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The Effect of Speed on Foldable ROPS Actuation Forces

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Abstract

The number of fatalities caused by tractor rollovers has decreased in recent years, but the number of fatal tractor rollover accidents with a folded-down rollover protective structure (ROPS) has increased. Operating a ROPS-equipped tractor in low overhead clearance zones is difficult and sometimes impossible. The foldable ROPS (FROPS) was designed to solve the rigid ROPS problem, but lowering and raising a conventional FROPS is a time-consuming and strenuous process. After operators fold down a FROPS to pass a low overhead clearance zone, some prefer to leave it in the folded or inoperative position, increasing the risk of a rollover fatality. The actuation forces for raising and lowering a FROPS are not well known and may be influenced by actuation speed. A completely randomized block design with two blocks, five levels of speed, and multiple replications was conducted to investigate the effect of speed on actuation torque. The blocks were two sizes of tractor FROPS. The test included five levels of speed, including two levels of static measurement and three levels of dynamic measurement. A variable-speed motor system was used to control the speed for raising and lowering the FROPS. The actuation torque is a function of the FROPS upper part shape, dimensions, material density, turning acceleration, and friction. A theoretical model was developed to predict the actuation torque based on the FROPS shape, dimensions, and material density. For one ROPS, due to friction, the dynamic actuation torque was greater for raising and less for lowering than the theoretical torque. Indicator variable regression was used to analyze the effect of speed on actuation torque. Results showed that speed had a significant ($p > 0.05$) effect on actuation torque. Although there were statistically significant differences between the dynamic actuation torques, these differences were relatively small and negligible compared to the differences between the static torques.

Keywords

Actuating force; Foldable rollover protective structure; Safety; Standards; Tractor

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Tractor rollovers are the major cause of occupational death in U.S. agriculture (NIOSH, 2014). The most effective way to prevent deaths during rollover accidents is the combined use of a rollover protective structure (ROPS) and a seatbelt (NIOSH, 2013). The ROPS is a structure that absorbs a portion of the impact energy generated by the tractor weight in a rollover accident. The ROPS decreases the possibility of severe injury by protecting the

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operator's clearance zone. The number of fatalities caused by tractor rollovers has decreased in recent years, partially due to retrofitting more tractors with ROPS. The Swedish government has required ROPS on all tractors built after 1957; consequently, the number of fatal rollover accidents decreased from 15 in 1957 to 1 in 1990 (Thelin, 1998). Since 1985, tractor manufacturers in the U.S. have equipped tractors with standardized ROPS (Ayers et al., 1994). The number of fatal rollovers has decreased using ROPS. The National Institute for Occupational Safety and Health (NIOSH, 2013) estimated that if ROPS were placed on all U.S. tractors, the number of fatal rollover accidents could be decreased by 71%. However, in 2012, only 59% of agricultural tractors were equipped with ROPS (NIOSH, 2014).

Overhead obstacles were reported as the most important reason for the operator not to install a ROPS (Spielholz et al., 2006). Working with ROPS-equipped tractors in low overhead clearance zones, such as orchards and animal confinement buildings, is difficult and in some cases impossible. To facilitate tractor operation in low overhead clearance zones, foldable ROPS (FROPS) have been developed. The FROPS is usually made of two parts: the upper part or the turning frame, and the lower part, which is fixed to the tractor (fig. 1). The upper part is attached to the lower part using a pin at the pivot point. The height of a conventional FROPS can be decreased by folding the upper part downward.

However, the FROPS only partially solves the problem of low clearance applications, and recent surveys have revealed a new issue. The number of fatal accidents and severe injuries in tractor rollover accidents with folded-down FROPS has increased in the last few years (NIOSH, 2015; Hoy, 2009; Pessina et al., 2015). In a March 2015 review of NIOSH Fatality Assessment and Control Evaluation (FACE) reports, there were no rollover fatalities involving tractors with folded-down FROPS prior to 2003 (NIOSH, 2015). Since 2005, 25% of rollover fatalities occurred with folded-down FROPS. Since 2010, 50% of reported fatal tractor rollover accidents occurred with folded-down FROPS. Although this is a small sample size, the trend is disturbing. A survey conducted by European Commission members showed that 40% of fatalities and serious injuries in tractor rollover accidents occurred when a FROPS was in the inoperative position (Hoy, 2009). Pessina et al. (2015) reported that 30% of tractor rollover fatalities in Italy from 2008 to 2014 resulted from a FROPS in the folded-down position.

