Likelihood of Entanglement when Materials are Dropped Vertically onto a Rotating PTO Knuckle

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Abstract
Power take-off (PTO) is a common method of transferring power from a tractor to a towed piece of machinery. The PTO is also a well-documented cause of severe and often permanent disabling injuries to farm operators. The physical conditions that cause entanglements are not well established. Several studies have explored the parameters of PTO entanglements as materials have been drawn across a rotating PTO knuckle to test for entanglement probability. The objective of this study was to determine probability of entanglement when materials are dropped vertically onto a PTO knuckle spinning at 540 rpm. A total of 360 randomized trials were conducted with ten replications for each of the six positions (center of yoke, edge of yoke rotating downward, edge of yoke rotating upward, center of cross, edge of cross rotating downward, and edge of cross rotating upward) and six different materials (woven cotton athletic shoe lace, cotton workboot lace, leather workboot lace, cotton twine, denim strip, and Tyvek strip). Not a single entanglement was recorded. Dramatic high-speed video imagery authenticated the material's motion and path as it interacted with the rotating PTO knuckle.

Keywords
Accident prevention, Farm safety, Probability, PTO, Safety

Disciplines
Agriculture | Bioresource and Agricultural Engineering | Ergonomics | Occupational Health and Industrial Hygiene | Operational Research

Comments
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C. V. Schwab, I. J. Rempe

ABSTRACT. Power take-off (PTO) is a common method of transferring power from a tractor to a towed piece of machinery. The PTO is also a well-documented cause of severe and often permanent disabling injuries to farm operators. The physical conditions that cause entanglements are not well established. Several studies have explored the parameters of PTO entanglements as materials have been drawn across a rotating PTO knuckle to test for entanglement probability. The objective of this study was to determine probability of entanglement when materials are dropped vertically onto a PTO knuckle spinning at 540 rpm. A total of 360 randomized trials were conducted with ten replications for each of the six positions (center of yoke, edge of yoke rotating downward, edge of yoke rotating upward, center of cross, edge of cross rotating downward, and edge of cross rotating upward) and six different materials (woven cotton athletic shoe lace, cotton workboot lace, leather workboot lace, cotton twine, denim strip, and Tyvek strip). Not a single entanglement was recorded. Dramatic high-speed video imagery authenticated the material’s motion and path as it interacted with the rotating PTO knuckle.

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Beer et al. (2007) conducted a review and provided a summary of prior research on PTO and driveline-related injuries. A total of 911 events were reported, and 400 fatalities were connected to PTO or drivelines entanglements using published studies by Knapp and Piercy (1966), McKnight (1984), Wilkinson (1991), and Beer and Field (2005). These events and fatality totals illustrate the common occurrence of PTO and driveline entanglements.

Freeman et al. (2006) investigated three physical parameters (type of material, length of material, and angle of introduction) that affect PTO entanglement probability. They reported that lighter materials were more readily entangled, an introduction angle perpendicular to the shaft was more likely to result in entanglement, and the likelihood of entanglement increased as the material length extended below the midline of the shaft. Another PTO entanglement study by Xu et al. (2010) examined a PTO shaft rotating at high speed and with different joint angles. The researchers concluded that the joint angle of the yoke greatly influenced the probability of entanglement, and a slower speed for material intro-
duction increased the probability of entanglement. Xu et al. (2010) confirmed the findings of Freeman et al. (2006) that the likelihood of entanglement increased as the material length increased.

A common feature of the two studies on PTO entanglement is how the material was introduced to the rotating PTO knuckle. The material was dragged across the rotating PTO knuckle at a set speed. This procedure can account for how materials are introduced to a rotating PTO knuckle in everyday events, but it does not cover all possible events. Another introduction procedure could be a vertical drop onto a rotating PTO knuckle. This study examines the likelihood of entanglement of materials that are dropped vertically into a PTO knuckle rotating at 540 rpm.

