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Factors Contributing to Entanglement around a PTO Shaft Rotating at High Speed

Jinke Xu (M.Sc. student)

Department of Biosystems Engineering, University of Manitoba, Winnipeg, MB, R3T 5V6

Annette Kroeker (B.Sc. student)

Department of Biosystems Engineering, University of Manitoba, Winnipeg, MB, R3T 5V6

Danny D. Mann (Professor & Acting Head)

Department of Biosystems Engineering, University of Manitoba, Winnipeg, MB, R3T 5V6

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Abstract. *Little research has been conducted on the parameters contributing to PTO entanglements. In this study, five parameters including material moisture content, joint angle, approach angle, approach velocity, and material (yarn) length were investigated using a knuckle rotating at 1140 rpm. Approach angles of +90° and -90° have different effects on the occurrence of entanglements. More entanglements occurred when strands of yarn were introduced from -90° than from +90°. An increase in material moisture content decreases the number of entanglements for materials introduced from +90º. For an approach angle of +90º, increasing the joint angle from -20º to +20º decreases the number of entanglements. When the approach angle is switched to -90º, there is a sudden decrease in the number of entanglements when the joint angle is switched from 4º to 8º, after which the number of entanglements increases again. The proportion of entanglements also increased when approach velocity was decreased from 50 cm/min to 10 cm/min and when yarn length below the midline of the rotating knuckle increased from 9 to 15 cm.*

Keywords. Power take-off (PTO), entanglement, joint angle

1. INTRODUCTION

A power take-off (PTO) drive, that transmits rotary power from a power unit to a machine, is a common component of agricultural machines (Srivastava et al. 1993). Universal joints are used in PTO drivelines to achieve load transmission between input and output shafts with angular misalignments (Hunt and Garver 1973).

PTO drivelines are often partly or completely guarded by safety shields to prevent wrap point hazards (Murphy 1992). Statistical studies have been conducted during the past few decades regarding these hazards. The results have indicated that PTO entanglements continue to be among the most serious of all agricultural hazards (Murphy 1992; Hyland-McGuire 1994; Beer and Field 2003; Beer et al. 2007). Solutions should be found to decrease the occurrence and risk of PTO entanglements.

Preliminary investigation of the factors contributing to the occurrence of PTO entanglements (including material type, material length, and angle of approach) was first conducted by Freeman et al. (2006). Their results indicated that lighter materials, such as cotton thread, could be more easily entangled than woven cotton lace or leather lace. They also found that approach angles of +90° and -90° (i.e., perpendicular to the rotating joint) yielded the greatest entanglement probability compared to the other approach angles tested (i.e., not perpendicular to the rotating joint). As might be expected, longer materials had a greater likelihood of becoming entangled than shorter materials. Freeman et al. (2006) did their experimental work with a PTO joint that was rotating at 540 rpm.

It is expected that several other factors might contribute to the probability of entanglement. The velocity at which loose clothing approaches the rotating joint could contribute to probability of entanglement. Other possible factors include the rotational speed of the joint, the joint angle, and the moisture content of the fabric (which is likely to change the coefficient of friction between the fabric and the PTO apparatus). The objective of this study was to determine the influence of approach velocity, approach angle, joint angle, material length, and material moisture content on the probability of entanglement for a PTO joint rotating at 1140 rpm.

2. MATERIALS AND METHODS

2.1 Experimental materials

Commercial yarn (95% cotton and 5% polyester) was selected for this study. Both dry and wet strands were tested. Moisture content of the wet strands was not measured, but a consistent procedure was used to wet the strands. Strands, wet to the point of dripping, were placed on filter paper for 5 min prior to their use as a test specimen. Three lengths of yarn were selected: 9, 12, and 15 cm below the midline of the PTO shaft.

