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ORIENTATION PERCEPTION IN FARM TRACTOR OVERTURN: A MODELING AND SIMULATION APPROACH

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Farm tractor overturn is a problem due partly to machine design and partly to human error. Human error contributions to overturn are considered here, from the joint perspective of modeling and empirical research, with the ultimate goal to provide recommendations for effective operator field training. Models obtained from the literature show that an operator's ability to sense changes in orientation degrades with current pitch or roll angle. A 3-axis simulator was constructed to test these predictions. In both younger and older subjects, errors in roll and pitch perception significantly increased with respective roll and pitch angles.

INTRODUCTION

Farm Tractor Overturn

With an overall death rate of 49 per 100,000 workers in 1987, agriculture (including forestry and fishing, but not logging) is the most hazardous industry classification. There were 3.4 million agriculture workers in 1987, with 1600 deaths and 160,000 reported injuries during this time (National Safety Council, 1988). Operation of tractors is one of the leading causes of injury on the farm, and tractor overturn is the most common cause of tractor-related fatality, accounting for over 52% of the 500 tractor fatalities in 1987. The death rate was 10.9 per 100,000 tractors, with about 4.44 million tractors in operation (National Safety Council, 1988). This incidence of tractor overturn has been constant over the past several years.

Pennsylvania statistics reveal that 50% of the 253 farm fatalities during 1980-1984 were tractor-related, and of these, about 70% were due to tractor overturn (Murphy, 1985). A 1987 cross-sectional analysis of Pennsylvania agricultural injuries revealed a low incidence for farm tractor injury-causing accidents, but high severity once an accident occurs. Farm tractors were responsible for only 5.3% of injuries, but

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accounted for over 165 lost workdays per injury, 6 times greater than any other injury source (Huizinga and Murphy, 1988).

These injury statistics are difficult to compile on a national basis, as separation of the home and workplace is difficult, and job/equipment contact time are unknown due to irregular shifts. Nevertheless, it is clear that farm tractors are hazardous; expected severity of tractor incidents places then near the top of the occupational hazard list.

Age Effects

Farming is an industry without occupational age restrictions, as evidenced by high fatality rates in extremely young and old operators. Fatality rates in Pennsylvania from 1980-1984 peaked at 0-4 years, 15-19 years, and at 55-59 years of age (Murphy, 1985). Fatal Georgia farm-tractor accidents from 1971-1981 revealed a steadily increasing mortality rate with age (Smith, et al., 1983). Fatalities per 100,000 male farm workers climbed from 6.7 (<20 years of age), to 22.3 (20-39 years), to 27.6 (40-59 years) to 54.1 (>60 years). The mechanism of these age differences in injury incidence is unknown, but differences in perceptual, decision-making, and responding capabilities are likely causative factors.

Stability Perception

Tractor overturns arise either from loss of stability due to inherent design characteristics, or from attempts to use the tractors beyond its designed stability limits (Spancer, Owen, and Glasbey, 1985). High centers of gravity coupled with changing loads and environmental conditions contribute to rapid side or rear overturn, once a point of instability has been reached (Murphy, et al., 1985). With an average age of a farm tractor approaching 20-30 years and 3 tractors per farm (Huizinga and Murphy, 1988), the time lag for design changes is significant. Instead, the present research has concentrated on operator capabilities, in order to provide recommendations for field training by farm safety specialists. Such training can have a rapid impact on tractor safety statistics.

Operator error in tractor overturn control can be divided into errors of perceiving appropriate information, deciding which response to make, or in making a response. The operator must maintain an accurate perception of tractor center of gravity, which changes as loads are varied or rear attachments are added. The operator must sense centrifugal force, rear axle torque, and drawbar leverage (Murphy and Johnson, 1982). Environmental characteristics to be sampled include slope angles, velocity, draft, ground surface, and turning angle (Goldberg and Parthasarathy, 1989; Goldberg, Parthasarathy, and Murphy, 1989a). Changes in these characteristics are proximally translated into changes in the visual scene, forces on the body, noises, and other sensations. Excess vibration and fatigue over a working day can clearly diminish the accuracy of sampling of these cues by an operator.