One possible explanation for leaving the FROPS in the folded-down position is that raising and lowering the FROPS is a time-consuming and strenuous process. After lowering the FROPS to pass an obstacle, some operators prefer to leave the FROPS in the folded-down position.

An OECD working draft is being considered to regulate rear-mounted FROPS actuation forces (i.e., the forces for raising and lowering the FROPS). Based on the OECD working draft, the maximum actuation force should be less than 100 N, but this criterion could increase by up to 50% for some points and for lowering the FROPS (OECD, 2014). The actuation force is measured at the grasping area on the upper part of the FROPS. An option exists to measure the torque for actuating the FROPS in 5° increments and then calculate the actuation force, knowing the upper part length. Although no recommendation is made in the working draft on the rotational speed of FROPS actuation, a maximum angular speed of 20° s^{-1} (3.3 rpm) has been recommended for testing an automatic locking system (OECD, 2014).

Current FROPS actuation forces are not well known. Pessina et al. (2015) measured the actuation forces for raising front-mounted FROPS. They measured the static actuation force for 17 tractors at five angles (0°, 30°, 45°, 60°, and 90°) using a force gauge and a digital inclinometer. The results showed that the actuation forces for nearly all of the FROPS were greater than the 100 N criteria based on the OECD working draft. The influence of rotational speed on actuation force was not investigated.

The aim of this study was to evaluate the effect of rotational speed on rear-mounted FROPS actuation torque. It was hypothesized that the raising and lowering speeds may affect the actuation torque. The effect of rotational speed on the actuation torque was investigated by actuating the FROPS at five speed levels that included two static actuation torque measurements. A theoretical model was developed to predict the actuation torque based on the geometry and material density of the FROPS.

Materials and Methods

The initial goal of this study was to measure the actuation torque as a function of the FROPS turning angle. The torque was measured at five speed levels that included two static torque levels. The procedure for the test included two steps: (1) developing the measurement setup, and (2) conducting the experimental tests to evaluate the influence of rotational speed on actuation torque.

Measurement Setup

In the first step, a measurement system was developed to measure the actuation torque and the angle. Based on the OECD working draft, the actuation force can be determined by measuring the actuation torque and then calculating the force at the grasping area (OECD, 2014). The OECD working draft defined the upper posts of the FROPS as the grasping area. Because specific grasping points have not been explored accurately, and the torque can easily be used to calculate the force at each grasping point, the actuation torque was the preferred measurement rather than the actuation force. The measurement system included a power setup and a sensing setup (fig. 2).

Power Setup

The actuation system was composed of a motor, platform, fork, speed controller, switch, and battery. A reversible gear motor (Groschop model PM801-PL73) was used to turn the upper part of the FROPS. The motor was mounted on a platform that was attached to the fixed section of the FROPS. The motor applied torque with a fork that gripped the upper part of the FROPS. The motor shaft was collinear with the pivot point of the FROPS (fig. 1). The speed controller (IronHorse model GSD1) was used to change the motor speed. The direction of the motor was controlled with a switch that was installed between the speed controller and the battery. The switch also controlled the start and stop of the turning process. The 12 VDC battery supplied the motor power (fig. 2).

Sensing Setup

The measuring system included angular displacement and torque measurement sensors. The turning angle is the relative angle of the upper part of the FROPS to the horizon, which is the Y direction in figure 1a. The turning range of the upper part is roughly 180° (fig. 1). The angle of the raised locked FROPS is usually less than +90° because the FROPS is often tilted rearward for better protection of the operator (fig. 1a). The turning angle is 0° when the upper part of the FROPS is in the horizontal position (fig. 1b). The angle of the completely folded FROPS is near −90° (fig. 1c). Usually, the FROPS is pinned in the lowered position before reaching −90°, which is called the lowered locking position.

The angle of the upper part was measured with an accelerometer (Crossbow model CXL04LP3). The tilting angle of an object can be measured using an accelerometer because objects are subject to gravitational force (g). At the low rotational speeds evaluated, the effects of tangential acceleration and centrifugal acceleration on the accelerometer output due to the circular motion of the upper part of the FROPS were negligible. The relationship between the angle and the acceleration depends on the installation direction. As the sensing axis (X) is parallel to the upper part of the FROPS, equation 1 can be used to calculate the tilting angle:

$$\theta = \sin^{-1}\left(\frac{V_{out} - V_0}{\Delta V / g}\right) \quad (1)$$

where

? = tilting angle (degrees)

V_{out} = accelerometer output (V)

V_0 = accelerometer output when sensing axis is horizontal (V)

? V/g = sensitivity (V s^2 m^{-1})

g = Earth gravity (9.81 m s^{-2}).