2.2 Experimental apparatus and procedure

This study used methods similar to those used in previous research (Judge 2004; Freeman et al. 2006). An apparatus was developed (Fig. 1) to pass strands through the spinning knuckle from both perpendicular directions (+90° and -90°) in the horizontal plane. The approach route was designed to be vertical to the straight shaft and through the middle of the knuckle. Two different approach velocities were chosen: 10 and 50 cm/min. The approach velocities were controlled precisely by a screw mechanism. Yarn was hung using a clip assembly; gravity kept the strand vertical. The clip assembly attached to the end of the moving screw allowed the yarn to be drawn across the knuckle. The clip assembly was required to easily release the strand of yarn if entanglement occurred; a paper clip was used to achieve this purpose. The joint angle could be changed in the horizontal plane. Along with the straight shaft condition (0°), another two joint angles (+16°, -16°) were tested during the experiments. The rotational speed of the PTO motor was constant during the experiments at 1140 rpm. The direction of rotation was clockwise (when looking toward the electric motor from the shaft). Each set of experimental conditions was replicated 10 times for a total of 720 trials. Data were recorded in binary format (i.e., 0 for no entanglement and 1 for entanglement).

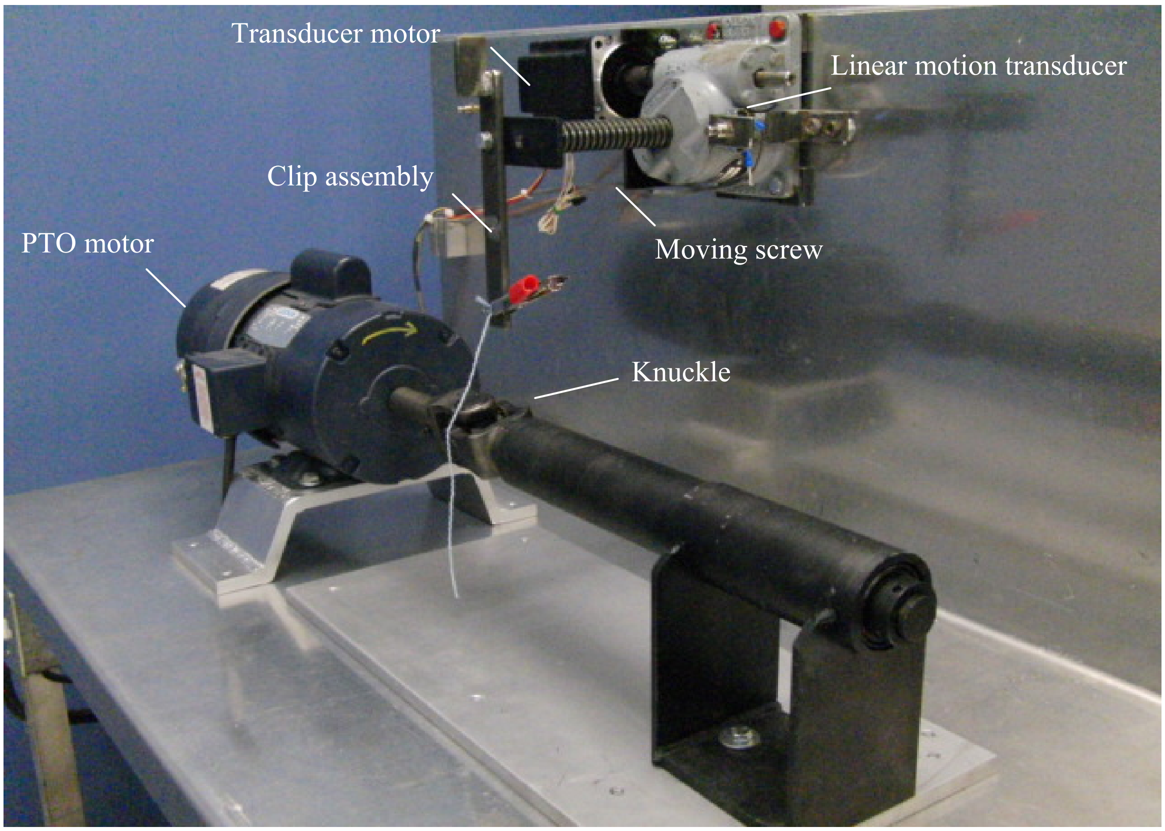

Figure 1. Experimental apparatus used to expose a hanging strand of yarn to a rotating PTO knuckle.

3. RESULTS

A total of 258 entanglements occurred out of 720 trials. Results are reported for dry strands of yarn (Table 1) and wet strands of yarn (Table 2). Overall, entanglements occurred in 35.8% of trials. All entanglements occurred on the downward rotation side, which is consistent with results from Freeman et al. (2006). Even when the strand of yarn was being introduced from the +90º approach angle, the yarn first had to be flipped over the knuckle before it would become entangled.

