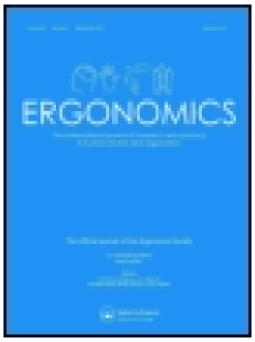

Ergonomics

ISSN: 0014-0139 (Print) 1366-5847 (Online) Journal homepage: http://www.tandfonline.com/loi/terg20

Ability of youth operators to reach farm tractor controls

F. A. Fathallah , J. H. Chang , W. Pickett & B. Marlenga

Ergonomics
Vol. 52, No. 6, June 2009, 685–694

Ability of youth operators to reach farm tractor controls

F.A. Fathallah[a]*, J.H. Chang[a], W. Pickett[b] and B. Marlenga[c]

[a]*Agricultural Ergonomics Research Center, Department of Biological and Agricultural Engineering, University of California, Davis, CA, USA;* [b]*Department of Community Health and Epidemiology, Queen's University, Kingston, Ontario, Canada;* [c]*Marshfield Clinic Research Foundation, National Farm Medicine Center, Marshfield, WI, USA*

Farm tractor work is commonly assigned to young people on North American farms, where tractors account for the majority of deaths and major portions of non-fatal trauma to working youths. However, little is known about the potential mismatch between the anthropometric and physical characteristics of children and tractor characteristics. The purpose of this study was to evaluate the ability of children of varying ages and percentiles to reach major controls on 45 tractors in common use in the US. The main study finding was that many tractor controls, especially those that are hand-operated, may not be effectively reached by the majority of youth operators aged 12 to 16 years. The study raises further serious questions about the ability of children to safely operate tractors in common use on US farms and calls for reconsideration of age guidelines for the assignment of children to tractor work on farms. This study provides novel ergonomic evidence about the ability of children to reach controls inside agricultural tractor cabins. The approach could be applied in similar situations where youths may operate other vehicles or machines. Study findings support the establishment and refinement of policies and guidelines related to youth tractor operation.

Keywords: agriculture; children; safety; reach; photogrammetry

1. Introduction

In the design and evaluation of workstations and vehicles it is important to consider the ability of the user population to efficiently reach critical controls and effectors. 'Reach' is typically defined in terms of a zone or a space that the user can access with an extremity (hand or foot). It is determined by incorporating the body characteristics of the target population, which are derived from anthropometric data, into the workspace of interest (Pheasant 1997).

Existing studies have examined the abilities of workers to effectively reach controls within vehicle cabs and other workstations (Bullock 1974, Moussa-hamouda and Mourant 1981, Li and Xi 1990, Eklund *et al*. 1994, Das *et al*. 2007). The advent of computer-aided design (CAD) human modelling (or ergonomics) programs has been an important advance for these types of studies. CAD has provided an efficient platform for combining digital mock-ups of both the workspace and the human user (Das and Sengupta 1995, Porter and Porter 1998, Porter *et al*. 1999, Yang *et al*. 2007). This facilitates the evaluation of existing workspaces with regard to target user reach ability. To the authors' knowledge, few existing studies have applied a CAD ergonomics program in the evaluation of the ability of tractor operators to reach key controls and no existing studies have specifically examined child workers in this same ergonomic context. This is unfortunate as childhood farm injuries represent an important public health problem in North America (Rivara 1997, Castillo *et al*. 1999, Pickett *et al*. 1999) and tractors are the leading cause of traumatic injury in this child-occupational context. As part of their tradition, many farm children are exposed to tractor-related jobs starting at an early age (Aherin and Todd 1989, Hawk *et al*. 1994, Freeman *et al*. 1998, Browning *et al*. 2001, Marlenga *et al*. 2001a,b, Park *et al*. 2003). There is a lack objective ergonomic evidence to inform health and safety professionals about this issue.

Past efforts to prevent the occurrence of tractor-related injuries to child workers include the *North American Guidelines for Children's Agricultural Tasks* (NAGCAT) (Lee and Marlenga 1999). Tractor operation guidelines developed for NAGCAT were built by expert consensus and suggested an age restriction on each tractor-related task based on the size of the tractors and the complexity of the job (Lee and Marlenga 1999). The implied need here was for consideration of anthropometric characteristics in making these job assignments; however, there were no available ergonomic data from which to inform

*Corresponding author. Email: fathallah@ucdavis.edu

ISSN 0014-0139 print/ISSN 1366-5847 online

DOI: 10.1080/00140130802524641
http://www.informaworld.com

NAGCAT. One specific data requirement surrounded the concept of a child's ability to reach key tractor controls.

The present study group had the opportunity to examine potential ergonomic and anthropometric mismatches between child characteristics and tractor operational requirements. An initial study focused on potential mismatches between the strength of children and forces required in operating farm tractor controls. The current analysis extends this work through an assessment of the abilities of children of varying anthropometric characteristics to reach key tractor controls. When considered together, it is hoped that these novel data will guide future decisions about the assignment of tractor work to children.