The sensitivity of the sensing axis (X direction) was 0.489 (V s^2 m^{-1}), and V_0 was 2.527 V. The sensor was attached to the top of the FROPS with a magnet. The magnet did not affect the sensor output.

A reaction torque cell (Omegadyne model TQ420-2K) was used to measure the torque. The torque transducer had a maximum limit of 225 Nm. The torque transducer was attached between the motor and the fork. A data logger (Campbell Scientific model CR23X) read and saved the accelerometer and torque transducer outputs at 20 Hz sampling frequency.

Experimental Test Design

The experimental tests were based on a completely randomized block design. The test included two blocks with five levels of speed and multiple replications within each block. The blocks were two different FROPS models. The FROPS were selected from two different weight categories of agricultural tractors. The first FROPS was Deere & Company model Se1 0095, which was designed for John Deere tractor models 4120, 4320, 4520, and 4720. The second FROPS was FEMCO model 301013466, for use on John Deere tractor models 2210 and 2305. The weight of the upper part of the Deere and FEMCO FROPS was 219.8 N and 109.8 N, respectively.

The five speed levels included three dynamic levels and two static levels. The speed levels were defined based on the motion of the ROPS. For the dynamic levels, the actuation forces were measured while the FROPS was continuously raised or lowered. For the static levels, the actuation forces were measured when the FROPS was stopped at a point or started moving from a static position.

The dynamic speed levels for each FROPS are listed in table 1. Torque and angle measurements were made while both raising and lowering each FROPS. Three replications were conducted for each dynamic test, except the high-speed Deere FROPS test. For safety concerns, only two high-speed dynamic tests were conducted with the heavier Deere FROPS.

Two concepts of static actuation torques were defined: holding torque and initiation torque. Holding torque was measured while the upper part of the FROPS was held at certain angles for at least 3 s. As the FROPS started its transition from static to dynamic movement, a sharp change in the torque values around the measured holding torque value was initially apparent. The initial value of the torque in the transient step was recorded as the initiation torque as the upper part of the ROPS was raised or lowered from a static position to 3.3 rpm (20° s^{-1}).

Developing a Theoretical Model

A mathematical model was developed to determine the theoretical actuation torque for the Deere and FEMCO FROPS. The FROPS actuation torque is a function of the weight, center of gravity (COG), turning acceleration of the upper part, and friction. The weight and COG of the upper part of the FROPS can be calculated from the shape, dimensions, and density of the upper part. The acceleration affects the inertial force and consequently the actuation torque. The friction force depends on the coefficient of friction and the normal force. The coefficient of friction is not a constant value and depends on several factors, such as the movement condition (static or dynamic) and contact surface properties. The model was developed based only on the shape, dimensions, and material density of the upper part of the FROPS.

Results and Discussion

The measured actuation torques for raising and lowering the Deere FROPS are shown in figure 3. The graph includes three replications of the lowest speed test and the theoretical torque. The measured torques tended to be greater than the theoretical torque for raising the FROPS and less for lowering the FROPS. Friction caused the differences between the theoretical model and the experimental test results. The vertical (about the horizon) components of the friction force and weight were in the same direction and toward the ground during the raising process. However, the vertical components of the friction force and weight were in opposite directions during the lowering process. Thus, the actuation torques for raising the FROPS were greater than the measured resistive torques when lowering the FROPS. Roughly, the theoretical torque plus the torque due to friction was equal to the raising torque. Conversely, the theoretical torque minus the torque due to friction produced the lowering torque.

The upper part of the Deere FROPS leaned 12° rearward from the vertical in the upright locked position. Therefore, the lowering process started around the upper lock point, which was 78°, and moved down to the lower locked position at −71°. The raising process started at −71° and rotated with a constant rotational speed up to 78°. During lowering, the actuation torque for the Deere FROPS was negative from 78° to 67° and then became positive. The point at which the actuation torque was equal to zero (about 67°) was called the breaking point. Before this point, the fork pushed the FROPS to overcome the friction. After the breaking point, the fork held the FROPS from folding. The peak point was defined as the angle at which the maximum torque occurred. The peak point for the Deere FROPS was approximately −13°. At that FROPS angle, the COG of the upper part was horizontal with the pivot point, as determined by the theoretical model.