To interpret the experimental data, the data were sorted according to the following five categories: material moisture content, joint angle, approach angle, approach velocity, and material length (Table 3).

Table 1. Number of entanglements (out of 10 trials) for dry strands of yarn.

Joint Angle	Approach Angle	Approach Velocity	Material Length Below Midline		
			9 cm	12 cm	15 cm
+16°	-90°	10 cm/min	0	1	1
		50 cm/min	0	0	0
	+90°	10 cm/min	0	0	0
		50 cm/min	0	0	0
0°	-90°	10 cm/min	6	8	10
		50 cm/min	3	7	10
	+90°	10 cm/min	2	2	4
		50 cm/min	1	1	1
-16°	-90°	10 cm/min	9	10	10
		50 cm/min	8	9	10
	+90°	10 cm/min	5	6	6
		50 cm/min	3	4	1

Among the 360 trials using dry strands of yarn, 138 (38.3%) entanglements occurred. By comparison, only 120 (33.3%) entanglements (out of 360 trials) occurred for wet strands of yarn. Among all 258 entanglements, 53.5% occurred with dry strands of yarn and 46.5% occurred with wet strands of yarn. The moisture content of the yarn does not seem to be a major factor contributing to entanglement.

With respect to joint angle, only 7 (2.9%) entanglements out of 240 trials occurred when the joint angle was +16°. With a joint angle of 0°, 110 (45.8%) entanglements were recorded. The joint angle of -16° led to 141 (58.8%) entanglements during 240 trials. The small number of entanglements at the positive joint angle is worthy of further investigation.

Table 2. Number of entanglements (out of 10 trials) for wet strands of yarn.

Joint Angle	Approach Angle	Approach Velocity	Material Length Below Midline		
			9 cm	12 cm	15 cm
+16°	-90°	10 cm/min	1	1	2
		50 cm/min	0	0	1
	+90°	10 cm/min	0	0	0
		50 cm/min	0	0	0
0°	-90°	10 cm/min	7	10	10
		50 cm/min	5	10	10
	+90°	10 cm/min	1	1	1
		50 cm/min	0	0	0
-16°	-90°	10 cm/min	10	10	10
		50 cm/min	8	10	10
	+90°	10 cm/min	0	1	0
		50 cm/min	0	0	1

There were 41 (11.4%) entanglements recorded during the 360 trials in which materials were introduced from +90°. There was a considerable increase in number of entanglements with a -90° approach angle (217 entanglements or 60.3% of the entanglements).

Entanglements occurred in 145 (40.3%) of the 360 tests with the approach velocity of 10 cm/min. When materials were introduced with a faster speed of 50 cm/min during the other 360 trials, 113 (31.4%) entanglements were recorded. Overall, the lower approach velocity allowed greater contact time between the strand of yarn and the rotating knuckle. With greater contact time, the probability of entanglement is expected to increase.

Materials with a length of 9 cm below the midline of the shaft became entangled 69 (28.8%) times, while the lengths of 12 cm and 15 cm became entangled 91 (37.9%) and 98 (40.8%) times, respectively. The results display a linear trend, with a higher proportion of entanglements occurring as strand length increased.

Table 3. Statistical summary of five comparison groups.

Comparison Group	Condition	Number of Entanglements/ Number of Trials
Material moisture	Dry	138/360 (38.3%)
	Wet	120/360 (33.3%)
Joint angle	+16°	7/240 (2.9%)
	0°	110/240 (45.8%)
	-16°	141/240 (58.5%)
Approach angle	+90°	41/360 (11.4%)
	-90°	217/360 (60.3%)
Approach velocity	10 cm/min	145/360 (40.3%)
	50 cm/min	113/360 (31.4%)
Material length	9 cm	69/240 (28.8%)
	12 cm	91/240 (37.9%)
	15 cm	98/240 (40.8%)
Overall	-	258/ 720 (35.8%)

4. DISCUSSION

The approach angle of -90° has a higher probability of inducing entanglements than the +90° approach angle. Figure 2 shows the proportion of the entanglements related to the two approach angles for each of the other four factors evaluated. These observed results disagree with those previously reported by Freeman et al. (2006) who found that the number of entanglements occurring at approach angles -90° and +90° were nearly the same.