2. Methods

2.1. Overview of the study design

The anthropometric characteristics of a youth operator dictate his/her ability to safely reach various controls on a tractor. Anthropometric characteristics of youths 12–16 years of age were used to create digital youth mock-ups, which were then incorporated into a digital tractor mock-up using CAD ergonomics software. The ergonomics software facilitated the evaluation of young people's abilities to reach (and, hence, effectively activate) various tractor controls. Controls that were considered included those essential for driving a tractor, namely: 1) brake pedals; 2) clutch pedal; 3) steering wheel; 4) hand throttle; 5) gearshift; as well as auxiliary controls (levers) that are less likely to be used while driving a tractor, namely: 1) power take-off (PTO); 2) 3-point implement; 3) hydraulic. The spatial locations of these controls were measured on a sample of 45 commonly used agricultural tractors of varying models, size and ages, which included 21 tractors with roll-over protection structures (ROPS) and 24 tractors without ROPS. The tractors were accessed from local tractor dealers and farmers in the states of California and Wisconsin. Corresponding youth anthropometric data were estimated from one of the only existing comprehensive anthropometric database on children (Snyder *et al.* 1977).

2.2. Models of tractors under study

In order to identify a list of common tractor models that youth were likely to operate, data were obtained from the 2001 National Tractor Survey conducted for the National Institute for Occupational Safety and Health by the National Agricultural Statistics Service (Myers 2003). Within each of the four regions of the United States (northeast, midwest, south, west), these data contained rankings for the 30 most common tractors with ROPS and the 30 most common tractors without ROPS. The model rankings were pooled across regions according to the presence or absence of ROPS and a combined ranking was created within each group based on the four regional rankings. The 25 tractors with the highest combined ranking were selected for ROPS and non-ROPS tractors (for a total of 50 tractors). In total, 45 (88%) of these tractor models were available to the study team and hence identified for focused study.

2.3. Apparatus

The apparatus can be divided into three main categories: 1) photogrammetry (3-D virtual tractor mock-up); 2) 3-D virtual youth mock-up; 3) ergonomic CAD software for reach evaluation.

2.3.1. Photogrammetry

Photogrammetry collects meaningful information from a series of photographs of a given object taken at various angles. Geometrical information about the object can be extracted, including the coordinates of points of interest and characteristics of curvature. Photogrammetry is used in many applications, including accident reconstruction, architecture and forensics. One of the widely used photogrammetry programs is PhotoModeler (Eos Systems, Vancouver, Canada) and this program was used in the present study.

The process of creating tractor virtual mock-ups in PhotoModeler follows a series of steps and is detailed elsewhere (Chang and Fathallah 2006). In general, multiple digital pictures of the object of interest are taken (in this case, the tractor). These images are imported into PhotoModeler, where the software connects matching points across imported digital images in order to compute the relationships between points; hence, creating an object (Figure 1). This process, called 'referencing', is usually performed manually; however, in this study, the software was equipped with a 'coded targets' module, which provided an automated matching process through the use of uniquely coded stickers placed throughout the tractor (Figure 1). Once they are properly processed, the coordinates of each point (i.e. sticker on the tractor) are calculated so they can be used to create lines, curves and even surfaces. The final output of the photogrammetry process results in a scaled 3-D virtual mock-up of the tractor, including its cab and controls (see Figure 2 for an example). The accuracy of the approach was demonstrated in an earlier study, with

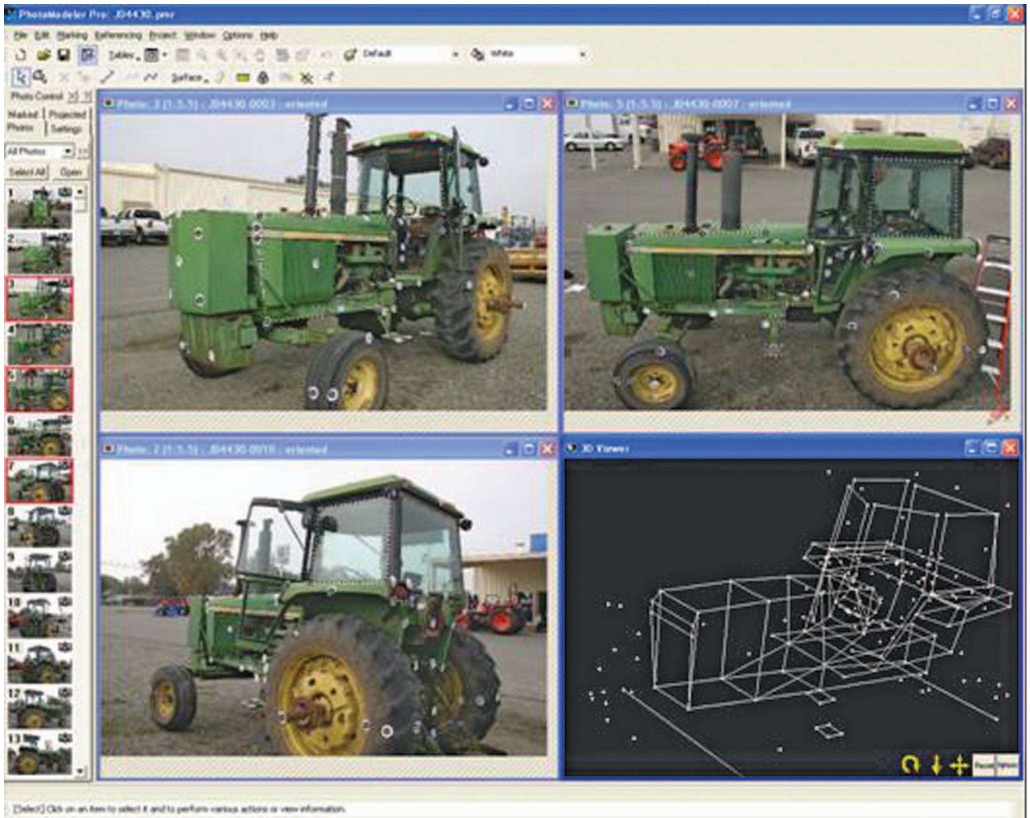

Figure 1. A sample screen from PhotoModeler showing digital images of a tractor, the 'coded targets' dispersed throughout the tractor and the resulting spatial representation of the tractor.

