2006

An Investigation of Three Physical Parameters of PTO Entanglements

Steven A. Freeman
Iowa State University, sfreeman@iastate.edu

Charles V. Schwab
Iowa State University, cvschwab@iastate.edu

John L.P. Judge
Iowa State University

An Investigation of Three Physical Parameters of PTO Entanglements

Abstract

The PTO driveline is the most common means of transferring power from a tractor to towed machinery and stationary equipment. While equipment manufacturers install shielding to protect operators and bystanders from coming in contact with operating PTO components (particularly around the knuckle), entanglement is still a cause of some of the most catastrophic agricultural work-related injuries. This study investigated the influence of material type, material length, and angle of material introduction on entanglements with a spinning PTO shaft knuckle. These variables were tested using a laboratory PTO apparatus where 165 entanglements were recorded during the 720 trials conducted. The results indicate that lighter materials, such as cotton thread, have a significantly higher probability of becoming entangled than heavier materials, such as leather bootlaces. Materials that were longer (i.e., extend further below the midline of the PTO knuckle) have higher probabilities of becoming entangled than do shorter materials. The horizontal path that the material traveled across the centerline of the PTO shaft impacted the probability of entanglement. When the angle of intersection of the horizontal path of travel relative to the centerline of the PTO shaft is 90°, or close to 90°, a higher probability of entanglement occurs. All 165 entanglements occurred on the downward rotational side of the PTO knuckle regardless of which side the horizontal path of travel started from. The results of this study provide the first look at understanding the physical phenomena associated with the initial stages of PTO entanglements and set the stage for future research.

Keywords

Entanglement, PTO, Safety

Disciplines

Agriculture | Bioresource and Agricultural Engineering

Comments

This article is from *Journal of Agricultural Safety and Health*, 12, no. 3 (2006): 191–197.

An Investigation of Three Physical Parameters of PTO Entanglements

S. A. Freeman, C. V. Schwab, J. L. P. Judge

Abstract. *The PTO driveline is the most common means of transferring power from a tractor to towed machinery and stationary equipment. While equipment manufacturers install shielding to protect operators and bystanders from coming in contact with operating PTO components (particularly around the knuckle), entanglement is still a cause of some of the most catastrophic agricultural work-related injuries. This study investigated the influence of material type, material length, and angle of material introduction on entanglements with a spinning PTO shaft knuckle. These variables were tested using a laboratory PTO apparatus where 165 entanglements were recorded during the 720 trials conducted. The results indicate that lighter materials, such as cotton thread, have a significantly higher probability of becoming entangled than heavier materials, such as leather bootlaces. Materials that were longer (i.e., extend further below the midline of the PTO knuckle) have higher probabilities of becoming entangled than do shorter materials. The horizontal path that the material traveled across the centerline of the PTO shaft impacted the probability of entanglement. When the angle of intersection of the horizontal path of travel relative to the centerline of the PTO shaft is 90°, or close to 90°, a higher probability of entanglement occurs. All 165 entanglements occurred on the downward rotational side of the PTO knuckle regardless of which side the horizontal path of travel started from. The results of this study provide the first look at understanding the physical phenomena associated with the initial stages of PTO entanglements and set the stage for future research.*

Keywords. *Entanglement, PTO, Safety.*

The PTO driveline is the most common means of transferring power from a tractor to towed machinery (e.g., balers, rotary mowers) and stationary equipment (e.g., augers, grinders). The PTO driveline is one of the oldest and most common farm machinery hazards (Murphy, 1992). Equipment manufacturers have installed shielding to minimize injuries to operators and bystanders that result from being exposed to rotating PTO shafts. Yet, coming in contact with an operating PTO is still a cause of some of the most catastrophic agricultural work-related injuries. This is particularly true when contact is made around the knuckle (universal joint) of the driveline (Wilkinson and Field, 1989). While data concerning PTO entanglements exist in the literature (Knapp and Piercy, 1966; McElfresh and Bryan, 1973; Sell, 1984; Sell et al., 1985; Campbell, 1987; Wilkinson and Field, 1988; Wilkinson, 1991; Murphy, 1992; Buchele, 1993; Beer and Field, 2003; Wilkinson et al., 2005), there is a distinct lack of data concerning the physical phenomena involved at the initial moment of entanglement. To address this gap,

---

Submitted for review in June 2005 as manuscript JASH 5942; approved for publication by the Journal of Agricultural Safety and Health of ASABE in February 2006.