Based on the observations of this study, all entanglements occurred at the jaws of either Cardan joint of the knuckle instead of the junction area of the two parts (Fig. 3). When materials are introduced from +90°, the occurrence of entanglement relies mostly on the possibility of material being tossed over the knuckle. Weight of the material is the key factor in these cases. However, for the approach angle of -90°, vibration of the material at the rotating knuckle leads to entanglements.

According to the number of entanglements observed using dry and wet cotton yarn, dry materials have a higher probability of becoming entangled. However, among the 138 entanglements occurring with dry materials, 102 occurred when the material was introduced from -90º and 36 occurred when the material was introduced from +90º. For wet materials, 115 of the 120 entanglements occurred when the yarn was introduced from -90°, and only 5 occurred from the other approach angle. Thus, wet strands of yarn are more likely to become entangled when introduced from the -90° direction than dry strands of yarn, and have very low probability of becoming entangled when introduced from the +90° direction.

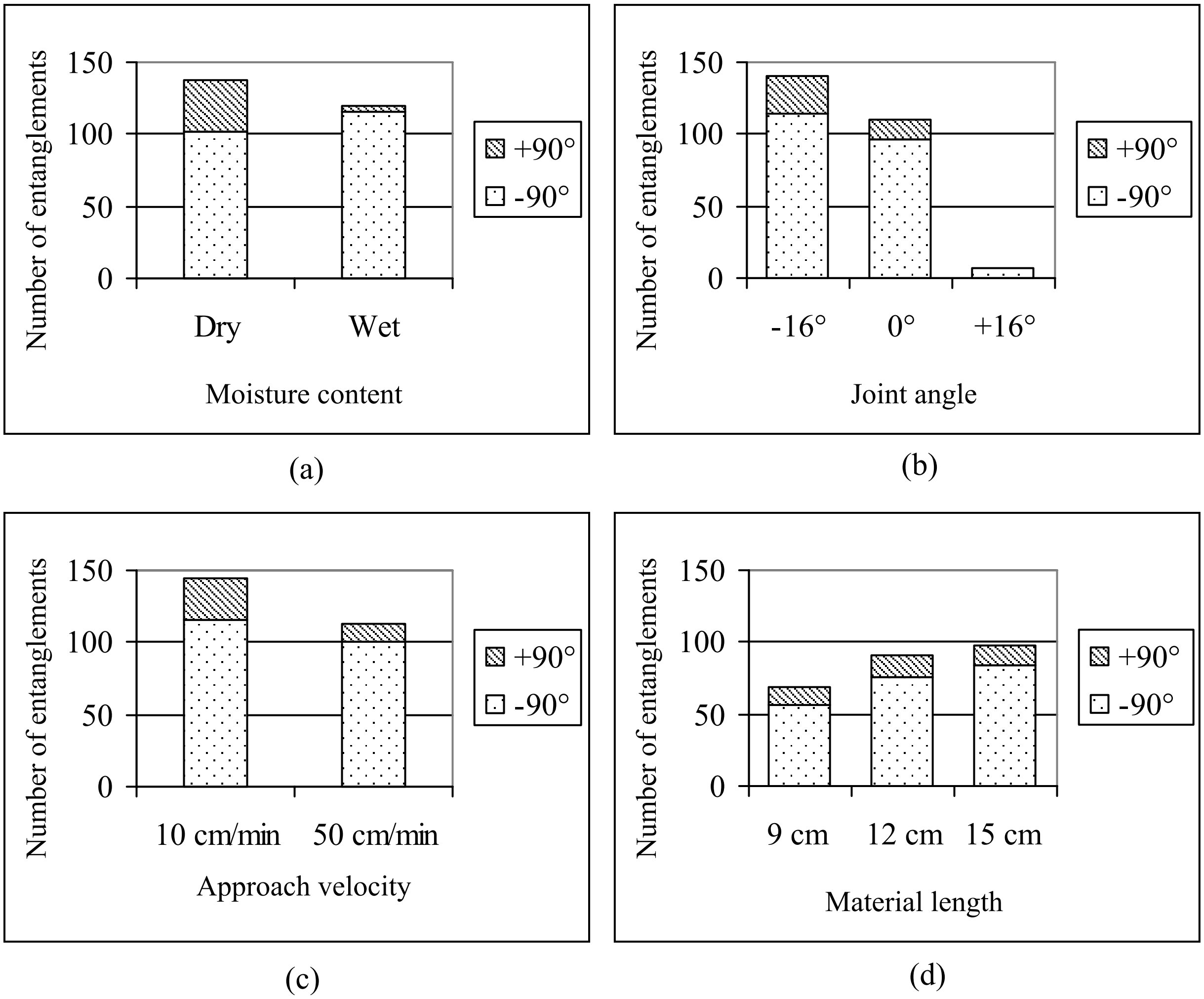

Figure 2. Distribution of number of entanglements at +90° and -90° approach angles in each comparison group: (a) Material moisture content; (b) Joint angle; (c) Approach velocity; (d) Material length