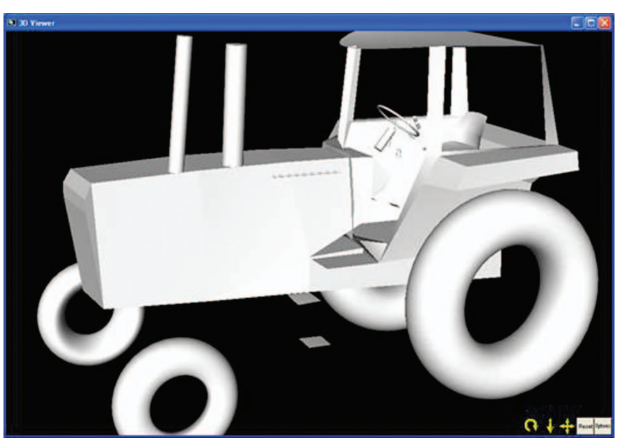

Figure 2. Example of a properly scaled 3-D virtual tractor mock-up using PhotoModeler.

an average error under 2 pixels (Chang and Fathallah 2006).

2.3.2. *Youth virtual mock-up*

This research utilised findings from one of the few available studies on the anthropometric characteristics of children (Snyder *et al*. 1977). The study included measurements from 3900 subjects from 2 to 18 years of age for both genders. Age-specific datasets were obtained (National Institute of Standards and Technology 2005) and used in this research to create human mock-ups at age 12, 14 and 16 years for both genders. To create the virtual youth mock-ups, selected variables from that database were used: stature; erect sitting height; buttock–knee length; knee height; biacromial breadth; acromion-radiale length; radiale-stylion length; hand length; suprasternale height; age in months. Eight external anthropometric variables were required by the simulation software, SAMMIE (SAMMIE CAD Inc., Loughborough, Leics., UK) for the creation of a customised human mock-up: stature; shoulder breadth; arm length; seated height; hand length; seated shoulder height; knee height; and buttock–knee length. Stature, seated height, hand length, knee height and buttock–knee were taken directly from the Snyder *et al.* (1977) database. The remaining variables were computed using the available anthropometric variables. Shoulder breadth was assumed to be the same as biacromial breadth. A combination of acromion-radiale length and radiale-stylion length was used for arm length.

Seated shoulder height was estimated by subtracting head and neck length from seated height. SAMMIE incorporates these anthropometric variables to create a virtual human mock-up as illustrated in Figure 3.

2.3.3. *Reach evaluation*

SAMMIE CAD software facilitated the youth reach evaluation by integrating the tractor virtual mock-ups developed in PhotoModeler (Figure 2) with the series of virtual youth mock-ups of varying age, gender and size developed in SAMMIE CAD (Figure 3). SAMMIE CAD provides several options for a given reach simulation. Any limb can be used independently, while the upper limbs and lower limbs could be used simultaneously. This flexibility is very useful when dealing with controls located in the middle, such as steering wheels and gear shifts. Three different types of hand configurations (fingertip, thumb tip and palm grip) can be used depending on the purpose of the simulation.

In this study, the left foot of the human mock-up was used for reach simulations on clutch pedals, except in the case of one tractor equipped with a hand clutch lever. That particular model had a different pedal configuration compared to the other tractors: two brakes located on each side separately. All other tractors had a clutch pedal on the left side and two brake pedals on the right side. Pedal configuration, along with steering wheels, was the most standardised control across the various tractor manufacturers. The right foot of the human mock-up was simulated on both brake pedals as well as throttle pedals, if applicable. Note that all clutch and brake pedals were set to their fully extended positions (i.e. tractors were turned off with no hydraulic assistance) in order to maintain a safe data collection environment during the photography sessions.

Figure 3. A 3-D virtual human mock-up in a sitting posture created using SAMMIE CAD.

Reach with the upper extremities was simulated with a palm grip since it was very realistic to manoeuvre levers and steering wheels with grips instead of fingertips and thumb tips. With the exception of steering wheels, hand controls were less standardised in configuration than were foot pedals. Most tractors had steering wheels in front of the operator seats. It was clear that operators would use their right hand for controls on the right side and vice versa. Reach simulation of hand controls was done with the right hand to the levers on the right side and the left hand to the levers on the left side. Steering wheels and levers located in the middle were simulated with both hands, although reach with the closest hand was taken into account in the results.

2.4. *Field measurement procedure*

Tractors used in this study were obtained from tractor dealers and farmers in California and Wisconsin. For a given tractor, characteristics of the tractor were first documented, including manufacturer, model, make year, serial number, tractor configuration, presence of ROPS and other mechanical characteristics.