The authors are **Steven A. Freeman, ASABE Member Engineer,** PhD, CSP, Associate Professor, **Charles V. Schwab, ASABE Member Engineer,** PhD, Professor and Extension Safety Specialist, and **Jon L. P. Judge,** MS, Former Graduate Student, Department of Agricultural and Biosystems Engineering, Iowa State University, Ames, Iowa. **Corresponding author:** Steven A. Freeman, 104 Industrial Education Building II, Iowa State University, Ames, IA 50011-3130; phone: 515-294-9541; fax: 515-294-1123; e-mail: sfreeman@iastate.edu.

  ISSN 1074-7583

this study investigated how three physical parameters (material type, material length, and angle of material introduction) affect the occurrence of a material entanglement with a spinning PTO shaft knuckle.

Methods

Experimental Design

Three materials significantly different in stiffness, yet still prevalent in the clothing worn by farmers, were selected for this study: (1) cotton thread, such as what is typical in cotton work clothing; (2) woven cotton lace, such as the drawstring of a hooded sweatshirt; and (3) leather lace, such as a work-boot lace. The lengths of material selected for study, as measured hanging below the midline of the PTO knuckle, were 7.62 cm (3 in.), 11.43 cm (4.5 in.), and 15.24 cm (6 in.). The material was introduced to the knuckle in a path that traveled horizontally across the centerline of the PTO shaft. Eight different angles of intersection between the horizontal path of travel and the centerline of the PTO shaft (±90°, ±75°, ±60°, and ±45°) were selected for the introduction of the material into the rotating knuckle. Four angles were selected on each side of the rotation of the shaft, as shown in figure 1. The additional angles (±105°, ±120°, and ±135°) were not selected for inclusion because of the symmetry of the test apparatus.

Each of the 72 experimental conditions (3 materials × 3 lengths × 8 angles) was replicated 10 times for a total 720 data points. The order of data collection was randomized by experimental condition. Once a condition was set (material, material

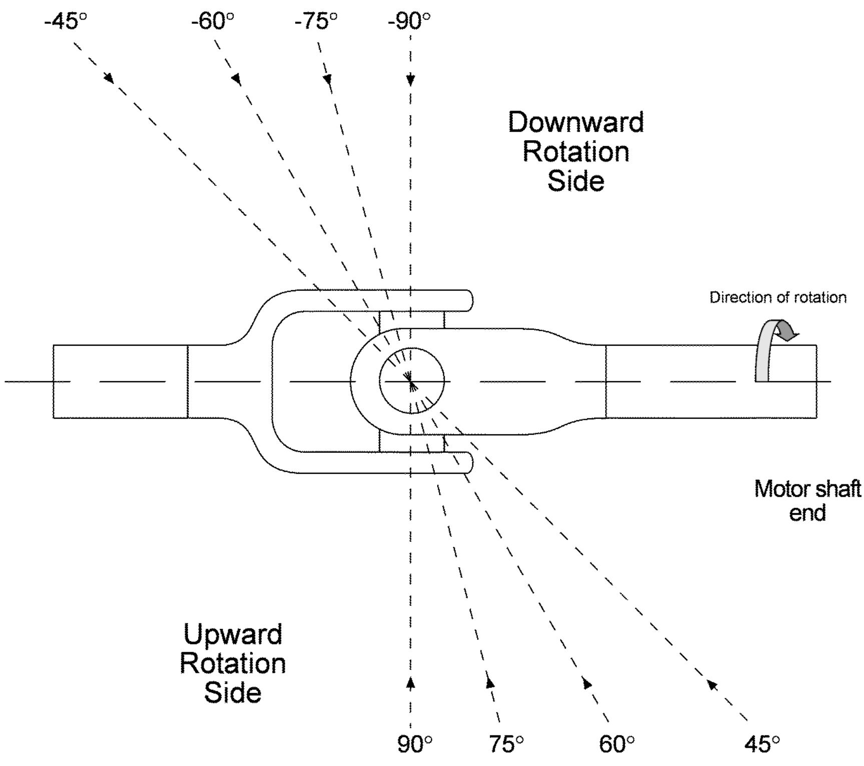

Figure 1. Top view of angles of material introduction relative to the PTO shaft and rotation.

length, and introduction angle), material was introduced into the rotating knuckle 10 times before moving on to the next condition. The speed of the rotating knuckle (540 rpm) and the speed at which the material was drawn across the knuckle (9.53 cm/min) were held constant (throughout the data collection).