**Methods**

**Samples**

Six different materials were selected as samples for this study. These samples are representative of materials that could be associated with activities near a PTO knuckle. The samples were: (1) a common woven cotton athletic shoe lace, (2) a compact woven workboot lace, (3) a square leather workboot lace, (4) a braided cotton cord, (5) a strip of denim jean fabric, and (6) a strip of Tyvek. All experimental samples were 43 cm (17 in.) in length. The physical surface characteristics and relative size of these samples are shown in figure 1.

**Locations**

This study selected six positions along the PTO knuckle as intended initial impact locations. These six positions and the direction of rotation for the PTO knuckle are shown in figures 2 and 3. Locations A and B are on the center line of the rotating shaft (fig. 2). Locations C, D, E, and F distinguish between the trailing edge and leading edge of the yoke arm (fig. 3). The difference between locations C and E is whether the edge of the yoke arm is moving toward the sample (leading) or moving away from the sample (trailing). The leading edge of the yoke arm is rising to meet the dropping sample, whereas the trailing edge of the yoke arm is falling away from the approaching sample. Locations D and F have a similar relationship as C and E with the trailing edge and leading edge of the yoke arm.

![Figure 1. Relative shape and construction of the six samples used in the experiments.](image-url)
Experimental Design
This study examined six samples introduced at six locations along the PTO knuckle (6 samples × 6 locations), for a total of 36 experimental conditions. Each condition was replicated ten times, for a total of 360 tests. The sequence of testing was governed by a complete randomization of sample and location variables, which was achieved using a spreadsheet and random number generator.

Experimental Apparatus
The experimental apparatus was the same as the apparatus described by Freeman et al. (2006), with some modifications to the components that suspended and introduced the samples to the rotating PTO knuckle. The motor, electronic control, frame, and PTO knuckle were not altered for this experiment.

The lead screw assembly and indexing plate were removed and replaced with a vertical drop mechanism. The vertical drop mechanism was centered over the top of the PTO shaft and secured. The vertical drop mechanism travels a distance of 56 cm (22 in.) and is 25 cm (10 in.) above the PTO knuckle. The sample and the vertical drop mechanism travel the 56 cm extension in 0.48 s, for an average speed of 117 cm s⁻¹. The experimental apparatus used in this study is shown in figure 4.

Recording Cameras
Two cameras (HERO4, Go-Pro, Inc., San Mateo, Cal.) were used to record video of each test run. One camera was mounted above and in-line with axis of the PTO shaft. The second camera was perpendicular to the axis of the PTO shaft and positioned facing the
The Go-Pro HERO4 features a wide-angle lens that allowed a complete image of each test. All videos were captured using WVGA resolution at 240 frames per second. With this high frame rate, it was possible to analyze the sample’s reaction to the PTO in more depth and clarity than would be possible with human eye observation or even with a standard video camera recording at 15 frames per second.

Experimental Procedure

The vertical drop mechanism was raised to the full drop height and secured in position with a release pin. Using the prescribed sample and impact location from the test randomization, the sample was placed in the appropriate clip on the vertical drop mechanism. The cameras at both positions were activated to record the test. A video marker board was used to tag the test sample, location, replication, and date. The power to the experimental apparatus was activated, causing the PTO knuckle to start rotating. After a few seconds, the PTO knuckle speed was tested with a tachometer. The preset speed of 540 rpm was desired. If the speed was outside the accepted range, the dial on the motor was adjusted accordingly. A second measurement of the speed was obtained with the tachometer. This process was repeated until the measured speed was within 7% of 540 rpm.

Figure 4. Experimental apparatus used in the vertical drop PTO entanglement study.
The release pin holding the vertical drop mechanism and sample was pulled. The vertical drop mechanism completed its downward path, engaging the sample with the rotating PTO knuckle. The outcome of the sample entangling with the PTO knuckle was recorded, as were any other observations that were made as the sample engaged the rotating PTO knuckle. Power to the experimental apparatus was then disconnected. After rotation had ceased, the sample was removed, and the vertical drop mechanism was reset for the next test.

Results

Impact Locations

The intended impact locations on the PTO knuckle were: (A) the gap between the yoke arms, (B) the center of the yoke arm, (C) the trailing edge of the yoke arm at position 1, (D) the trailing edge of yoke arm at position 2, (E) the leading edge of the yoke arm at position 1, and (F) the leading edge of the yoke arm at position 2. These intended locations were not always achieved. Because the PTO knuckle was spinning at 540 rpm, there was a chance that the dropped sample could hit another part of the PTO knuckle. There was no synchronization between the vertical drop speed, the time when the release pin was pulled, and the PTO knuckle rotational speed.