Digital images of each tractor were taken under different light conditions. Indoor shooting was preferred, while outdoor images were taken for the majority of farm-operated tractors. Tractors were moved to face the sunlight for outdoor shooting so that both the left and right sides of a tractor had relatively similar exposure conditions. Glass materials were adjusted, if possible, to minimise glare and reflections including those from windshields. A 'flash light' was used for all indoor photography to enhance the strength of the light, as well as for some of the outdoor photography to decrease the exposure differences between objects in sunlight and shaded ones.

Markers or 'coded targets' were placed on key points of tractors so that they could be used afterwards to create tractor 3-D digital mock-ups of the tractor frame. The size of the tractor and the complexity of its exterior dictated the total number of markers used. If the tractor had been retrofitted for a specific purpose and/or equipped with special attachments, for instance, front loaders or sprayer systems, those parts were not included in the mock-up.

Photographs of tractors were taken at numerous angles. Depending on the size of the tractor, digital images were captured at every 15 to 25° around the tractor, while vertical locations of the shooting were altered as low, standing, medium high and high. The difference between the lowest and highest shooting position was as far as 12 feet (3.7 m). An 8-foot (2.4-m) ladder was used for pictures taken at higher shooting positions. Vertical adjustment of the shooting position was required for high crop tractors and tractors with cabin type ROPS. The total number of images taken for each tractor varied due to the tractor's size and the complexity of its exterior. Approximately 100 to 150 images were taken per tractor in most cases.

2.5. *Data analysis*

SAMMIE CAD was used to investigate whether or not a given control can be reached by an upper or lower limb, as appropriate. In cases where the control was 'unreachable', SAMMIE CAD software revealed the distance (mm) between the limb and the control (this is useful information in cases where control redesign is desired). Reachable and unreachable controls were classified into a binary variable. For each control under study, the percentage of reachable controls was determined for 5th, 50th and 95th percentile male and female youth aged 12, 14 and 16 years of age.

Secondary analysis was conducted to assess, in general terms, the effectiveness of the NAGCAT tractor operation guidelines. The percentage of tractors deemed reachable by male children of various age (12, 14 and 16 years) and anthropometric percentile (5th, 50th and 95th) was classified into the 'tractor size' by 'job complexity' matrix recommended by NAGCAT (Lee and Marlenga 1999). Since there were no tractors less than 20 horsepower in the sample (a category recommended by NAGCAT, but uncommon among agricultural tractors), the tractor size comparison was made for two levels: less than 70 horsepower; and greater than or equal to 70 horsepower.

The other part of the matrix focused on the complexity of tractor operation, which included the following four levels of increasing complexity: 1) operating a farm tractor; 2) 3-point implement; 3) remote hydraulic; 4) PTO-powered implement. In this study, the controls were matched to the job complexity that best reflected the use of these controls. For example, the basic job requirement of operating a farm tractor requires the use of foot brake(s), clutch (if non-automatic), steering wheel, hand throttle and a gear; hence, these controls were considered for the 'operating a farm tractor' category of the job complexity part of the matrix.

3. Results

Characteristics of the 45 tractor models under study are listed in Table 1. Most (82%) were manufactured prior to 1985. Horsepower ranged from 20 to 156, with 62% in the range of 20–70 horsepower.

Table 1. Description of tractors under study.

	ROPS tractors* (n = 21)		Non-ROPS tractors† (n = 24)		Total (n = 45)	
	n	%	n	%	n	%
Year manufactured						
Pre 1970	1	4.8	17	70.8	18	40.0
1970–1984	12	57.1	7	29.2	19	42.2
1985 and newer	8	38.1	0	0	8	17.8
Horsepower						
Under 70	6	28.6	22	91.7	28	62.2
70 and over	15	71.4	2	8.3	17	37.8

*ROPS = roll-over protection structures.

Percentages of observations for which controls were located within different reach distances are listed in Table 2. Some controls yielded a relatively high percentage for reach among children, for instance, foot brakes and clutches. On the other hand, the majority of hand controls were out of reach, except for steering wheels. More than 90% of the gears were out of reach for male children in all age groups, while only one tractor had a gear within reach distance for all female children of all ages. Less than 10% of tractors had PTO levers within reach distance for all male and female age groups. Less than 15% of tractors had 3-point levers within reach distance for all male and female age groups. Up to 40% of tractors were equipped with hydraulic levers at reachable distance for male children; however, the value decreased to 24% for female children. Hand throttles were located at the farthest position, showing 0% of observations for all age groups in both genders.

For the controls that were identified as unreachable, the distance needed to reach the controls was, on average, highest for the auxiliary controls including the 3-point, hydraulic and PTO levers, reaching as high as 250 mm; whereas one of the closest controls was, as expected, the steering wheel; under 58 mm. Representative data on average distance away from a given control for each age/percentile combination, regardless of gender, for the 3-point lever and the steering wheel, are shown in Figure 4. Unlike the steering wheel, the 3-point lever did not show large variation with age or size of children; essentially, that lever was out of reach for most children regardless of age or size.

It was also interesting to see the results of the simulation on adult mock-ups in the 50th percentile in anthropometry, although it was not a primary

Table 2. Percentage of observations (n = 45) for which controls were located within reach distance for male and female children of various age and percentiles.

