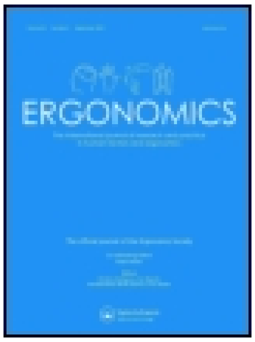

Ergonomics

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

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Ergonomics
Vol. 51, No. 7, July 2008, 1096–1108

Forces required to operate controls on farm tractors: Implications for young operators

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Farm tractors account for the majority of fatal injuries to adolescents working in agriculture and therefore remain a leading occupational priority. The question of whether these injuries occur because adolescents are assigned tractor jobs beyond their physical capabilities has not been answered. The purpose of this study was to estimate the activation forces required to operate controls on 40 tractors in common use in the US and compare them with existing estimates of physical strength for children of varying ages and with recommended ergonomic force limits for repeatedly engaging controls. Activation forces for steering, brakes and clutch were measured on each tractor. The main study finding was that the activation forces required to operate tractors typically exceeded the physical abilities of most children aged 13 to 17 years. This raises serious questions about the ability of children to safely operate tractors in common use on US farms. This study provides an ergonomic approach for evaluating the potential mismatch between young people's strength capabilities and forces required in operating farm tractors. This approach could be used in similar situations where adolescents may operate vehicles (e.g. all-terrain vehicles), machinery or other mechanical devices requiring activation of levers and controls. Study findings potentially inform the establishment of occupational policies surrounding tractor operation by young people.

Keywords: agriculture; children; safety; strength

1. Introduction

Farm tractors account for the majority of fatal injuries to adolescents working on farms in North America (Castillo *et al.* 1999, Pickett *et al.* 1999, Hard and Myers 2006). Tractors are also an important source of non-fatal trauma (Pickett *et al.* 2001) and therefore remain a leading occupational priority for paediatric injury prevention.

It is well documented that adolescents commonly operate tractors on farms (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). In the United States, the Fair Labor Standards Act protects young people working in agriculture by providing minimum age standards and hours that adolescents may work and identifies hazardous jobs that are prohibited for young people under the age of 16 years (US Department of Labor 2007). However, family

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ISSN 0014-0139 print/ISSN 1366-5847 online

DOI: 10.1080/00140130801961901
http://www.informaworld.com

farms are exempted from these child labour laws, as well as from occupational safety regulations (US Department of Labor 2006), thus allowing parents to decide when their children are ready to begin operating a tractor and to what extent children will be involved in tractor work on their farm.

Farm tractors require both physical strength and acquired skills to operate them safely. There have been several studies and guidelines on recommended force limits for activating tractor controls and pedals for adults (Pheasant and Harris 1982, Society of Automotive Engineers 1993, International Organization for Standardization 2002, Mehta *et al*. 2007). Some of these studies and standards have warned about the potential mismatch between recommended activation limits and the capabilities of portions of the adult population. For example, Pheasant and Harris (1982) has shown how existing recommended maximal allowable activation force on tractor pedals may not be operable by 20% of male and 60% female adults. More recently, Mehta *et al*. (2007) have compared leg strengths of Indian adult tractor drivers to existing Indian and international standards on tractor pedal actuating force limits and found that the existing standards tend to be too high for the Indian adult tractor operator population. International standards also have cautioned that some of the recommended force limits may not be appropriate for the lower percentiles of the male and female adult populations (International Organization for Standardization 2002). These studies highlight the fact that operating farm tractors may be challenging for some adult operators, which raises serious questions about the ability of youths to operate such vehicles.

There is a lack of quantitative information about how the physical requirements for operating tractors compare with the physical capabilities of adolescents at different stages of development. It is unknown whether young operators can consistently meet the physical requirements of tractor operation. It has been hypothesised that many tractor-related injuries occur because adolescents are assigned tractor jobs that are beyond their physical capabilities (Lee and Marlenga 1999). There is little available scientific evidence in the ergonomic or biomedical literatures to support this hypothesis. The present study group had the opportunity to look at these potential ergonomic and anthropometric mismatches. It was hoped that information could be provided that could guide decisions about the assignment of tractor work to children.