There is evidence that an operator traveling along or into a slope has diminished ability to sense changes in stability, compared with an operator traveling on a flat field. Goldberg and Parthasarathy (1989) established from the aerospace studies that errors in the static perception of upright increase with increasing body tilt:

$$\psi(\alpha) = 3.45 + .07\ (\alpha) \quad (1)$$
$$\psi(\beta) = 1.48 + .29\ (\beta) \quad (2)$$

where α is the absolute roll angle (degrees), β is the absolute pitch angle (degrees), and $\psi(\ )$ is the minimal perceived change in roll or pitch angle (degrees). These equations apply only to blindfolded operators, and to static conditions, neither of which is the case for the real world tractor operator. Furthermore, the operator tends to place stronger emphasis on visual information when visual and proprioceptive senses are in conflict. However, Equations 1 and 2 can shed some light on why a tractor operator can fail to control his machine before it reaches the critical angle of instability.

Given that instability has been perceived, the operator must execute an appropriate response, such as a steering or throttle correction. The reaction time for response initiation can easily exceed 500 msec, and is degraded by exposure to vibration (Stephens, et al., 1972). Average reaction time for power cutoff has been measured between 337-613 msec, depending on placement and type of power cutoff device (Pattie, 1973). Steering change completion is relatively slow, requiring close to 1 second to complete a 50° change (Rehkugler, 1980). Unfortunately, these studies have not always separated true reaction time, movement time, and control activation time, so that pure changes in control type or location cannot be predicted.

Objectives

A preliminary investigation was conducted to further model individual operators' ability to perceive changes in pitch and roll, and the interaction between pitch and roll on errors in angle judgement. Furthermore, both older and younger age groups were introduced to seek regular age effects. Pure vestibular and proprioceptive ability was isolated in this study by blindfolding all subjects.

METHOD

Subjects

Ten male subjects were recruited for this investigation; 5 from a younger (ages 21, 23, 24, 24, 26 years) and 5 from an older (ages 65, 67, 71, 79, 85 years) age group. All subjects were active and healthy. The younger group were recruited from Industrial Engineering graduate students at Penn State, whereas the older group was recruited from a community senior citizen's activity center. Each was paid $5/hour for 4 hours of participation, spread over two sessions.

Tractor Simulator

A 3-axis tractor overturn simulator was constructed to support this research. A brief summary of its design and capabilities is presented here; see Goldberg, Parthasarathy, and Murphy (1989b) for more detailed specifications. Realistic motions could be produced in side-to-side roll, front-to-back pitch, and yaw axes. Figure 1 presents a photograph of the simulator in a rolled, but non-pitched position. The operator sat in a John Deere tractor seat suspended within independently gimbaled pitch, roll, and yaw tubular steel frames. The maximum operator payload was 180 pounds, due to torque limitations in the drive motors. Leg space in the cockpit was limited to further decrease required torque. Limit switches restricted roll and pitch motion to ±37°.

The simulator was powered by stepper motors interfaced to a computer and controller. Three-stage speed reduction was provided by belts and pulleys to raise the final torque to 170 ft-lbs. in both pitch and roll axes. A lower-torque chain drive was used for yaw control, due to relatively low speed and torque requirements.

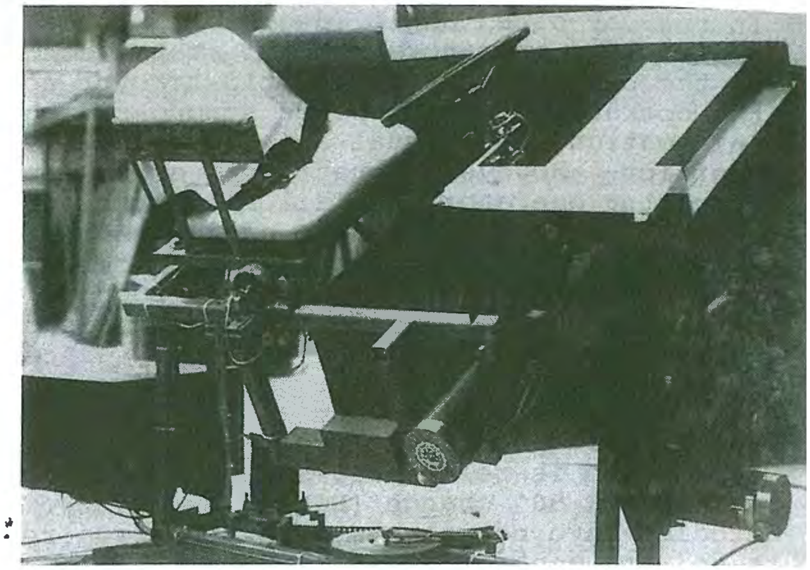

Figure 1. Tractor Overturn Simulator

Feedback and control of simulator position are diagrammed in Figure 2. Inputs include steering angle, throttle, brake, clutch, and power cutoff, which are digitized via an analog/digital converter. The computer sends digital instructions to the motor controller, which moves the simulator. Position of each axis is sampled via potentiometers, in addition to software algorithms. For the present experiment, a joystick in the hands of the subject controlled pitch and roll position. Yaw motion was not utilized in this pilot study.

