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# Factors contributing to single yarn entanglement around a Cardan joint rotating at high speed

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Xu, J., A. Kroeker and D.D. Mann. 2010. **Factors contributing to single yarn entanglement around a Cardan joint rotating at high speed.** Canadian Biosystems Engineering/Le génie des biosystèmes au Canada. 52: 2.17–2.21. Entanglements around rotating power take-off shafts continue to cause farm injuries. Research is necessary to understand the factors that contribute to entanglements so that, if possible, design modifications can be made to reduce their probability. In this study, five parameters (material moisture content, joint angle, approach direction, approach velocity, and material length) were investigated using a Cardan joint rotating at 1140 rpm. A total of 258 entanglements occurred out of 720 trials; all entanglements occurred at the jaws of the Cardan joints. Of the two approach directions tested, entanglements were more likely to occur when the periphery of the rotating joint moved toward the free end of the hanging yarn. The moisture content of the yarn does not seem to contribute to the probability of entanglement for single strands of yarn. Long strands of yarn tended to be entangled more readily than short strands of yarn. More entanglements occurred with an approach speed of 10 cm/min than with an approach speed of 50 cm/min. Joint angle plays an important role in determining the probability of entanglement for a single strand of yarn. Positive joint angles cause fewer entanglements than negative joint angles. Further investigation is needed to explain this observation. **Keywords:** Power take-off, entangle, joint angle.

L'enroulement autour des arbres de prise de force en rotation continue d'être une cause de blessures sur la ferme. Il est nécessaire de poursuivre les recherches sur les facteurs qui contribuent aux enroulements et, si possible, de modifier la conception de ces mécanismes de transmission de puissance pour réduire les risques d'enroulement. Dans cette étude, cinq paramètres (teneur en eau du matériel, angle du joint universel, direction d'approche, vitesse d'approche et longueur du matériel) ont été étudiés en utilisant un joint Cardan ayant une vitesse de rotation de 1 140 tpm. Au total, 258 enroulements sont survenus durant le cours des 720 essais réalisés; tous les enroulements sont survenus au niveau des mâchoires du joint Cardan. Des deux directions d'approche évaluées, les enroulements étaient le plus susceptible de survenir lorsque la périphérie du joint en rotation se déplaçait vers la fin du fil. La teneur en eau du fil n'a pas semblé contribuer à la probabilité d'enroulement pour les fibres individuelles du fil. Les longues fibres du fil avaient tendance à s'emmêler plus facilement que les fibres plus courtes. Une vitesse d'approche de 10 cm/min a résulté en un plus grand nombre d'enroulement qu'une vitesse d'approche de 50 cm/min. L'angle du joint joue un rôle important dans la détermination de la probabilité de l'enroulement pour un fil de fibre simple. Des angles positifs pour le joint causait moins d'enroulements que des angles négatifs. Une recherche plus poussée est nécessaire pour expliquer cette observation. **Mots clés:** prise de force, enrouler, angle du joint.

## 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). Cardan joints are used in PTO drivelines to achieve load transmission between input and output shafts with angular misalignments (Hunt and Garver 1973).

Power take-off 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 Cardan joint 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 Cardan joint entanglements.

Preliminary investigation of the factors contributing to the occurrence of Cardan joint 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 the greatest probability of entanglement occurred when the material's horizontal path of travel was perpendicular to the centerline of the Cardan 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 Cardan joint that was rotating at 540 rpm.

It is expected that several other factors might contribute to the probability of entanglement. The length of material hanging below the midline of the joint and the velocity at which the material approaches the rotating joint both affect the nature of the contact between the hanging material and the rotating Cardan joint (i.e., the length of material available to contact the rotating joint and the duration of the contact with the rotating joint). The coefficient of friction between the material and the rotating Cardan joint is another relevant characteristic. Previous researchers have reported that moisture can change the coefficient of friction of fabrics (Gupta and Mogahzy 1991; Sukigara 2002; Hes et al. 2008); therefore, moisture content might affect the probability of entanglement with a rotating Cardan joint. Other possible factors include the material stiffness, the peripheral speed of the

joint, and the joint angle. 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 Cardan joint rotating at 1140 rpm.

## MATERIALS and METHODS

### Experimental materials

Commercial yarn composed of 95% cotton and 5% polyester (Promofil 02-3006341) was selected for this study. The yarn is a single strand with an approximate diameter of 2 mm. Both dry and wet strands were tested. The 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 (considered as saturated with water), were placed on filter paper for 5 min prior to their use as test specimens. Three lengths of yarn were selected: 9, 12, and 15 cm. Yarn length is defined as the length of material hanging below the horizontal midline plane of the Cardan joint.