The theoretical and experimental test results for the FEMCO FROPS actuated at low rotational speed are shown in figure 4. The differences between the raising, lowering, and theoretical torques were small, which means that the dynamic friction resistance was low. There was a gap between the pivot point plates of the FEMCO FROPS; therefore, the normal force and consequently the friction were low. The FEMCO FROPS leaned 19° rearward from the vertical in the upright locked position. Therefore, the lowering started at around 71° and rotated down to −71°. The actuation torques were positive for both raising and lowering. There was no breaking point for the FEMCO FROPS because there was minimal friction and no need to push the FROPS for lowering. The maximum torque occurred at −8°, which coincided with the theoretical model results. Figures 3 and 4 show good repeatability of the measurement setup, based on similar results for three replications.

Figures 5 and 6 show the results for raising and lowering the FROPS at three dynamic speed levels. The graphs show that the measured torques were similar for the three dynamic speed levels. Analysis of variance (ANOVA) was conducted with SAS to examine the ef-fect of speed on torque at the three dynamic speed levels. The maximum torque that occurred at the peak point was selected for the statistical analysis. The peak angle was −13° for the Deere FROPS and −8° for the FEMCO FROPS. For the Deere FROPS, the average torque values between −12° and −14° from each treatment were calculated and used as the peak torque values. The average torque values between −7° and −9° were used for the FEMCO ROPS. The means were compared with Fisher’s LSD at the 5% significance level. The ANOVA results showed that speed affected the peak values of dynamic torque ($p > 0.05$), but there was no obvious trend in the mean peak values. The differences in the peak values were less than 5% (table 2).

During the raising of the FROPS from a static position, a peak of initial torque above the holding torque was apparent as the FROPS started its transition from static to dynamic movement. As the FROPS was lowered from its holding position, a substantial lowering of the torque was seen (fig. 7). The initial value of the torque in the transient step was recorded as the static initiation torque as the upper part of the ROPS was raised or lowered from a static condition to a rotational speed of 3.3 rpm (20° s^{-1}).

The results of the holding and initiation torque measurements for raising and lowering the Deere and FEMCO FROPS are shown in figures 7 and 8, respectively. The initiation torques at the peak point when raising the FROPS were 30% and 19% above the holding torques for the Deere and FEMCO FROPS, respectively. When lowering the FROPS, the initiation torques dropped by 33% and 25% from the holding torques for the Deere and FEMCO FROPS, respectively. The initiation torque values were higher for the Deere FROPS than for the FEMCO FROPS because the friction and weight of the Deere ROPS were greater than for the FEMCO FROPS. The inertial force is higher for a heaver FROPS than for a lighter one FROPS with the same acceleration.

The static holding torque includes the moment of static friction and the weight of the upper part around the pivot point. The holding torques had a good agreement with the theoretical curves, considering the effect of friction (figs. 7 and 8). The initiation torque comprised the weight, dynamic friction, and inertial force effects. The inertial force, dynamic friction, and weight vectors were in the same direction for transient raising. The inertial and frictional force vectors were in the opposite direction of weight for transient lowering.

An indicator variable regression was used to analyze the effect of speed on the actuation torque (T) as a function of angle (?). Quadratic regression lines were fit separately to the five speed levels (figs. 9 through 12). The models explained more than 95% of the variations in the measured torques for almost all of the treatments (tables 3 through 6). Statistical analysis results showed that intercepts ($p > 0.05$), linear slopes ($p > 0.05$), and quadratic slopes ($p > 0.05$) were significantly different among speed treatments (tables 3 through 6). Therefore, speed had a statistically significant but small effect on actuation torque.

Although there were statistically significant differences between the dynamic actuation torques, these differences were relatively small compared to the differences among the static torques, especially for the initiation treatments (figs. 9 through 12). The difference between the holding torque and dynamic torque for the Deere FROPS was greater than for the FEMCO FROPS due to the higher frictional force in the Deere FROPS. The difference between the holding torque and transient static torque was due to the effects of dissimilar friction forces and the inertial force.