<u>Procedure</u>

Upon arriving at the testing site, subjects signed an informed consent form and received full experimental instructions. The first day presented 2 hours of training and practice, and will not be further described here.

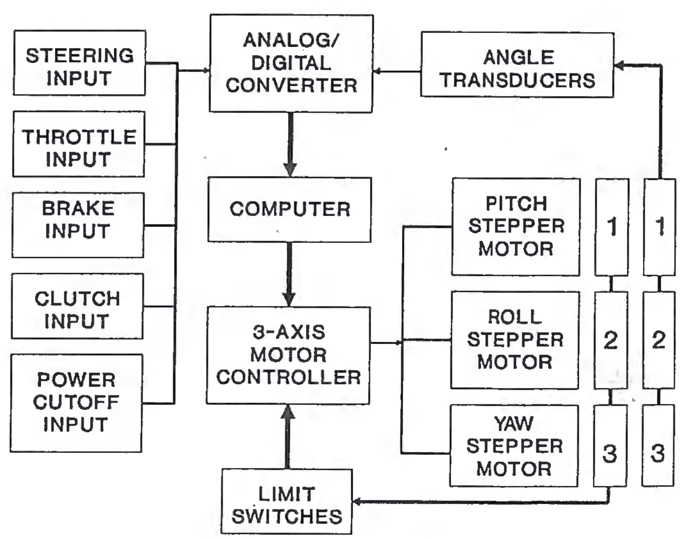

Figure 2. Simulator Feedback and Control

Each of 196 trials was run in an identical manner. The subject initially sat, with seatbelt fastened, in a 0° pitch, 0° roll position. A positive roll was defined as one to the subject's right, and a negative roll as one to the subject's left. A positive pitch was a backward tilt, and a negative pitch was defined as a forward tilt. After 5 seconds, the simulator automatically moved into a defined standard angle position, defined by pitch and roll angles between -18° and 18°. The blindfolded subject memorized this position, and pressed a button on the joystick to indicate he was ready. The simulator moved to a random location in the opposite pitch and roll quadrant, to ensure it moved far enough so the subject could not simply note how much time elapsed during simulator motion. The subject now used the joystick to move the simulator cockpit back to the original standard position. When he felt he was at the original standard, he pressed a button on the joystick, and the cockpit moved back to the 0° pitch, 0° roll position to start the next trial. Using the power cutoff button, the experiment could be paused or halted at any point, but no subjects required this additional break.

Design

The independent variables were subject, age group, standard pitch angle, and standard roll angle. The dependent variables were the angular error in subjects' responses for both pitch and roll axes. Positive and negative angular sign conventions were maintained as described above. A total of 196 response trials, each with a pitch and roll error, were gathered for each subject. These were defined by:

7 Standard Pitch Angles (-18°, -12°, -6°, 0°, 6°, 12°, 18°) x
7 Standard Roll Angles (-18°, -12°, -6°, 0°, 6°, 12°, 18°) x
4 Replicates = 196 trials

The order of the 196 trials was completely randomized, defining a 4-factor factorial design. Subjects were actually nested within age groups, but were treated as covariates in the following analyses.

RESULTS

All results below are pooled across the five subjects in each respective age group, due to space limitations. Response error in pitch and roll axes, the dependent variables, was defined by the difference between the standard angle and the actual angle of the subject's position when the button was pressed. A positive roll error indicates an actual position to the right of the standard, and a positive pitch error indicates an actual position to the subject's rear of the standard. Since subjects were informed to come as close as possible to the memorized standard, roll and pitch errors are analogous to minimal perceived angular differences, presented in Equations 1 and 2.

Table 1 summarizes pitch and roll response errors as a function of subject group, standard axis, and standard angle. Most of the pitch error showed a strong negative bias, towards the rear of the standard. Analysis of Variance (ANOVA) was conducted on both pitch errors and roll errors as a function of the independent variables. In these ANOVAs, Subjects and Age Group were treated as covariates; as such, no interactions between these and any other independent variables were interpreted. Of primary interest were pitch and roll errors as a function of the standard pitch and roll angles, and their interaction.