This difference might be explained by the different sequence of events that led to entanglement for the two approach angles. When materials were introduced from -90°, the threads contacted the spinning knuckle on the downward rotation side. The continuous contact caused entanglement to occur in some situations. For the +90° approach angle, materials were introduced to the knuckle and contacted the knuckle on the upward rotation side first. Entanglements only occurred when the rotation of the knuckle tossed the materials over the joint and then entangled the threads underneath. The heavier wet yarn could not be easily tossed by the knuckle, thus decreasing the likelihood of entanglement. In some cases, the yarn was thrown up into the air and dropped to the downward rotation side. In most cases when this occurred, the yarn was dropped far enough away from the knuckle to provide little chance of entanglement.

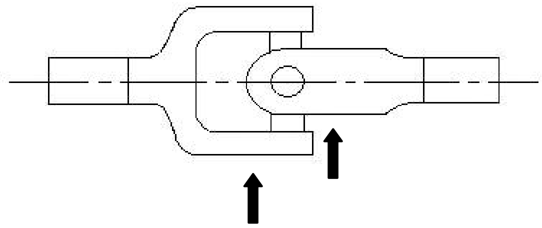

Figure 3. Positions where entanglements occurred at the knuckle

Of the five factors that were studied, the results of joint angle were most surprising. It is not known why so few entanglements occurred at a joint angle of +16°. It was observed that the rotating PTO shaft created air movement that tended to cause the strand of yarn to "vibrate" against the rotating shaft. It is hypothesized that the amount of air movement, or perhaps the degree of turbulence of the air, varies with joint angle. Figure 4 illustrates what may be happening at the rotating knuckle. For knuckles with a joint angle of +16°, the airstream may be limiting the swing distance experienced by the yarn (reducing the probability of entanglement). Joint angles of 0° and -16° provide much more free space for vibration, so the yarn can be easily induced to entanglement positions. To further investigate the influence of joint angle on probability of entanglement, a follow-up study was conducted.