Conclusions

A measurement setup was developed to measure the actuation torque and turning angle of the upper part of FROPS. The influence of rotational speed on the actuation torque of FROPS was investigated. Actuation torques were measured for three dynamic levels and two static levels for two different FROPS. The static levels included the initiation and holding torques. Experimental test results showed that the dynamic actuation torque for raising the FROPS was greater than when lowering if frictional resistance existed. A mathematical model was developed based on the dimensions, shape, and material density of the FROPS upper part. The developed model can predict the dynamic actuation torque for FROPS that have little friction. With friction, the theoretical torque at a given angle was between the measured raising and lowering torques. The static initiation torque was higher for raising the FROPS than for lowering. The initiation torque values for raising the FROPS at the peak points were 30% and 19% higher than the holding values for the Deere and FEMCO FROPS, respectively. The initiation torque values for lowering the FROPS decreased by 33% and 25% for the Deere and FEMCO FROPS, respectively, compared to the static holding torque.

Regression analysis of indicator variables showed significant differences ($p > 0.05$) between quadratic regression parameters for the five speed levels. The torque-angle relationships were modeled using nonlinear regression lines. Although the results showed that speed had a significant effect on actuation torque, the differences between the three regression lines for dynamic actuation torques were relatively small. The static and dynamic levels were apparently different. The static initiation torque included the inertial force and was distinctly different from all other speed levels.

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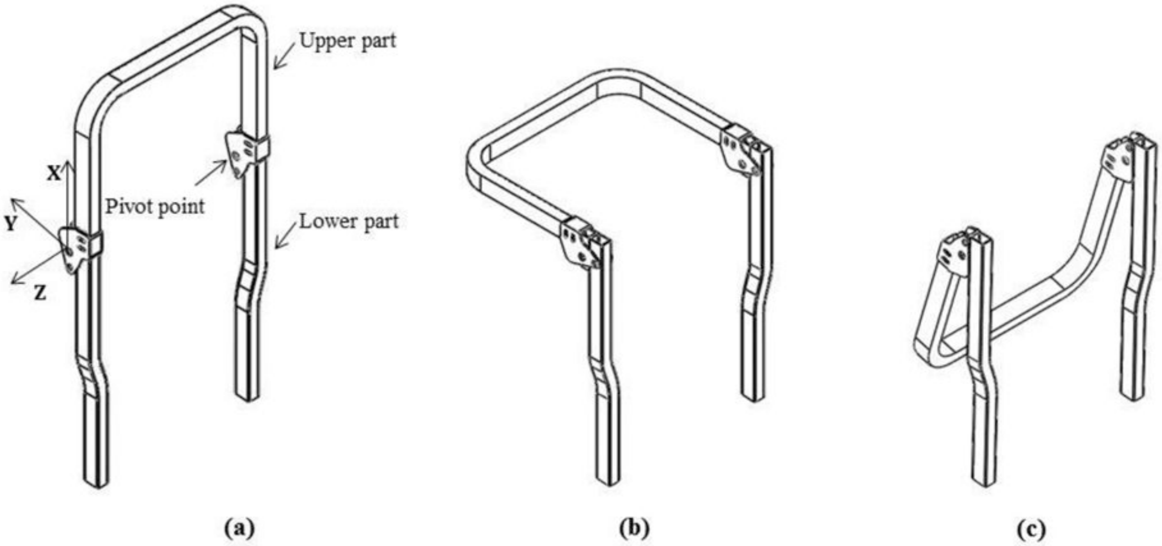

Figure 1.

FROPS positions: (a) FROPS in the raised or protective position, (b) FROPS in the horizontal position, and (c) FROPS in the folded or inoperative position.