The overall goal of this research was to estimate the activation forces required to operate tractors in common use in the United States and compare them with existing estimates of physical strength for children of varying ages. This was done to identify any potential strength mismatches between the physical characteristics of young people aged 13–17 years and the tractors they are operating. The specific objectives were to characterise the activation forces required to activate controls for sentinel tractor operations (brake, clutch, steering) and to compare these forces with existing estimates of physical strength for children of varying ages, and with suggested control and lever operational guidelines.

2. Methods

2.1. Overview of the study design

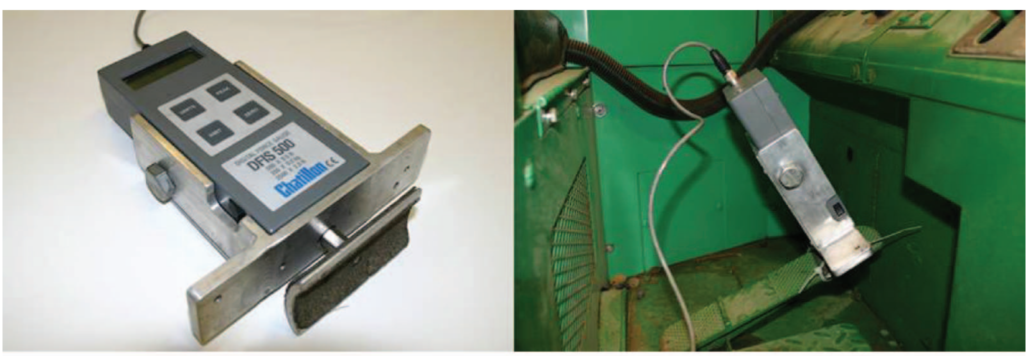
The strength of a young operator dictates his/her ability to properly activate various controls on a tractor. The physical strengths of adolescents aged 13–17 years were compared to the activation forces of three major controls, namely: 1) brake pedal; 2) clutch pedal; 3) steering wheel. These controls are the most frequently used in tractor operation. The activation forces for these controls were measured from a sample of 40 commonly used agricultural tractors of varying models, size and ages, which included 18 tractors with roll over protection structures (ROPS) and 22 tractors without ROPS. The tractors were accessed from local tractor dealers and farmers in the states of California and Wisconsin. Corresponding youth physical strength data were estimated from various sources, due to the lack of exact data for US youth.

2.2. *Models of tractors under study*

In order to identify a list of common tractor models that adolescents were likely to operate, data were obtained from the 2001 National Tractor Survey conducted for the National Institute for Occupational Safety and Health (NIOSH) 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). A total of 40 (80%) of these tractor models were available to the study team and hence identified for focused study.

2.3. *Instrumentation system*

A hand-held digital force gauge, Chatillon DFIS-500 (AMATEK Inc., Largo, FL, USA), was used to measure the resistance force for the major controls. Peak and continuous force measurements were obtained through an RS232 serial connection to a portable computer via custom-built software written in Visual Basic. The device force range is 0–2500 N, in 2 N increments. Manufacturer-certified calibration was performed prior to data acquisition procedures. It was necessary to maintain the position of the force gauge during data acquisition in order to obtain reliable data. Hence, specially designed attachments were built to assure proper force measurements of the tractor controls. Figures 1 and 2 depict the force gauge and the corresponding attachments for measuring the pedal force and steering force, respectively. A concave plate attachment was used for a secure connection on convex pedals (see Figure 1). If required, additional housing was used along with the plate attachment in order to support foot operation. An L-shaped



(a) (b)

Figure 1. Plate attachment for pedals (a) and its application (b).

attachment was used to measure tangential resistance forces for steering wheels (see Figure 2). Furthermore, a ramp was constructed to assist in the measurement of minimally required braking forces on the tractors (see Figure 3).

2.4. Field measurement procedure

Tractors used in this study were obtained from tractor dealers and farmers in California and Wisconsin. Once a cooperating dealer or farmer was identified to have one of the targeted tractors, the first step in the data collection procedure was to ensure that the tractor of interest was operational. A dedicated research team member was trained and assigned to gather the activation forces for controls on each study tractor. Custom-made attachments were used for different controls and connected to the digital force gauge (as described above; Figures 1 and 2).