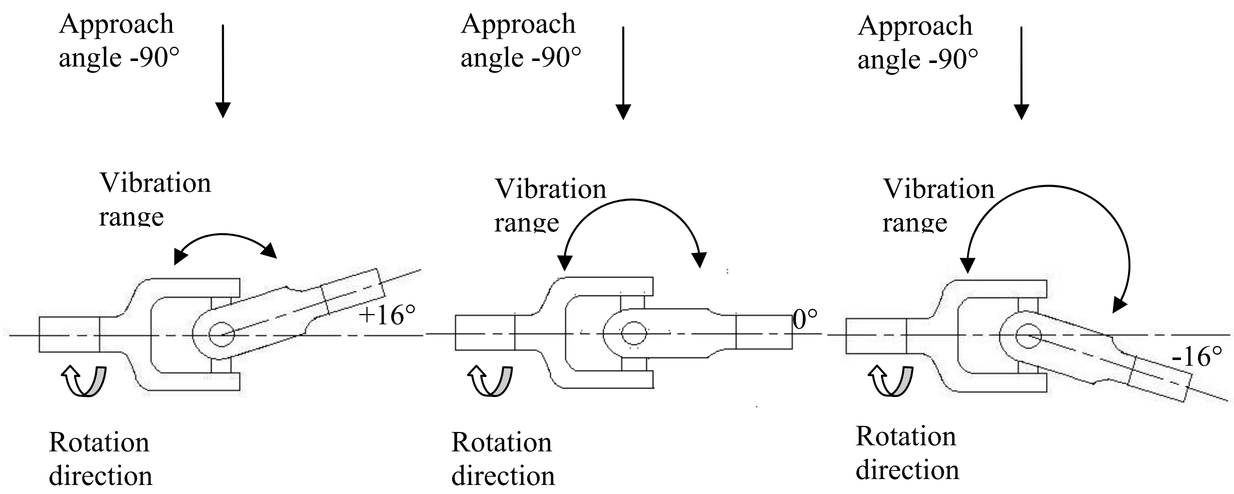

Figure 4. Vibration ranges at the spinning knuckle with different joint angles (Top view)

5. FOLLOW-UP STUDY

5.1 Experimental methods

In the follow-up study, the material used was 100% cotton yarn. Samples were kept dry throughout testing. Only one length of yarn was tested: 15 cm below the midline of the PTO shaft, and the approach velocity was held constant at 10 cm/min. These two conditions were chosen because they were the ones leading to the most entanglements in the original study.

The apparatus used for the follow-up study was the same one as used in the original study. Cotton yarn was introduced to the PTO knuckle at angles -90º and +90º in the horizontal plane, with a speed of 10 cm/min. The yarn was attached to the clip assembly at the end of the moving screw. The only modification was the use of a binder clip in the follow-up study instead of the alligator clip used in the original study. The rotation speed was maintained at 1140 rpm.

The joint angles tested were +20º, +16º, +12º, +8º, +4º, 0º, -4º, -8º, -12º, -16º, and -20º. Each combination of approach angle and joint angle was tested 10 times, giving a total of 220 trials.

5.2 Results

Out of 220 trials, there were 134 entanglements. Table 4 displays the number of entanglements for each condition. Overall, entanglements occurred in 60.9% of trials. It is reasonable that a greater proportion of entanglements occurred than observed in the original study because the slowest approach velocity and longest yarn length were used in the follow-up study. As with the original study, entanglements only occurred on the downward rotation side. More than two-thirds (i.e., 67.9%) of the observed entanglements occurred with an approach angle of -90º.

Table 4. Number of entanglements (out of 10 trials) in follow-up study.

Joint Angle	Approach Angle	Entanglements
+20º	-90º	10
	+90º	0
+16º	-90º	6
	+90º	0
+12º	-90º	3
	+90º	1
+8º	-90º	2
	+90º	0
+4º	-90º	10
	+90º	2
0º	-90º	10
	+90º	2
-4º	-90º	10
	+90º	3
-8º	-90º	10
	+90º	8
-12º	-90º	10
	+90º	9
-16º	-90º	10
	+90º	8
-20º	-90º	10
	+90º	10

Data from both the original study and the follow-up study were graphed with respect to joint angle (Figs. 5 and 6). With an approach angle of +90º, the percentage of entanglements decreased as the joint angle changed from -20º to +20º (Fig. 5). At the joint angle of -20º, all ten trials resulted in an entanglement, whereas with a joint angle of +20º, there were no entanglements. With an approach angle of -90º, the trials conducted with joint angles -20º to +4º resulted in 100% entanglement. At +8º, the entanglement percentage suddenly dropped to 20%. With further increase in joint angle, the percentage of entanglements increased (Fig. 6).

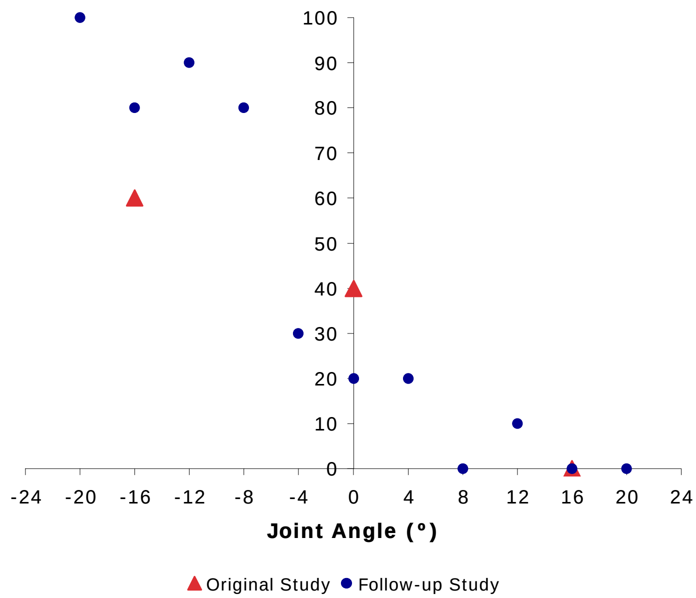

Figure 5. Percentage of entanglements observed with an approach angle of +90°.