	Male									
Age	12			14			16			Adult
Percentile	5th	50th	95th	5th	50th	95th	5th	50th	95th	50th
Foot brake right	28.9	77.8	93.2	82.2	93.2	100	90.9	100	100	100
Foot brake left	37.8	82.2	93.0	88.9	93.0	100	93.2	100	100	100
Foot clutch	47.7	86.4	97.4	90.7	97.5	97.3	95.1	97.4	96.4	100
Steering wheel	26.7	37.8	57.8	37.8	51.1	57.8	37.8	55.6	68.9	100
Hand throttle	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	60.0
Gear	0.0	6.7	6.7	6.7	6.7	6.7	6.7	6.7	8.9	53.3
3-point	7.0	9.3	14.0	14.0	14.0	9.3	9.3	9.3	14.0	58.1
Power take-off	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	29.5
Hydraulic	24.3	27.0	34.2	33.3	34.2	36.8	24.3	36.8	39.5	57.9
	Female									
Age	12			14			16			Adult
Percentile	5th	50th	95th	5th	50th	95th	5th	50th	95th	50th
Foot brake right	22.2	71.1	90.9	57.8	86.7	100	77.8	90.9	100	91.1
Foot brake left	33.3	77.8	93.2	64.4	91.1	100	86.7	93.2	100	91.1
Foot clutch	43.2	77.3	95.3	68.2	90.7	97.5	88.6	95.3	97.5	95.3
Steering wheel	22.2	31.1	35.6	24.4	33.3	35.6	33.3	33.3	35.6	93.3
Hand throttle	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	35.6
Gear	0.0	0.0	2.2	0.0	0.0	0.0	0.0	0.0	0.0	42.2
3-point	2.3	4.7	7.0	4.7	4.7	7.0	4.7	4.7	4.7	55.8
Power take-off	0.0	9.1	9.1	9.1	9.1	4.5	4.5	4.5	0.0	18.2
Hydraulic	15.8	21.6	23.7	21.6	21.6	23.7	21.6	23.7	23.7	60.5

Note: Adult 50th percentile results are shown for comparative purposes.

objective of the study. The 50th percentile male mock-up showed a 100% of reach for foot brakes and clutches, while the female mock-ups showed 91% and 95% of reach for foot brakes and clutches, respectively. A relatively smaller percentage of reach was observed for hand controls among both genders. PTO was the worst control for the adult population; a 50th percentile male adult could reach the PTO levers on 13 particular tractors (approximately 30%) and a 50th percentile female adult could reach the PTO levers on eight particular tractors (approximately 18%). The hand throttle, which was the most inaccessible control for children, was located within reach distance of a 50th percentile male adult on 27 tractors and was located within reach distance of a 50th percentile female adult on 16 tractors.

The comparison between the NAGCAT tractor operation guidelines matrix and the percentage of male children who could reach a given control, based on the size of the tractor and job complexity, is shown in Table 3. These results demonstrate that for some tractor controls and field applications, many children would be able to reach, and possibly activate, the control under study. However, for most tractor controls, a substantial portion of children would not have the requisite anthropometric characteristics to reach the control.

4. Discussion

The major finding of this comprehensive anthropometric study was that substantial proportions of children do not have the physical capabilities to reach essential controls on tractors. Specifically, hand throttles were identified as the least accessible control for both genders, followed by gear (female) and PTO (male). PTO levers were identified as the least accessible controls for an average-sized adult digital human mock-up, which is consistent with recent reach evaluation of agricultural tractor controls among Indian adults (Kumar *et al.* 2009). In general, foot-operated controls yielded a higher percentage for reach among youth operators, compared to hand-operated controls, with an exception of the steering wheels.

Some of the results in Tables 2 and 3 may indicate an apparent counter-intuitive trend in reach ability among 14 year-old children of increasing anthropometric percentiles. However, there is an explanation for these apparent inconsistencies. The slight inconsistency was observed only in the auxiliary controls, namely, the PTO, 3-point and hydraulic levers. These levers vary widely with regard to their locations among tractors and they were the farthest from the operator (see Figure 4). Therefore, it is conceivable, due to the location and orientation of the