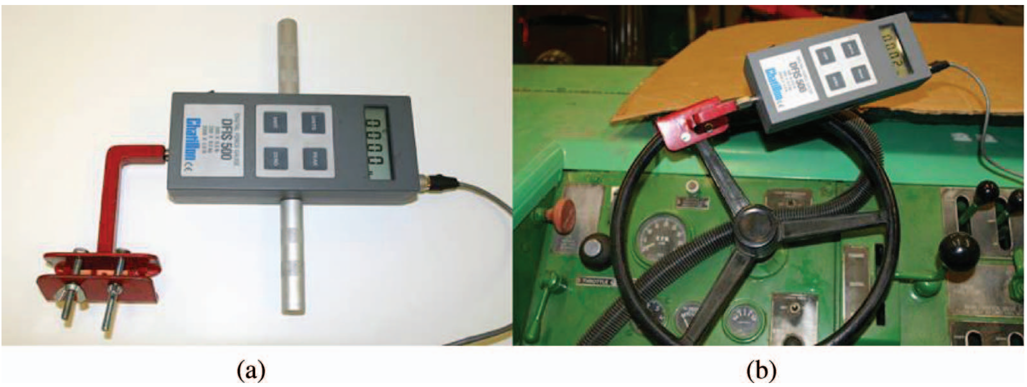


Figure 2. L-shape attachment for steering wheels (a) and its application (b).

Figure 3. Tractor ramp constructed to capture braking force.

In general, the team member with the force gauge was trained to maintain the force gauge perpendicular to the tractor control and to move the force gauge at a slow and constant pace. In addition, the operator was instructed in specific measurement techniques for each tractor control. For the steering wheel control, the force gauge was attached at the apex of the steering wheel and rotated to the lowest position clockwise and counter-clockwise, i.e. 180° rotation in both directions. Forces on the foot clutch were identified as the pedalling force until the point that the clutch could not be pressed further. Pedalling forces on the foot brake, on the other hand, were measured in two different ways. Originally, the tractor was located on a ramp to measure braking forces under the same conditions (Figure 3). While the clutch was disengaged, a gauge-attached brake pedal was fully pressed. The brake pedal was slowly released and pressed again at the moment when the tractor started rolling down the ramp. The lowest data point was identified as the minimum resistance force required for stopping the tractor. Using the ramp approach provided a standardised environment for braking force measurement; however, due to practical reasons, this method was not available when tractors were measured in Wisconsin. For those tractors, the same method used for clutch force measurement was implemented for braking force measurement (i.e. pressing down on the pedal up to the stopping point).

Another team member was dedicated to capturing the continuous digital force data using a portable computer. Three to five trials were performed on each control mechanism and the peak force reading from the gauge was recorded manually for each trial (in case of any unexpected loss of data communication).

Along with the force measurements, descriptive information about the tractor was also collected. Identification and the characteristics of the tractor included general information about the tractor, including manufacturer, model, year of manufacture, horsepower, serial number, presence of ROPS, steering wheel and braking types.

2.5. Data analysis

Data for the tractors selected for study are presented in tabular and graphical form using standard summary statistics. Descriptive data include tractor characteristics such as year of manufacture, horsepower and the types of brakes and steering.

The primary results for this study consist of measures of the activation forces required for steering and operation of the brake and clutch pedals of the tractors. Force measurements were replicated three to five times for each tractor model, with median coefficients of variation among replicates of 4%, 9% and 11%, for clutch, brake and steering forces, respectively. All analyses that follow are based upon the median force for each tractor model.

Pedal force data were related to the physical capabilities of children using published data on the mean for maximum quadriceps contraction force for boys and girls ages 5–17 years (Parker *et al.* 1990). In that study, the young subjects performed maximum voluntary contractions while seated in a chair with a backrest and a knee flexion of 90°. The subjects' arms rested passively on an adjustable shelf and hip elevation was prevented by securing the hip and chest using straps. A force gauge was attached to the subject's ankle. Note that this posture is expected to solicit maximum leg strength since a backrest was used and the quadriceps muscle was set at its resting length (90° knee flexion). Therefore, the force estimates from the Parker *et al.* study may be overestimates of what adolescents could generate in less than optimal leg or trunk postures, such as extending the leg to push on the brake pedal with no backrest while driving a tractor.

Regression models were fit to the published means and standard deviations to obtain estimates for boys and girls aged 13, 15 and 17 years. Tractor force data were then expressed relative to 'reasonable exertion' in boys or girls of a given age, where 'reasonable exertion' was defined to be 30% of maximum force (Dupuis 1959, Pheasant and Harris 1982) since operation of a tractor requires the ability to repeatedly engage the controls. Data are presented both in terms of which tractors exceeded these limits and in terms of the ratio of the force for each tractor to the limit.