Experimental Apparatus

To collect data, an experimental apparatus (Judge, 2004) was developed with the following characteristics:

- A PTO knuckle joint operated by an electric motor capable of maintaining a constant, set rotational speed.
- An indexing plate to control the precise angle of introduction of the material into the rotating knuckle.
- A lead screw assembly connected to another electric motor capable of moving the material across the PTO knuckle at a constant speed.
- A clip assembly that held the material in a vertical position so that gravity could keep the material hanging down as it was drawn across the PTO knuckle, yet release the material without damage if it became entangled.
- An overall design that allowed the PTO knuckle to be visible while still protecting the investigators during data collection.

The completed experimental apparatus is shown in figure 2.

Results

The experimental results of this study are shown in table 1 for each condition. Each permutation represented in the table is further divided to indicate on which side of the rotating knuckle the material became entangled. The upper number in each cell represents entanglements that occurred on the downward rotation side of the knuckle (fig. 1). The lower number in each cell represents entanglements that occurred on the

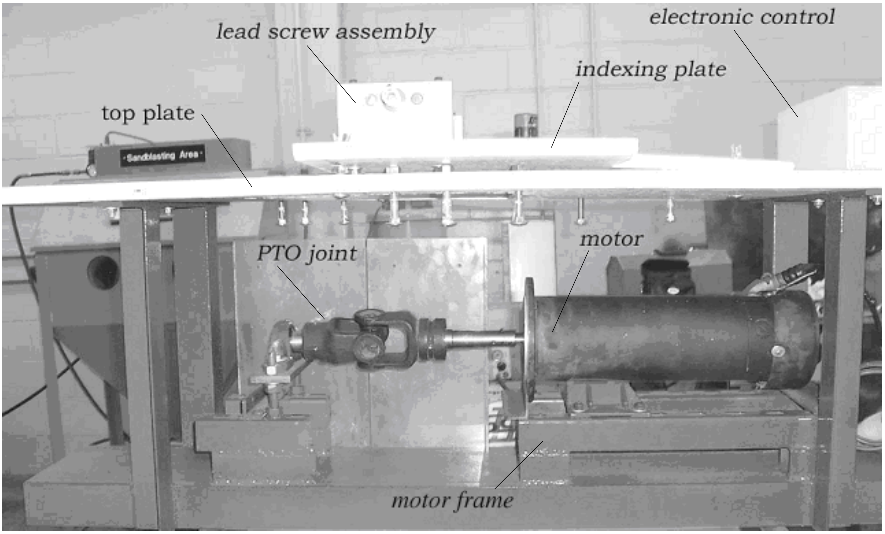

Figure 2. PTO entanglement apparatus.

upward rotation side of the knuckle. The shaded cells indicate that no entanglements occurred under those conditions.

During the 720 trials, 165 entanglements occurred. Cotton thread accounted for 157 (95%) of the recorded entanglements, and cotton thread became entangled in 65% of the 240 trials involving that material. The woven cotton lace became entangled six times out of the 240 trials involving cotton lace, and the leather lace entangled twice in the 240 trials involving leather lace.

The number of entanglements increased as the length of the material hanging below the midline increased. Sixty-seven (41%) of all entanglements occurred with a material length of 15.24 cm (6 in.) below the midline. Five of the six entanglements recorded with the cotton lace and both of the entanglements recorded with the leather lace occurred at this length. A length of 11.43 cm (4.5 in.) became entangled 54 (33%) times, and 7.62 cm (3 in.) materials entangled 44 (27%) times.

The angles of introduction involved with the most entanglements were the two angles perpendicular (±90°) to the centerline of the PTO shaft. These two angles accounted for 40% of all recorded entanglements and all the entanglements involving either cotton lace or leather lace. The data also indicate that 61% of the recorded entanglements occurred when the material was introduced from the downward rotation side of the shaft (negative angles in table 1). In these occurrences, as the material came in contact with the knuckle, it wound under the knuckle and entangled. For the 65 entanglements that occurred when the material was introduced from the upward rotation side (positive angles in table 1), the material never became entangled on that side but was instead thrown over the knuckle and became entangled on the downward side of the knuckle.

Because each permutation had one of two outcomes, i.e., either the material entangled or it did not entangle, a binary logistic regression procedure was selected to analyze the data (Mertler and Vannatta, 2002). The analysis indicated that all three variables (material type, material length, and angle of introduction) had a statistically significant influence

Table 1. Permutation combinations with number of entanglements per permutation.