### 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 of freely hanging yarn over the rotating Cardan joint from both perpendicular directions ( $+90^\circ$  and  $-90^\circ$ ) in the horizontal plane as shown in Fig. 2. The approach route was designed to be vertical to the straight shaft and through the middle of the joint. 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 that would easily release the yarn if entanglement occurred; gravity kept the strand vertical. The clip assembly attached to the end of the moving screw allowed the yarn to be drawn across the rotating joint. The joint angle could be changed in the horizontal plane. Along with the straight shaft condition ( $0^\circ$ ), another two joint angles ( $+16^\circ$ ,  $-16^\circ$ ) were tested during the experiments (Fig. 2). From a top view, a positive joint angle occurs when the joint has been bent counter-clockwise; a negative joint angle occurs when the joint has been bent clockwise. The rotational speed of the PTO motor was constant at 1140 rpm during the experiments. 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).

## RESULTS and DISCUSSION

A total of 258 entanglements occurred out of 720 trials (35.8% of trials). All entanglements occurred when the periphery of the joint moved toward the free end of the yarn, which is consistent with results from Freeman et al. (2006). Even when the strand of yarn was introduced from the opposite side ( $+90^\circ$  approach angle), the yarn first had to be flipped over the joint before it became entangled. Based on the observations of this study, all entanglements

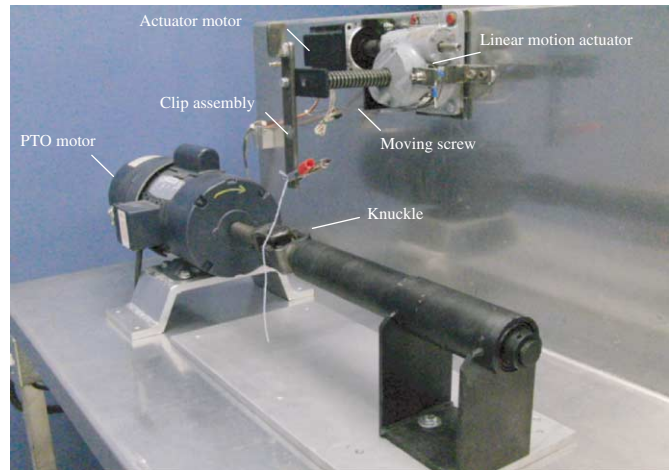


Fig. 1. Experimental apparatus used to expose a hanging strand of yarn to a rotating Cardan joint.

occurred at the jaws of either Cardan joint instead of the junction area between the two jaws (Fig. 3). 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 1).

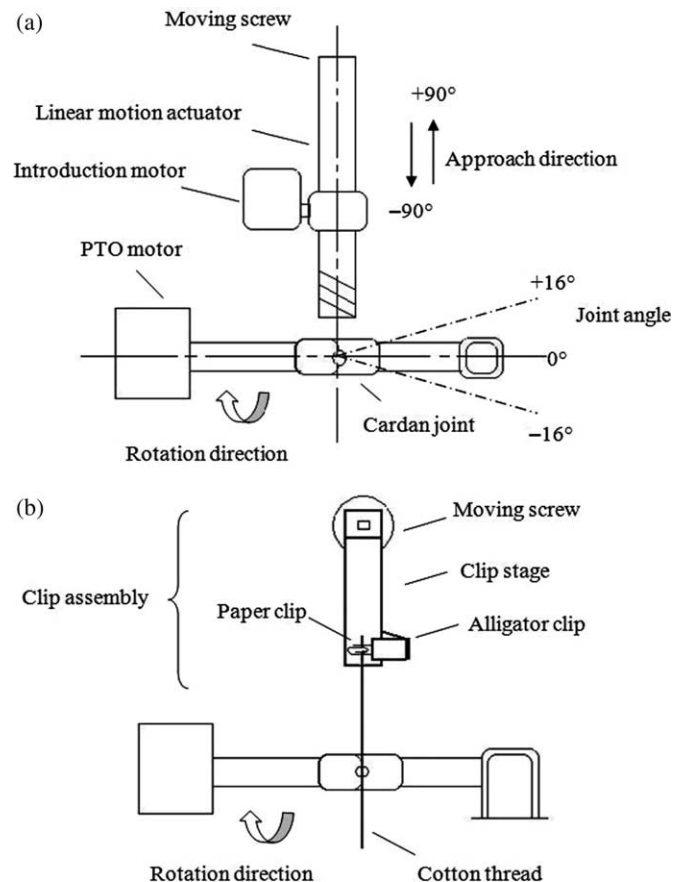
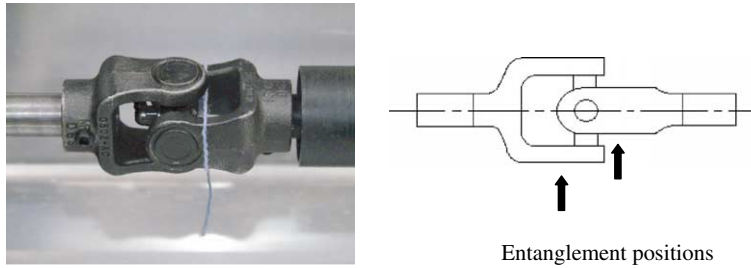