Reference strength data for children that would be directly applicable to steering force do not exist. Therefore, published recommendations that steering force should be less than 220 N in adults (Weimer 1993) (and should not exceed 250 N (International Organization for Standardization 1995)) were scaled down as necessary for children of different ages. This was accomplished by proportionally reducing the reference limits based upon the quadriceps contraction data described above. Using the mean estimates for maximum quadriceps force, the proportion by gender and age group relative to females aged 18 years was calculated and when less than 1, the proportion was multiplied by 220 to reduce the 220 N reference limit accordingly. As with pedal force, the steering force data are presented both in terms of which tractors exceeded these limits and in terms of the ratio of the force for each tractor to the limit.

This study represents a first attempt to relate the physical requirements of tractors to the capabilities of children and, as such, no attempt is made to use statistical inference to apply these results beyond the tractors included for study. The tractor selection was non-random and, although it was directed at tractor models known to be those used most commonly throughout the United States, the tractors actually evaluated represent a convenience sample, based on availability, of one tractor from each of those common models.

3. Results

The characteristics of the tractor models under study are listed in Table 1. Of the 40 tractors, 18 (45%) were equipped with ROPS and most (87%) were manufactured prior to 1985. Horsepower ranged from 20 to 156, with 58% in the range of 20–70 horsepower.

Tables 2 and 3 summarise the brake and clutch forces, respectively, by age and gender. The maximum quadriceps forces are shown by age and gender and the force limits for each group are shown together with the number and percentage of tractors that exceeded the limit. Note that the proposed foot-operated limits for male and female adolescents (99–127 N; Table 2) fall within the range of ISO recommended 'maximum' control actuation force for foot-operated controls by adults (International Organization for Standardization 2002). Clutch forces were generally substantially higher than brake forces in these tractors, with 100% exceeding the recommended limits for girls at all ages and 95% exceeding the recommended limit even for boys aged 17 years. The pedal force data are shown more completely in Figures 4 and 5, where the brake and clutch forces for individual tractors are presented as the ratio to the force limits; points above the reference line at 1.0 show those tractors that exceeded the limits. The same tractors are shown for each age and gender group, each time substituting the appropriate limit in calculating the ratio. The tractor steering forces are summarised in Table 4 and Figure 6. Relatively few tractors exceeded recommended steering force limits for girls or boys.

Table 5 shows tractors that exceeded the recommended force limits for the three sentinel tractor operations (brake, clutch, steering). There were only two tractors

Table 1. Description of tractors under study.

	ROPS tractors* (n = 18)		Non-ROPS tractors† (n = 22)		Total (n = 40‡)	
	n	%	n	%	n	%
Year manufactured						
Pre 1970	0	0	14	70.0	14	36.8
1970–1984	13	72.2	6	30.0	19	50.0
1985 and newer	5	27.8	0	0	5	13.2
State						
California	4	22.2	6	27.3	10	25.0
Wisconsin	14	77.8	16	72.7	30	75.0
Brake type						
Hydraulic	16	88.9	5	22.7	21	52.5
Mechanical	2	11.1	17	77.3	19	47.5
Power steering						
No	0	0	10	45.5	0	25.0
Yes	18	100	12	54.5	30	75.0
Horsepower						
20–70	4	22.2	18	90.0	22	57.9
71–120	8	44.4	2	10.0	10	26.3
>120	6	33.3	0	0	6	15.8

ROPS = rollover protection structures.

*ROPS: Ford 3930; International Harvester 966, 986, 1066, 1486; John Deere 2350, 2555, 2950, 4230, 4240, 4320, 4430, 4440, 4450, 4630, 4640, 5300, 5400.

†Non-ROPS: Allis-Chalmers D-17; Farmall 140, 560, 656, 706, C, Super C, H, M; Ford 8N, 641, 2000, 3600, 4000, 5000; John Deere 60, 2440, 3010, 3020 4020; Massey Ferguson 135, 245.

‡Due to missing data, totals for year manufactured and horsepower are 38.

Table 2. Percentage of tractors with brake forces exceeding recommended limits*.