Material	Length Below Midline	Angle of Material Introduction							
		−90°	−75°	−60°	−45°	45°	60°	75°	90°
Cotton thread	7.62 cm (3 in.)	10 0	9 0	5 0	3 0	0 0	0 0	8 0	9 0
	11.43 cm (4.5 in.)	10 0	10 0	7 0	5 0	1 0	2 0	9 0	9 0
	15.24 cm (6 in.)	10 0	10 0	9 0	7 0	2 0	3 0	9 0	10 0
Cotton lace	7.62 cm (3 in.)	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0
	11.43 cm (4.5 in.)	1 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0
	15.24 cm (6 in.)	3 0	0 0	0 0	0 0	0 0	0 0	0 0	2 0
Leather lace	7.62 cm (3 in.)	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0
	11.43 cm (4.5 in.)	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0
	15.24 cm (6 in.)	1 0	0 0	0 0	0 0	0 0	0 0	0 0	1 0

on determining the likelihood of the material becoming entangled with the rotating PTO knuckle. The resulting odds ratios related to material type indicate that the probability of entangling woven cotton lace is 3.5 times higher than that of leather lace, and the probability of entangling cotton thread is 6,500 times higher than that of leather lace. The resulting odds ratios related to length of material indicate that the probability of entangling material extending 11.43 cm (4.5 in.) below the midline is 3 times higher than that of material extending 7.62 cm (3 in.) below the midline, and the probability of entangling material extending 15.24 cm (6 in.) below the midline is 10 times higher than that of material extending 7.62 cm (3 in.) below the midline.

The results for angle of introduction indicated significant reduction in the likelihood of entanglements as the angle moved away from perpendicular and based on the side of approach. The odds ratios indicate that the probability of entangling material introduced from −45° is 12.7 times higher than the likelihood of an entanglement when the material is introduced from 45°. The probability of entangling material introduced from 90° (perpendicular on the upward rotation side of the knuckle) is 758 times higher than that of material introduced from 45°, and the probability of entangling material introduced from −90° (perpendicular on the downward rotation side of the knuckle) is 2,632 times higher than that of material introduced from 45°. All of the resulting odds ratios can be found in table 2.

Discussion

The results of this study confirmed some expectations of the investigators. For example, it was expected that lighter, more flexible materials would entangle more readily because they would bend more easily around the PTO shaft or knuckle. This was demonstrated by the results, where the cotton thread (the lightest and most flexible material used) entangled most often while in many trials the much stiffer leather lace simply bounced off the knuckle without becoming entangled.

It was also expected that longer material lengths would be more likely to entangle because there would be more loose material to become wrapped around the PTO and the rotation of the knuckle would wrap the material around in the direction of rotation. Both of these assumptions were confirmed by the experimental results: the likelihood of

Table 2. Odds ratios for predicting entanglements by type of material, angle of introduction, and material length below the midline of the shaft.

		Odds Ratio
Type of material	Cotton thread	6502.4
	Cotton lace	3.4
	Leather lace	Reference material
Angle of introduction	−90°	2632.0
	−75°	300.3
	−60°	34.7
	−45°	12.7
	90°	757.8
	75°	103.5
	60°	1.9
	45°	Reference angle
Material length below midline	15.24 cm	10.1
	11.43 cm	2.9
	7.62 cm	Reference length

entanglement increased as material length below the midline increased, and all entanglements occurred on the downward rotational side of the knuckle.

The results associated with angle of introduction led to a couple of interpretations. First, the side of introduction was significant. Materials that were introduced from the downward rotational side were more likely to entangle because, during the entire time the material was drawn across the rotating knuckle, the motion of the rotation was drawing the material around underneath the knuckle to become entangled. When material was introduced from the upward rotational side, the rotation of the knuckle threw the material up in the air so that it was not drawn under and entangled. Entanglements only occurred from the upward side when the material was tossed over the knuckle and then wrapped underneath. Depending on when this happened, the material may already have been moving away from the knuckle, thus decreasing the likelihood of entanglement. In addition, as the angle of introduction moved away from perpendicular, the time the material was in contact with the knuckle increased because the travel distance across the knuckle increased. However, the diagonal travel path also increased the effective diameter of the knuckle along the travel path, resulting in less material hanging down below the knuckle. The decrease in entanglements as the angle moved away from perpendicular may be due to this effective reduction in material length hanging down below the midline of the knuckle.

Finally, this study opens a new line of research investigating the full range of physical parameters and conditions that may influence the occurrence of PTO entanglements (e.g., weather, different material types and shapes, different methods of material introduction, etc.) at the initial stages of entanglement. The long-term goal of such research would be the generation of an encompassing model to predict material entanglements in any rotating driveline. A greater understanding of how driveline entanglements occur may lead to the development of more effective intervention strategies through redesign of driveline components and guarding mechanisms, redesign of work clothing, or new educational programs targeting the safe use of PTO-operated equipment.