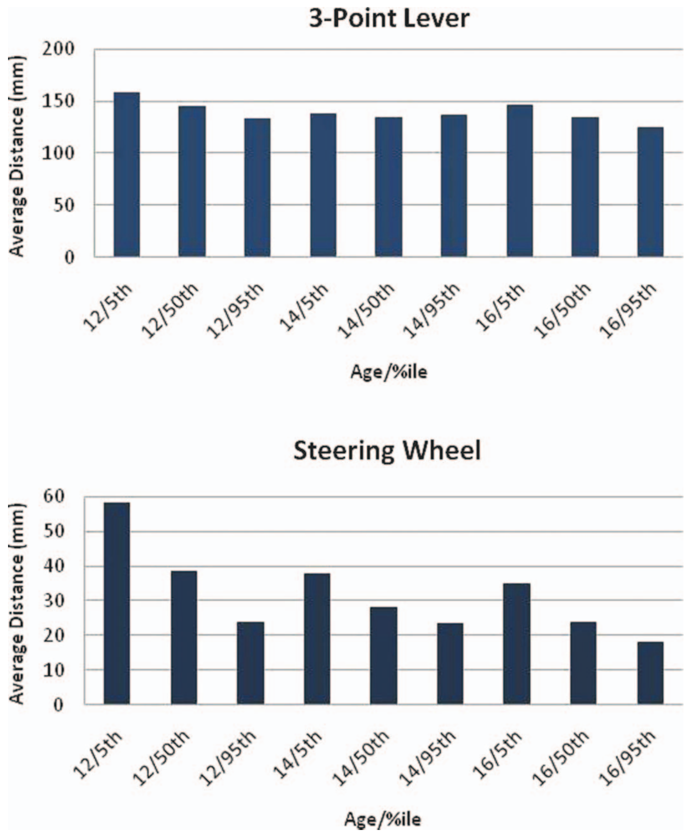

Figure 4. Average distance away from the 3-point and steering wheel controls by age and percentile of combined male and female youths.

levers, combined with the standardised child's mock-up posture, that a 95th percentile 14-year-old male youth may be at a more disadvantage to reach some of these levers than a 5th percentile male youth. This was indeed the case for a couple of tractors. Note that this inconsistency never was observed in controls that are located in somewhat standardised locations, such as the steering wheel or the clutch.

The establishment of age-appropriate guidelines for children and their involvement in farm tractor work has been a contentious subject in the occupational health and safety literature. Despite the prohibition of some youth workers under the age of 16 years from operating tractors, exceptions exist for youth 14–15 years old who complete a tractor certification course and for all youth working on their parents' farms (US Department of Labor 2007). Nonetheless, the American Academy of Pediatrics (2001) recommends a minimum age of 16 years for the operation of any farm vehicle with no exceptions. Part of the inconsistency in age assignment is that most existing guidelines are based upon the consensus of experts in the field. There is a lack of objective data on the physical abilities of children to operate farm tractors, including their ability to effectively reach critical controls. This study provides novel data that can contribute to the development of a better consensus about when it might be appropriate to introduce children to tractor work.

Several findings can be applied to the evaluation of the NAGCAT recommended tractor operation guidelines. First, the tractor size variable listed by NAGCAT seemed to provide an acceptable guideline for reaching foot-operated controls for larger tractors, where the recommended age is 14–15 years. However, smaller-sized (especially those below 50th percentile) children less than 14 years of age may experience difficulty in reaching the foot controls of smaller-sized tractors (under 70 horsepower). Second, the NAGCAT recommended tractor size and corresponding age ranges were insufficient for hand-operated controls under the basic tractor operation job (steering wheel, hand throttle and gear). While steering wheels were in reach, the hand throttle and gear for almost all tractors were unreachable by most male children at all recommended ages, irrespective of tractor size. Controls required for more complex tractor jobs were also unreachable by almost all children, irrespective of child age or tractor size. This may require the child to make non-optimal and potentially unsafe postural adaptations to activate the controls; possibly including

Table 3. Percentage of tractors (n = 45) for which controls were located within reach distance for male children of various age and percentiles compared to the NAGCAT recommended youth age range by tractor size and job complexity.

Increased complexity of job – 1–4	NAGCAT Tractor Size																	
	Small Tractor: 20–70 hp (n = 28*)									Medium/Large Tractor: >70 hp (n = 17[†])								
1. Operating a farm tractor	NAGCAT Recommended age: 12–13 years									NAGCAT Recommended age: 14–15 years								
Age (years)	12			14			16			12			14			16		
Percentile	5%	50%	95%	5%	50%	95%	5%	50%	95%	5%	50%	95%	5%	50%	95%	5%	50%	95%
Foot brake right	36	79	96	86	96	100	93	100	100	18	76	88	76	88	100	88	100	100
Foot brake left	39	86	96	93	96	100	96	100	100	35	76	88	82	88	100	88	100	100
Foot clutch	52	93	95	74	96	95	92	95	96	41	76	100	88	100	100	100	100	100
Steering wheel	25	43	68	43	57	68	43	64	82	29	29	41	29	41	41	29	41	47
Hand throttle	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Gear	0	11	11	11	11	11	11	11	11	0	0	0	0	0	0	0	0	6
2. 3-point implement	NAGCAT Recommended age: 14–15 years									NAGCAT Recommended age: 14–15 years								
Age (years)	12			14			16			12			14			16		
Percentile	5%	50%	95%	5%	50%	95%	5%	50%	95%	5%	50%	95%	5%	50%	95%	5%	50%	95%
3-point lever	0	0	8	8	8	0	0	0	8	18	24	24	24	24	24	24	24	24
3. Remote hydraulic	NAGCAT Recommended age: 14–15 years									NAGCAT Recommended age: 14–15 years								
Age (years)	12			14			16			12			14			16		
Percentile	5%	50%	95%	5%	50%	95%	5%	50%	95%	5%	50%	95%	5%	50%	95%	5%	50%	95%
Hydraulic lever	15	15	20	16	19	24	10	24	29	35	41	53	53	53	53	41	53	53
4. PTO-powered implement	NAGCAT Recommended age: 14–15 years									NAGCAT Recommended age: 14–15 years								
Age (years)	12			14			16			12			14			16		
Percentile	5%	50%	95%	5%	50%	95%	5%	50%	95%	5%	50%	95%	5%	50%	95%	5%	50%	95%
PTO lever	7	7	7	7	7	7	7	7	7	0	0	0	0	0	0	0	0	0