			Tractors exceed-ing			Tractors exceeding	
Gender	Age (years)	Force limit (N)	n	%	30% of limit (N)	n	%
Male	13	391.5	0	0.0	117.5	30	81.1
	15	523.7	0	0.0	157.1	28	75.7
	17	643.9	0	0.0	193.2	17	45.9
Female	13	330.0	0	0.0	99.0	30	81.1
	15	381.8	0	0.0	114.5	30	81.1
	17	423.5	0	0.0	127.0	29	78.4

*Recommended limits are based on the mean for the maximum quadriceps contraction force as estimated from Parker *et al.* (1990).

that did not exceed any force limits, but this was true for only 17-year-old boys. For girls aged 13, 15 and 17 years and boys aged 13 and 15 years, all tractors exceeded at least one recommended force limit and the majority of tractors exceed two force limits. A few tractors exceed all three force limits for both genders in all age categories.

Table 3. Percentage of tractors with clutch forces exceeding recommended limits*.

Gender	Age (years)	Force limit (N)	Tractors exceeding		30% of limit (N)	Tractors exceeding	
			n	%		n	%
Male	13	391.5	5	12.8	117.5	39	100.0
	15	523.7	0	0.0	157.1	38	97.4
	17	643.9	0	0.0	193.2	37	94.9
Female	13	330.0	12	30.8	99.0	39	100.0
	15	381.8	6	15.4	114.5	39	100.0
	17	423.5	4	10.3	127.0	39	100.0

*Recommended limits are based on the mean for maximum quadriceps contraction force as estimated from Parker *et al.* (1990).

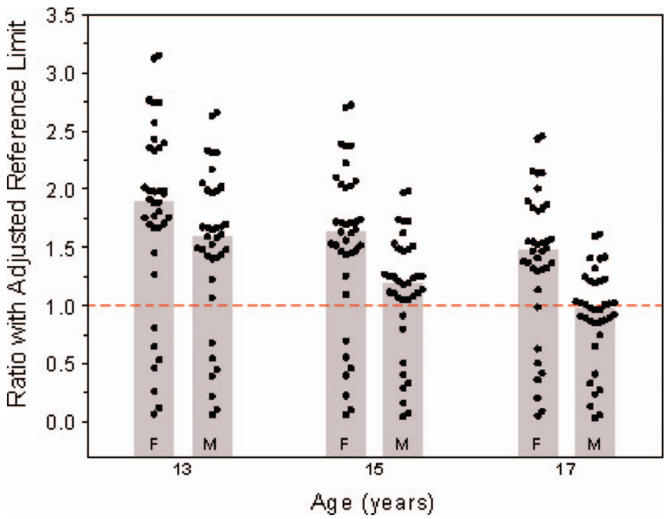


Figure 4. Brake pedal force data by age and gender. A total of 37 tractors relative to quadriceps data of Parker *et al.* (1990). Bars extend to the median.

4. Discussion

This study examined the activation forces required to operate the clutch, brakes and steering wheels of 40 tractor models in common use in the US. Estimated activation forces were subsequently compared with the physical capabilities of young people aged 13–17 years, as inferred from existing ergonomic databases (Parker *et al.* 1990). The main study finding was that the activation forces required to operate tractors typically exceeded the physical abilities of children. This raises serious questions about the ability of children to safely operate tractors in common use on US farms.

In order to operate a tractor both efficiently and safely, tractor operators must be able to activate a number of controls with some consistency. The current analysis focused upon the activation forces involved in three of the most crucial tractor functions, namely, the depression of the clutch to change gears, activation of the brakes to reduce speed or stop the tractor and basic operation of the steering wheel. Inability of an operator to

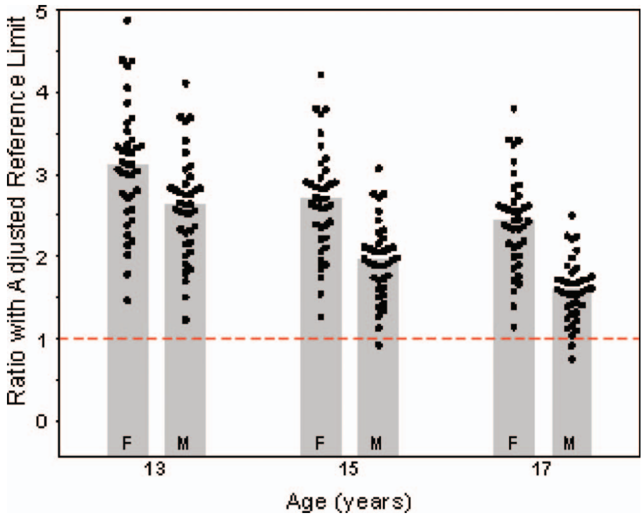


Figure 5. Clutch pedal force data by age and gender. A total of 39 tractors relative to quadriceps data of Parker *et al*. (1990). Bars extend to the median.