Conclusions

Based on the results of this study, the following conclusions may be drawn:

- Different types of materials have different probabilities of becoming entangled in the spinning PTO knuckle. Lighter materials, cotton thread for example, entangle more readily in the PTO knuckle than do heavier materials such as woven cotton lace or leather lace.
- The angle at which material is introduced to a spinning PTO knuckle influences the probability of that material becoming entangled in the knuckle. The highest probability of entanglement occurred when material was introduced perpendicular to the PTO shaft.
- Regardless of the direction of introduction, materials entangle on the downward side of rotation of the knuckle. The entanglements that occurred when the material was being introduced from the upward side of the rotation only occurred after the material was cast over the knuckle and entangled on the downward side.
- The length of material extending below the midline of the PTO shaft influences the probability of the material becoming entangled in the knuckle. The likelihood of entanglement increased as the length below the midline increased.

Recommendations for Future Research

The data collected in this study came from a limited set of conditions. To fully understand PTO entanglements, additional studies need to be conducted under a wider variety of conditions to evaluate the impact of different variables involved. Additional studies should include:

- Variations in the physical setup of the PTO knuckle apparatus. For example: investigating the influence of the speed of rotation or the angle of the knuckle in relation to the shaft.
- Investigating entanglements using different portions of the PTO. For example: unguarded shafts of various designs.
- Investigating the efficacy of PTO guarding by introducing materials to PTOs that are guarded by a variety of tunnel and tube shields.
- Variations in the condition of the PTO shaft or knuckle to investigate the influence of nicks, dents, mud, protruding bolts, etc.
- Variations in the speed at which the material is introduced to the knuckle (or shaft) or variations in the time the material is in contact with the knuckle (or shaft).

The need also exists to expand this study to collect additional data under the same control conditions:

- A variety of materials need to be investigated to develop a better understanding of how material properties (e.g., fiber type, stiffness, density, etc.) influence the probability of entanglements.
- A variety of material lengths need to be investigated to determine the minimum and maximum lengths that may entangle for a variety of materials.

References

Beer, S., and W. E. Field. 2003. Analysis of power take-off related injuries and fatalities involving children and adolescents. ASAE Paper No. 038007. St. Joseph, Mich.: ASAE.

Buchele, W. F. 1993. Agricultural safety, design first, then educate! ASAE Paper No. 938001. St. Joseph, Mich.: ASAE.

Campbell, W. P. 1987. The condition of agricultural driveline system shielding and its impact on injuries and fatalities. Unpublished MS thesis. West Lafayette, Ind.: Purdue University.

Judge, J. L. P. 2004. An investigation of the physical parameters of PTO entanglements. Unpublished MS thesis. Ames, Iowa: Iowa State University.

Knapp, L. W., and L. R. Piercy. 1966. An epidemiological study of power take-off accidents. Bulletin No. 10. Iowa City, Iowa: University of Iowa, Institute of Agricultural Medicine.

McElfresh, E. C., and R. S. Bryan. 1973. Power take-off injuries. *J. Trauma* 13(9): 775-782.

Mertler, C. A., and R. A. Vannatta. 2002. *Advanced and Multivariate Statistical Methods.* Los Angeles, Cal.: Pryczak Publishing.

Murphy, D. J. 1992. *Safety and Health for Production Agriculture.* St. Joseph, Mich.: ASAE.

Sell, W. E. 1984. The nature of power take-off accidents. Unpublished MS thesis. West Lafayette, Ind.: Purdue University.

Sell, W. E., W. P. Campbell, and W. E. Field. 1985. Summary of on-farm PTO-related accidents. ASAE Paper No. 855513. St. Joseph, Mich.: ASAE.

Wilkinson, T. L. 1991. Power take-off entanglement risk factor analysis for grain augers. Unpublished PhD diss. West Lafayette, Ind.: Purdue University.

Wilkinson, T. L., and W. E. Field. 1988. Summary of accidents with power take-off driven augers and elevators. ASAE Paper No. 885519. St. Joseph, Mich.: ASAE.

Wilkinson, T. L., and W. E. Field. 1989. The effect of exposure to power take-off drivelines on operator behavior. ASAE Paper No. 891113. St. Joseph, Mich.: ASAE.

Wilkinson, T. L., S. R. Beer, and W. E. Field. 2005. Measurement of operator exposure to power take-off driven augers. *J. Agric. Safety and Health* 11(3): 301-314.