A video review was used to determine if the impact location was achieved because the real-time speed of the events created observational errors. The video review allowed accurate assessment of the impact location at the exact moment when the impact occurred. The likelihood of the sample landing on the intended impact location was close to 50%. Figure 5 shows the results of all 360 tests in contacting the intended impact location.

Acknowledging that the leading edge of the yoke arm (location E) is similar to location F and is just a different position (1 vs. 2) on the leading edge of the yoke arm, these results were combined for reporting the impact location observations. The same was true for the trailing edge of the yoke arm (locations C and D). If all intended impact locations were achieved, the expected distribution would be 60 for the gap between yoke arms.

Figure 5. Likelihood of sample landing on the intended impact location for all tests.
(location A), 60 for the center of the yoke arm (location B), 120 for the trailing edge of the yoke arm (locations C and D), and 120 for the leading edge of the yoke arm (locations E and F). Any tests in which the sample did not initially contact the PTO knuckle at one of the six locations were eliminated from the data set. There were 96 tests in which the sample did not contact the PTO knuckle or initially contacted another part of the PTO knuckle not previously described. Due to its wide surface area and lightweight material, sample 6 did not fall uniformly and had more tests in which it never contacted the PTO knuckle than any other sample. The actual distribution of the impact locations is shown in figure 6. Three of the four intended impact locations recorded lower values than expected, while one location, the center of yoke arm (location B), exceeded the expected value.

Initial Bend and Wrap Angles

The vertically positioned sample traveled downward until it contacted the PTO knuckle. After the initial point of contact, the sample was typically deflected or bounced to the side. The sample formed an angle from the initial vertical travel direction, which was identified as the initial bend angle. Figure 7a shows the deflected shape of a sample and the angle measurement that was superimposed on the video frame. A video frame review was used to determine the initial bend angle because the real-time speed of the events made it impossible to determine this angle in real time.

The sample continued its downward, outward path and typically wrapped around the PTO knuckle or swung out and then back, causing it to bend around the PTO knuckle. As the sample passed through to the other side of the vertical axis from which the initial bend angle was measured, it formed another angle with the vertical axis. This angle was identified as the wrap angle. Figure 7b shows the deflected shape of a sample and how the wrap angle was measured.

The initial bend and wrap angles for each sample were recorded, and the average values of these angles are shown in figure 8. Data from five tests were not included because the video records of those tests were damaged and could not be reviewed. Sample 4 had both the largest average initial bend angle and average wrap angle of all the samples. Sample 6 had the lowest average initial bend angle (9°) of all the samples. Due to its wide surface area and lightweight material, sample 6 was often moved by air currents or air resistance, which partly explains its low initial bend angle. Sample 6 was never observed to wrap around the PTO knuckle, so it does not have an average wrap angle.
Entanglement Outcome

No sample in all 360 tests was observed to entangle in the PTO knuckle. There were several tests in which entanglement was considered to be almost achieved, but the sample came back to a resting position against the PTO knuckle. The resting position for nearly all tests (91%) was on the trailing side (downward rotational side) of the PTO knuckle. In
3% of the tests, the sample remained on the leading side (upward rotational side) of the PTO knuckle, and the remaining 6% of the tests consisted of sample 6 missing contact with the PTO knuckle.

**Visual Observations of Samples**

Each of the 355 high-speed video records was reviewed one or more times. Video recordings from five tests were not available because the video record was damaged during transfer. The video recordings from the two camera locations (in-line with the axis of the PTO shaft and perpendicular to the axis of the PTO shaft) were synchronized and viewed as a split screen to show both views simultaneously. This permitted the observer to see how the sample interacted in two planes at the same moment. While it is impractical to present all the video imagery, highlights of tests with the six samples are shown in figures 9 through 14.