Table 4. Percentage of tractors with steering forces exceeding recommended limits*.

			Tractors exceeding	
Gender	Age (years)	Force limit (N)	n	%
Male	13	205.7	5	12.8
	15	220.0	4	10.3
	17	220.0	4	10.3
Female	13	173.4	8	20.5
	15	200.6	6	15.4
	17	220.0	4	10.3

*Recommended limits are reduced from 220 N (Weimer 1993) for some age/gender combinations in relation to 30% of maximum quadriceps contraction force as estimated from Parker *et al.* (1990).

consistently activate these tractor components would clearly place operators and potentially others at risk. Common causes of fatal and traumatic injury involving farm tractors include rollovers, run-overs of passengers or bystanders and collisions (Pickett *et al*. 1999, 2001, Hard and Myers 2006), all of which imply a functional loss of control of the vehicle or a failure to avoid an unexpected hazard. If young people do not have the ability to activate tractor controls with 100% certainty, this leaves them vulnerable to these injury events.

The present findings that, starting at an early age, almost all children of both genders have the physical strength to operate steering wheels on tractors are not surprising. Steering activation forces appear to be low and well within reasonable limits for ongoing ergonomic tasks. There are many tractor-related activities on farms where children could be placed on a tractor and drive it with a minimal need to touch any control besides the steering wheel. This indeed explains the anecdotal stories one hears of children as young as 6 years driving tractors on a routine basis. However, the safe and efficient use of farm

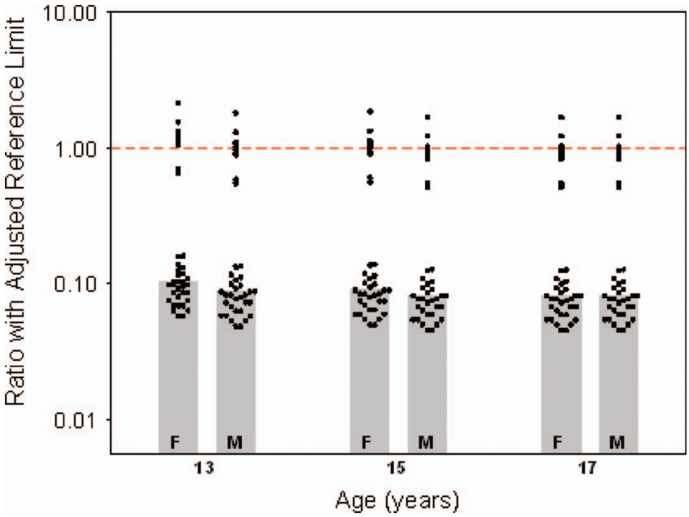


Figure 6. Steering wheel force data by age and gender. A total of 39 tractors relative to adjusted 220 N reference limit (Weimer 1993). Bars extend to the median.

Table 5. Tractors exceeding recommended limits for clutch, brake or steering forces.

		Number of limits exceeded							
		None		1		2		All 3*	
Gender	Age (years)	n	%	n	%	n	%	n	%
Male	13	0	–	9	22.5	28	70.0	3	7.5
	15	0	–	13	32.5	24	60.0	3	7.5
	17	2	5.0	20	50.0	16	40.0	2	5.0
Female	13	0	–	7	17.5	29	72.5	4	10.0
	15	0	–	8	20.0	29	72.5	3	7.5
	17	0	–	11	27.5	26	65.0	3	7.5

*Brake force was not available for three tractors; clutch and steering forces were not available for one tractor. In these few cases, the maximum possible is <3.

tractors clearly involves the ability to reach and activate all controls in an effective manner. The anthropometric mismatches observed in the current study provide one explanation for the number of children who are killed or maimed in tractor-related injury events every year. Some of these are likely attributable to a physical inability to activate controls such as the brake or clutch in a timely manner.