Pitch Errors

Subject differences were only marginally significant on pitc errors ($F_{4,921}=2.3$, $p=.06$). The Standard Pitch angle was quite influential on these errors ($F_{6,921}=28.4$, $p<.001$), but Age, Standard Roll angle, and the Pitch by Roll angle interaction we not ($p>.10$). Inspection of the data for both pitch and roll errors did not reveal any nonlinear trends, probably due to the large amount of variability present in the data. A multiple regression for Pitch Error, shown in Table 2, was conducted to obtain quantitative estimates of independent variable influence (While included to explain variability, the Subject indicator variables should not be interpreted, as subjects were nested within age groups.) Pitch Error increased by 0.2° for each 1° increase in Pitch Angle.

Table 1. Pitch/Roll Response Errors by Subject Group

Standard		Younger Subjects		Older Subjects	
Axis	Angle	Pitch	Roll	Pitch	Roll
Pitch	-18	-1.94	-0.19	-5.61	1.28
	-12	-1.48	0.29	-4.01	0.19
	-6	-0.98	0.70	-3.47	0.62
	0	-0.97	0.11	-0.47	0.84
	6	-1.02	-0.10	3.24	-0.41
	12	0.45	0.70	3.40	0.72
	18	1.50	-0.25	3.74	2.83
Roll	-18	-0.84	-2.59	1.19	-0.51
	-12	-1.43	-0.23	-1.10	-0.01
	-6	-0.60	-0.36	-0.71	0.85
	0	0.23	-0.33	-0.64	-0.29
	6	-0.64	1.00	-0.14	2.20
	12	-0.74	1.45	-0.42	1.68
	18	-0.43	2.31	-1.36	2.16
Pooled		-0.64	0.18	-0.46	0.87

Table 2. Pitch and Roll Error Regression Models

Regression Model Term	Model for: Pitch Error	Roll Erro
Intercept	-1.17 **	0.15 ns
Age Group Indicator (0=younger, 1=older)	0.18 ns	0.69 *
Subject 1 Indicator	1.10 *	0.40 ns
Subject 2 Indicator	-0.10 ns	1.08 *
Subject 3 Indicator	0.48 ns	-1.11 *
Subject 4 Indicator	1.18 *	-0.23 ns
Standard Pitch Angle	0.19 ***	0.01 ns
Standard Roll Angle	-0.01 ns	0.10 ***
Standard Pitch x Standard Roll	0.00 ns	-0.004 **

ns = not significant * p<.05 ** p<.01 *** p<.001

Roll Errors

Variability was generally smaller for roll error then pitch error, so results were more significant. Strong differences in roll error were noted between Subjects ($F_{4,926}$=5.9, p<.001) and Age Groups ($F_{1,926}$=5.4, p<.05). While Standard Pitch angle was not influential (p>.10), the Standard Roll angle was ($F_{6,926}$=11.5, p<.001). In addition, the interaction between Standard Pitch and Roll was significant ($F_{36,926}$=1.85, p<.01).

Multiple regression (see Table 2) indicated an increase in roll error of 0.7° in the older subjects. Furthermore, roll error increased by 0.1° per 1° increase in Roll Angle. This dependence on Roll Angle was, however, also dependent on the current Standard Pitch angle, as evidenced by the interaction.

CONCLUSIONS

This experiment demonstrated that accuracy in the perception of angular pitch is quite dependent on one's current pitch angle; similarly, accuracy in roll perception is dependent on one's roll angle. Aging plays a role in increasing errors in roll perception, but much less so for errors in pitch perception.

These results were very much in agreement with prior results. Here, the slope for error in pitch perception was 0.19°/pitch degree change. From Equation 2, the slope was 0.29°/pitch change. Similarly, the present slope for error in roll perception was 0.10°/roll degree change, whereas Equation 1 presented a slope of 0.07°/roll change. The presence of an interaction between pitch and roll axes on roll perception is an important result; changing the roll angle can induce changes in both roll and pitch errors.

Implications for the tractor operator are clear, for relatively static situations. When operating on a steep slope, the standard roll and/or pitch angles increase. As demonstrated above, the operator's ability to sense a change in roll and/or pitch declines in proportion to the slope. Thus, the minimal detectable change in tractor orientation is increased, and the tractor is closer to the angle of instability before the angle is perceived. The time in which a corrective action may be successfully executed is now decreased in proportion to the slope angle, and the probability of an overturn increases. The desired training strategy for this situation should be to increase the accuracy and efficiency of sampling one's internal and visual stability cues. An overturn simulator would thus be an ideal field training tool to demonstrate these stability cues.

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