Sample 1 was observed to ride on top of the rotating PTO knuckle while bouncing up and down until it was tossed off to the downward side of rotation. This behavior is captured in figure 9 (timecode 13:01:58). Sample 1 was also observed to be bent by interaction with the PTO knuckle (timecode 13:07:13). Only four of the 522 captured frames that span from the first timecode (12:58:29) to the last timecode (13:07:13), equivalent to approximately 2.2 s of elapsed time, are shown in figure 9.

Samples 2 and 3 were stiff boot laces and were often observed to be tossed out and away from the PTO knuckle upon impact, as shown in figure 10 (timecode 9:34:07) and figure 11 (timecode 4:36:09). These samples then swung back into contact with the PTO knuckle and bounced around until the test was stopped. An example of a return contact with the PTO knuckle is shown in figure 11 (timecode 4:40:56). Only four of the 334 captured frames from the first timecode (9:32:38) to the last timecode (9:38:12), equivalent to approximately 1.4 s of elapsed time, are shown in figure 10. Figure 11 shows only four of 400 captured frames, equivalent to approximately 1.7 s of elapsed time.

Sample 4 often wrapped around the rotating PTO knuckle but never became entangled. Figure 12 (timecode 2:51:58) shows how the sample wrapped around the PTO knuckle. In some tests, sample 4 remained partially wrapped around the PTO knuckle for multiple revolutions until it was tossed out and away, as shown in figure 12 (timecode 2:53:18). Figure 12 shows only four of 157 captured frames, equivalent to approximately 0.7 s of elapsed time.

The last two samples (5 and 6) were observed to have very different interactions with the PTO knuckle compared to the other samples. Sample 5 folded up on the PTO knuckle until it was pushed off by the rotation. The folded condition is shown in figure 13 (timecodes 9:08:41, 9:09:27, and 9:10:20). Timecode 9:14:14 in figure 13 shows how the folded sample 5 was pushed off by the rotation. Sample 6 rarely connected with the PTO knuckle. When it interacted with the PTO knuckle, it appeared to float nearby but was never in contact because of air movement. The behavior of sample 6 is shown in figure 14. Only four of nearly 340 captured frames, equivalent to approximately 1.4 and 1.3 s of elapsed time, respectively, are shown in figures 13 and 14.
Figure 9. Selected still frames of entanglement tests highlighting various behaviors of sample 1.
Figure 10. Selected still frames of entanglement tests highlighting various behaviors of sample 2.
Figure 11. Selected still frames of entanglement tests highlighting various behaviors of sample 3.
Figure 12. Selected still frames of entanglement tests highlighting various behaviors of sample 4.
Figure 13. Selected still frames of entanglement tests highlighting various behaviors of sample 5.
Figure 14. Selected still frames of entanglement tests highlighting various behaviors of sample 6.
Summary

The hypothesis that a vertically dropped sample might entangle more frequently than a sample introduced into a revolving PTO knuckle by being pulled laterally over the center line of rotation has been rejected. Not one entanglement was observed in 360 tests in which six samples were dropped vertically onto a rotating PTO knuckle. Reconciling the numerous reports of PTO injuries caused by entanglements and the inability to measure or observe a staged laboratory entanglement with a PTO knuckle is extremely perplexing.

The findings of this experiment are not intended to pronounce PTOs safe because no entanglements were recorded. Rather, the intent of this experiment was to develop a better understanding of the circumstances that create PTO entanglements. The high-speed videos of the 360 tests generated additional understanding as each sample hit and interacted with the rotating PTO knuckle. These high-speed videos allowed each test to be examined and re-examined a number of times.

Sample 4, a braided cotton cord, was determined to be the liveliest of all samples, having the most interaction and contact with the rotating PTO knuckle. Sample 4 also had the highest average initial bend angle and highest average wrap angle of all the samples in this experiment. Sample 4 also experienced the only near entanglements of any sample.

Clearly, entanglement phenomena remain obscure, and the ability to characterize the potential for PTO entanglement is beyond the current understanding gained from this experiment and from two earlier experiments. As each new experiment examines potential parameters, a better understanding is being developed. It appears that primary PTO entanglement phenomena still elude observation in staged laboratory conditions.

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