Fig. 2. Scheme of the experimental apparatus. (a) Top view. (b) Front view.



**Fig. 3. Positions where entanglements occurred at the joint.**

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.

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

There were 41 (11.4%) entanglements recorded during the 360 trials in which materials were introduced from  $+90^\circ$ . There was a considerable increase in the number of entanglements with a  $-90^\circ$  approach angle (217 entanglements out of 360 or 60.3%). These observed results disagree with those previously reported by Freeman et al. (2006), who found that the number of entanglements occurring at approach angles  $-90^\circ$  and  $+90^\circ$  were nearly the same. When materials were introduced from  $-90^\circ$ , the yarn contacted the rotating joint on the downward rotation side which, caused “bouncing” of the yarn. Entanglement happened in some cases due to this continuous bouncing action. For the  $+90^\circ$  approach angle, materials were introduced to the joint and contacted the joint on the upward rotation side first. Entanglements only occurred when the rotation of the joint tossed the yarn over the joint and then entangled the yarn

underneath. In most cases, however, the yarn was dropped far enough away from the joint to provide little chance of entanglement. Figure 4 shows the proportion of the entanglements related to the two approach angles for each of the other four factors evaluated.

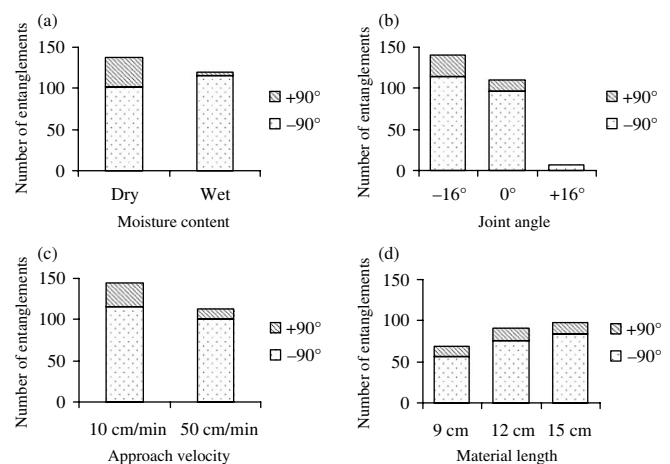
Entanglements occurred in 145 (40.3%) of the 360 tests with the approach velocity of 10 cm/min. When materials were introduced with a faster speed of 50 cm/min during the other 360 trials, 113 (31.4%) entanglements were recorded. Overall, the lower approach velocity allowed greater contact time between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

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  $+16^\circ$ . It was observed that the rotating Cardan joint created air movement that moved the strand of yarn. To further investigate the influence of joint angle on probability of entanglement, a follow-up study was conducted.

**Table 1. 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	$+16^\circ$	7/240 (2.9%)
	$0^\circ$	110/240 (45.8%)
	$-16^\circ$	141/240 (58.5%)
Approach direction	$+90^\circ$	41/360 (11.4%)
	$-90^\circ$	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%)



**Fig. 4. Distribution of number of entanglements at  $+90^\circ$  and  $-90^\circ$  approach directions in each comparison group: (a) Material moisture content; (b) Joint angle; (c) Approach velocity; (d) Material length.**

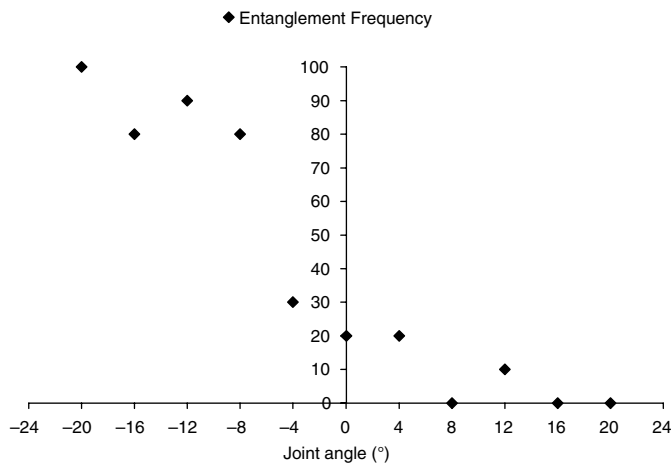
## FOLLOW-UP STUDY

The objective of the follow-up study was to focus on the effect of the joint angle. The material used was 100% cotton yarn (Bernat Handicrafter Cotton) because the previous yarn was unavailable. Samples were kept dry throughout testing. Only one length of yarn was tested: 15 cm below the midline of the Cardan joint, and the approach velocity was held constant at 10 cm/min.