There is an ongoing debate in the agricultural health and safety literature surrounding the minimum age that a child should be in order to operate a farm tractor. This debate has suffered from a lack of objective data on the physical abilities of children and how they match up with data surrounding the forces required to operate tractors. The US Fair Labor Standards Act, Hazardous Occupations Orders for Agriculture prohibits adolescent workers younger than 16 years from operating tractors. However, 14 and 15 year olds who have successfully completed a tractor and machinery training course are exempt from this minimum age and can operate tractors for hire. Furthermore, children working on their parents' farms are exempt from these minimum ages and training requirements and can operate tractors at any age deemed suitable by their parents (US Department of Labor 2007). The American Academy of Pediatrics recommends a minimum age of 16 years for the operation of any farm vehicle with no exceptions (American Academy of Pediatrics 2001). Published guidelines for parents entitled the *North American Guidelines for Children's Agricultural Tasks* suggest the introduction of simple tractor work involving trailed and/or 3-point implements at the age of 12–13 years and a minimum age of 14 years for more complex tasks or work involving tractors >70 horsepower (Lee and Marlenga 1999). Based upon this review, there appears to be no agreement on the minimum age standards and none of these recommendations was informed by the types of ergonomic data described in the current analysis. The present study findings provide some objective evidence in support of a higher age limit for tractor operations, with no exemptions or exceptions.

4.1. Strengths and limitations

An important strength of the current analysis is its novelty; the authors are unaware of any existing study that has attempted to develop an objective assessment of the strength of children and relate it to the forces required for tractor operation. Second, this study provides objective evidence to assist in the establishment of evidence-based recommendations for children and tractor operation. Prior recommendations about minimum ages for tractor operation suggested by the US Department of Labor (2007), the American Academy of Pediatrics (2001) and the *North American Guidelines for Children's Agricultural Tasks* (Lee and Marlenga 1999) have been made in the absence of such evidence. Third, efforts were made to measure the forces required to operate tractor controls in 'real-life' field settings using tractor models that US children were likely to encounter. This enhances the generalisability of the study findings. Finally, the tractor force data were collected as part of a larger set of anthropometric variables that also include reach distances and fields of vision. Collectively, these three analyses should provide a more comprehensive picture of the ability of children of different ages to effectively operate tractors in common use in the US, and the factors that impinge upon their safety, than has previously been available.

Several limitations of this analysis warrant recognition. First, although the study used a systematic approach to the identification of a sample of tractors in common use in the US, the sample is small, subject to sampling error and is not necessarily representative of the tractors driven by children. Second, safe and effective operation of farm tractors involves consideration of issues other than the forces required to operate brakes, clutches and steering wheels. Most tractor work involves auxiliary controls and trailed implements that themselves pose additional physical requirements and hazards. Therefore, the current analysis and associated recommendations are clearly conservative because they do not consider these additional operational factors. Third, the braking force measurements were not standard methods (e.g. as described in Society of Automotive Engineers or ISO standards); however, since braking forces were affected by many factors, such as ground conditions, tyre abrasion, general condition of the brake system, etc., which are very difficult to control, the approaches adopted provided conservative (minimal force) alternative methods. Finally, the database describing maximum quadricep forces for children (Parker *et al.* 1990) and the published limits for steering force (Weimer 1993) were both developed for other purposes. Unfortunately, no analogous data were available to describe the specific forces required for children to operate tractors.

5. Conclusion

Young people on American farms commonly operate agricultural equipment, especially tractors. This study focused on the evaluation of the potential mismatch between the operational requirement of key controls on common tractors and adolescent strength capabilities. The main study finding was that the activation forces required to operate tractors typically exceeded the physical abilities of most children aged 13 to 17 years. This raises serious questions about the ability of children to safely operate tractors in common use on US farms.

Acknowledgements

This research was supported by NIOSH Research Grant #R01 OH07850 and by the University of California Western Center for Agricultural Health and Safety. The authors would like to thank the invaluable contribution of Brandon Miller, Nancy Esser, Jennifer Plasse, Erica Garcia and Victor Duraj during the data collection phase of this study. The authors extend their gratitude to John Myers at NIOSH for sharing data from the 2001 National Tractor Survey and Dr. Mark Purschwitz for technical expertise regarding tractor makes and models. Finally, the authors extend their 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.

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