PTO = power take-off.
*Maximum number of tractors; number of tractors ranged between 21 (hydraulic lever) and 28 (all other controls).
[†]Maximum number of tractors; number of tractors ranged between 16 (PTO lever) and 17 (all other controls).
Note: The four selected jobs from NAGCAT focused on jobs involving tractor operation and use of controls.

not using the seatbelt in ROPS tractors. The concerns about lack of reach to key controls among youth operators and the need to assume different driving postures were also shared in a recent study on Indian tractor adult operators (Kumar *et al.* 2009). This evaluation, therefore, raises questions about the effectiveness of the NAGCAT approach in using tractor size and youth age as a means to assign tractor-related jobs to children.

4.1. Strengths and limitations

Strengths of this analysis include its novelty, its direct application to the establishment of evidence-based recommendations that are sorely needed and the efforts to examine these issues in 'real-life' field settings. Prior recommendations about minimum ages for tractor operation suggested by the US Department of Labor (2007), the American Academy of Pediatrics (2001) and NAGCAT (Lee and Marlenga 1999) have been made in the absence of such evidence. While this particular analysis focused upon the reach ability of youth, other analyses involving the same sample considered force requirement (Fathallah *et al.* 2008), as well as impairment to the field of vision experienced by children of different ages. Collectively, this should provide a comprehensive picture of the physical ability of children of different ages to effectively operate tractors in common use in the US and the factors that impinge upon their safety.

Several limitations of this analysis warrant comment. First, although a systematic approach to the identification of a sample of common tractors in the US was used, the sample might be considered small; however, from a tractor cab design perspective, the within-tractor variation of the same model should be minimal. Hence, the sample should provide an adequate representation of the commonly used tractors in the US. Second, the anthropometric data used in this research were very intensive and reliable (Snyder *et al.* 1977), although somewhat dated. There is no clear evidence for the extent of the secular trend in anthropometry among US children over the past 30 years. However, it is reasonable to assume that an average 14 year old in 2008 is not smaller than an average 14 year old was in 1977. Such a potential difference should be considered in the interpretation of the results of this study. Third, a control might be located at different positions from the operator's standpoint, depending on given tasks. The absolute location of each control had to be determined due to feasibility issues. Mid-position was used as the standard position for all controls with gradual adjustments, such as hand throttle levers, 3-point control levers, etc. Gear levers and remote hydraulic levers were located at neutral positions. PTO control levers were set to the off position due to the safety features on some tractors. Pedals were set to the fully extended position due to safety issues and lack of hydraulic assistance during the photography sessions. Fourth, the reach evaluation was conducted in one assumed optimal driving seated posture, where the back of the child mock-up was against the tractor seat back support with an angle of about 90° between the trunk and the legs. The effect of postural adaptation to reach controls on driving performance and safety warrants further assessment. Furthermore, tractor seat design characteristics, especially the fore–aft adjustment, could affect operator reach ability (Mehta *et al.* 2008); therefore, tractor seats in the collected sample were adjusted, whenever possible, to their most forward position. This approach provided a 'best-case' scenario from a reach standpoint, since many users, including children, may not adjust their seats when operating tractors and the pedal reach evaluation was conducted at the closest point to the operator (pedal fully extended). Finally, the reach simulation was based on an 'optimal' seated position that did not allow any trunk or hip movement. In real driving situations, children may shift their hips forward and/or bend their trunks in order to reach an otherwise unreachable control. However, these compensatory mechanisms do not provide safe and efficient driving conditions, since they may entail not using the seat belt and/or severely reducing the operator's field of vision.

5. Conclusion

Youth on American farms commonly operate agricultural equipment, especially tractors. This study focused on the evaluation of the potential mismatch between the operational requirement of major controls on common tractors and youth reach capabilities. The main study finding was that many tractor controls, especially those that are hand operated, may not be effectively reached by the majority of youth operators. Combining this finding with a recent finding regarding forces required for effective tractor operation (Fathallah *et al.* 2008) calls into question the ability of children to safely operate tractors on US farms.

Acknowledgements

This research was supported by the National Institute for Occupational Safety and Health (NIOSH) Research Grant # R01 OH07850 and by the University of California Western Center for Agricultural Health and Safety. We would like to thank Brandon Miller and Nancy Esser for their invaluable and critical contributions to the data collection phase of this project. We would like to also thank Jennifer Plasse, Erica Garcia and Victor Duraj for their great help on this study. A special thank you goes to John Myers at NIOSH for sharing data from the 2001 National Tractor Survey and to Dr Mark Purschwitz for technical expertise regarding tractor makes and models. Finally, we extend our appreciation to Dr John Miles and Dr James Meyers of the University of California Agricultural Ergonomics Research Center for their enduring support and guidance on this project.

References

Aherin, R.A. and Todd, C.M., 1989. *Accident risk taking behavior and injury experience of farm youth*. St Joseph, MI: American Society of Agricultural Engineers, 895530.

American Academy of Pediatrics, 2001. Prevention of agricultural injuries among children and adolescents. *Pediatrics*, 108 (4), 1016–1019.