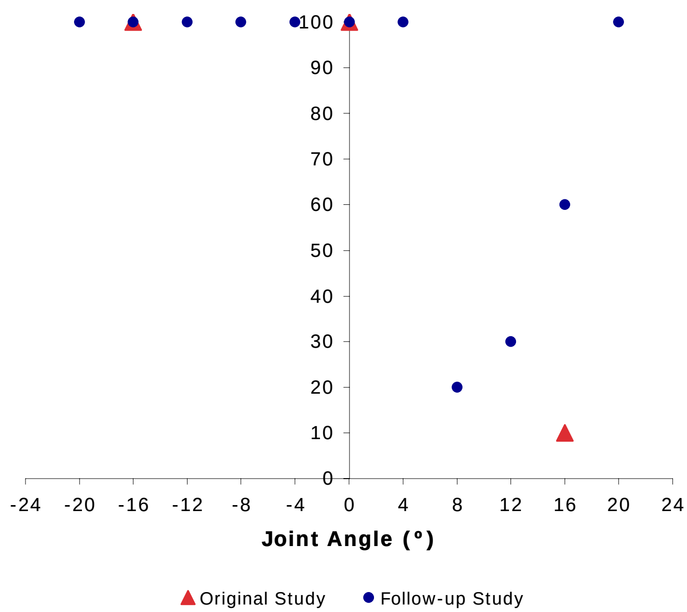

Figure 6. Percentage of entanglements observed with an approach angle of -90°.

6. CONCLUSION

All entanglements occurred at the jaws of Cardan joints. Approach angles of -90° and +90° have different entanglement mechanisms. Materials introduced from -90° have a much higher probability of becoming entangled than those introduced from +90°. Wet materials are more easily wrapped around the knuckle for -90° conditions, but have a lower likelihood of entanglement compared to dry conditions when introduced from +90° direction due to increased weight. Approach velocity determines the contact time. Slower speeds provide more contact time between the material and the PTO joint knuckle, which leads to a higher probability of entanglement. Longer materials have a higher possibility of becoming tangled. Joint angle plays an important role in determining the probability of entanglement. With an approach angle of +90º, the percentage of entanglements decreased as the joint angle changed from -20º to +20º. With an approach angle of -90º, the trials conducted with joint angles -20º to +4º resulted in 100% entanglement. At +8º, the entanglement percentage suddenly dropped to 20%. With further increase in joint angle, the percentage of entanglements increased in an exponential fashion.

7. RECOMMENDATIONS FOR FUTURE RESEARCH

This research has suggested that possibility that joint angle might be used to reduce the probability of PTO entanglements. Further investigation is needed to explain this observation.

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REFERENCES

Srivastava, A. K., C. E. Goering, and R. P. Rohrbach. 1993. Engineering principles of agricultural machines. ASAE Textbook Number 6, LCCN 92-73957; ISBN 0-929355-33-4.

Hunt, D. R., and L. W. Garver. 1973. Farm machinery mechanisms. The Iowa State University Press. First edition. Ames, Iowa 50010.

Murphy, D. J. 1992. Safety and health for production agriculture. ASAE Textbook Number 5. First edition.

Hyland-Mcguire, P. 1994. Farm accidents involving power take-off devices. Journal of Accident and Emergency Medicine, 11(2): 121-124.

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.

Beer, S. R., G. R. Deboy, and W. E. Field. 2007. Analysis of 151 agricultural driveline-related incidents resulting in fatal and non-fatal injuries to U.S. children and adolescents under age 18 from 1970 through 2004. Journal of Agricultural Safety and Health, 13(2): 147-164.

Freeman, S. A., C. V. Schwab, and J. L. P. Judge. 2006. An investigation of three physical parameters of PTO entanglements. Journal of Agricultural Safety and Health, 12(3): 191−197.

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