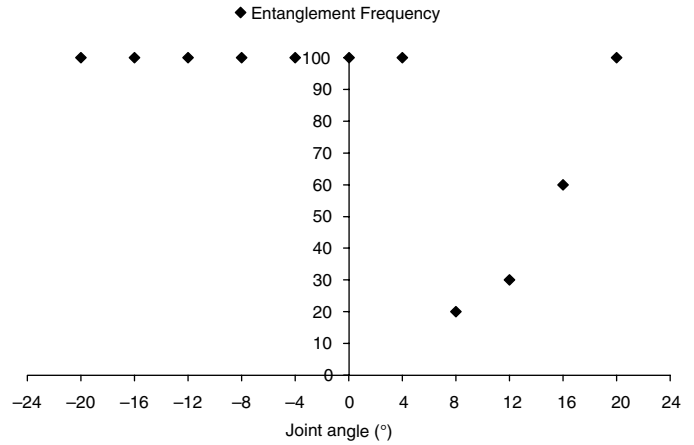
The apparatus used for the follow-up study was the same one as used in the original study. Cotton yarn was introduced to the Cardan joint at angles of  $-90^\circ$  and  $+90^\circ$  in the horizontal plane, with a speed of 10 cm/min. The rotation speed was maintained at 1140 rpm. The joint angles tested were  $+20^\circ$ ,  $+16^\circ$ ,  $+12^\circ$ ,  $+8^\circ$ ,  $+4^\circ$ ,  $0^\circ$ ,  $-4^\circ$ ,  $-8^\circ$ ,  $-12^\circ$ ,  $-16^\circ$ , and  $-20^\circ$ . Each combination of approach angle and joint angle was tested 10 times, giving a total of 220 trials.

Out of 220 trials, there were 134 entanglements. Overall, entanglements occurred in 60.9% of trials. More than two-thirds (i.e., 67.9%) of the observed entanglements occurred with an approach angle of  $-90^\circ$ . Data from the follow-up study were graphed with respect to joint angle (Figs. 5 and 6). With an approach angle of  $+90^\circ$ , the percentage of entanglements decreased as the joint angle changed from  $-20^\circ$  to  $+20^\circ$  (Fig. 5). At the joint angle of  $-20^\circ$ , all 10 trials resulted in an entanglement, whereas with a joint angle of  $+20^\circ$ , there were no entanglements. With an approach angle of  $-90^\circ$ , the trials conducted with joint angles from  $-20^\circ$  to  $4^\circ$  resulted in 100% entanglement. At  $+8^\circ$ , the entanglement percentage dropped to 20%. With further increase in joint angle, the percentage of entanglements increased (Fig. 6).

The results from the follow-up study show that joint angle is an important factor associated with entanglements around rotating Cardan joints. Without detailed investigation of the microenvironment surrounding a rotating Cardan joint, it is impossible to provide an explanation for



**Fig. 5. Percentage of entanglements observed with an approach angle of  $+90^\circ$  (10 replications for each joint angle).**



**Fig. 6. Percentage of entanglements observed with an approach angle of  $-90^\circ$  (10 replications for each joint angle).**

the results that have been observed. One hypothesis is that the amount of air movement surrounding the Cardan joint, or perhaps the degree of turbulence of the air, varies with joint angle.

One important limitation of this research is that a single strand of yarn was used during all the experiments. It is unknown whether the results can be scaled up from a single strand of yarn to an actual garment.

## CONCLUSIONS

All entanglements occurred at the jaws of the Cardan joints. Entanglements occurred when the periphery of the rotating joint moved toward the free end of the hanging yarn. The moisture content of the yarn does not seem to be a major factor contributing to entanglement. Longer materials with slower approach speed tended to be entangled more readily than short materials at greater approach speed. Joint angle plays an important role in determining the probability of entanglement for a single strand of yarn. Positive joint angles cause fewer entanglements than negative joint angles. Further investigation is needed to explain this observation.

## ACKNOWLEDGEMENTS

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