Browning, S.R., Westneat, S.C., and Szeluga, R., 2001. Tractor driving among Kentucky farm youth: results from the farm family health and hazard surveillance project. *Journal of Agricultural Safety and Health*, 7 (3), 155–167.

Bullock, M.I., 1974. Determination of functional arm reach boundaries for operation of manual controls. *Ergonomics*, 17 (3), 375–388.

Castillo, D.N., Adekoya, N., and Myers, J.R., 1999. Fatal work-related injuries in the agricultural production and services sectors among youth in the United States, 1992–96. *Journal of Agromedicine*, 6 (3), 27–41.

Chang, J.H. and Fathallah, F.A., 2006. An approach for evaluating 3-D workspace using photogrammetry and CAD software. *In: Human Factors and Ergonomics Society 50th annual meeting*, San Francisco: Human Factors and Ergonomics Society.

Das, B. and Sengupta, A.K., 1995. Computer-aided human modeling programs for workstation design. *Ergonomics*, 38 (9), 1958–1972.

Das, B., Shikdar, A.A., and Winters, T., 2007. Workstation redesign for a repetitive drill press operation: A combined work design and ergonomics approach. *Human Factors and Ergonomics in Manufacturing*, 17 (4), 395–410.

Eklund, J., *et al*., 1994. Head posture measurements among work vehicle drivers and implications for work and workplace design. *Ergonomics*, 37 (4), 623–639.

Fathallah, F.A., *et al*., 2008. Forces required to operate controls on farm tractors: Implications for youth operators. *Ergonomics*, 51 (7), 1096–1108.

Freeman, S.A., Whitman, S.D., and Tormoehlen, R.L., 1998. Baseline childhood farm safety data for Indiana. *Journal of Agricultural Safety and Health*, 4 (2), 119–130.

Hawk, C., Donham, K.J., and Gay, J., 1994. Pediatric exposure to agricultural machinery: Implication for primary prevention. *Journal of Agromedicine*, 1 (1), 57–74.

Kumar, A., Gaikwad, B., and Singh, J.K., 2009. Assessment of controls layout of Indian tractors. *Applied Ergonomics*, 40 (1), 91–102.

Lee, B. and Marlenga, B., 1999. *Professional resource manual: North American guidelines for children's agricultural tasks*. Marshfield, WI: Marshfield Clinic.

Li, S. and Xi, Z.H., 1990. The measurement of functional arm reach envelopes for young Chinese males. *Ergonomics*, 33 (7), 967–978.

Marlenga, B., Pickett, W., and Berg, R.L., 2001a. Agricultural work activities reported for children and youth on 498 North American farms. *Journal of Agricultural Safety and Health*, 7 (4), 241–252.

Marlenga, B., Pickett, W., and Berg, R.L., 2001b. Assignment of work involving farm tractors to children on North American farms. *American Journal of Industrial Medicine*, 40 (1), 15–22.

Mehta, C.R., *et al*., 2008. Review of anthropometric considerations for tractor seat design. *International Journal of Industrial Ergonomics*, 38 (2008), 546–554.

Moussahamouda, E. and Mourant, R.R., 1981. Vehicle fingertip reach controls – human-factors recommendations. *Applied Ergonomics*, 12 (2), 66–70.

Myers, J.R., 2003. Tractor occupational safety and health update. *In: Record of tractor-related injury and death meeting*, edited by NIOSH. Pittsburgh, PA: NIOSH, 5–23.

National Institute of Standards and Technology, 2005. *AnthroKids - Anthropometric data of children* [online]. Available from: http://www.itl.nist.gov/iaui/ovrt/projects/anthrokids/ [Accessed 25 November 2005].

Park, H., *et al*., 2003. Characterization of agricultural tasks performed by youth in the Keokuk County Rural Health Study. *Applied Occupational and Environmental Hygiene*, 18 (6), 418–429.

Pheasant, S., 1997. *Bodyspace: Anthropometry, ergonomics, and the design of work*, 2nd edition. London: Taylor & Francis.

Pickett, W., *et al*., 1999. Fatal work-related farm injuries in Canada, 1991–1995. Canadian Agricultural Injury Surveillance Program. *Canadian Medical Association Journal*, 160 (13), 1843–1848.

Porter, J.M., Case, K., and Freer, M.T., 1999. Computer aided design and human models. *In*: W. Karwowski and W. Marrai, eds. *Handbook of occupational ergonomics*. Boca Raton, FL: CRC Press LLC, 479–500.

Porter, J.M. and Porter, C.S., 1998. Turning automotive design 'inside-out'. *International Journal of Vehicle Design*, 19 (4), 385–401.

Rivara, F.P., 1997. Fatal and non-fatal farm injuries to children and adolescents in the United States, 1990–3. *Injury Prevention*, 3 (3), 190–194.

Snyder, R.G., *et al*., 1977. *Anthropometry of infants, children, and youths to age 18 for product safety design*. Ann Arbor, MI: Highway Safety Research Institute, University of Michigan, UM-HSRI-77–17.

US Department of Labor, 2007. *Child labor requirements in agricultural occupations under the Fair Labor Standards Act* (Child Labor Bulletin 102). Washington, DC: Employment Standards Administration – Wage and Hour Division, WH-1295.

Yang, J.Z., *et al*., 2007. A new digital human environment and assessment of vehicle interior design. *Computer Aided Design*, 39 (7), 548–558.