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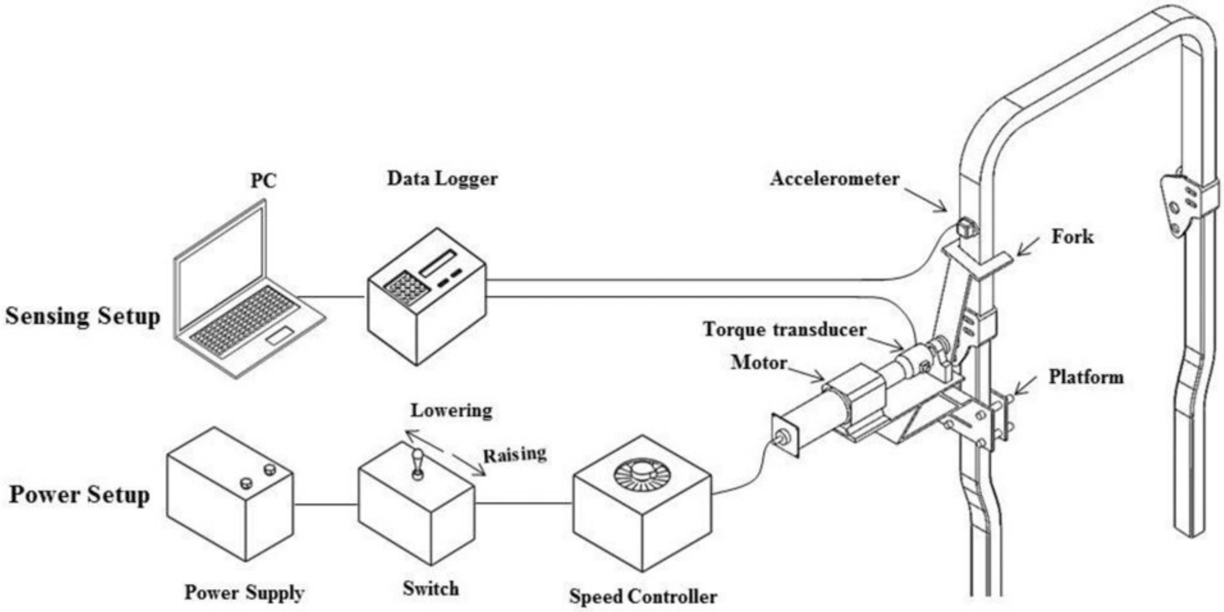

Figure 2.
Measurement setup.

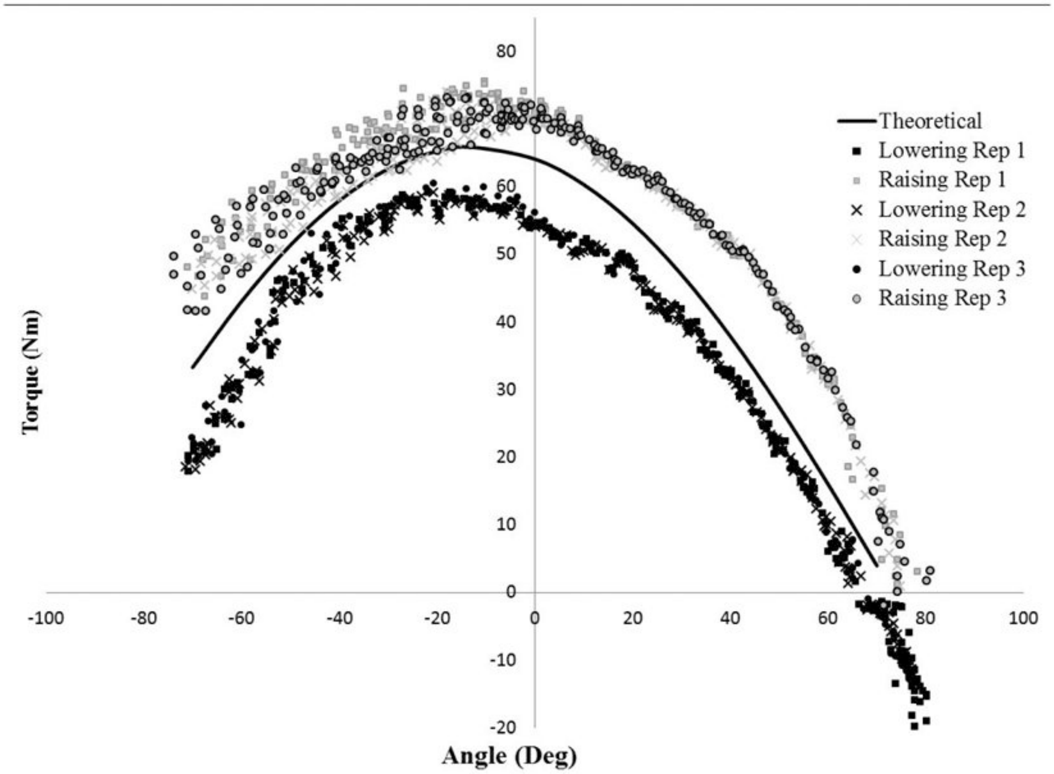

Figure 3.

Actuation torques for raising (speed = 2.6 rpm) and lowering (speed = 2.5 rpm) for three replications with the Deere FROPS and the theoretical torque for raising and lowering.

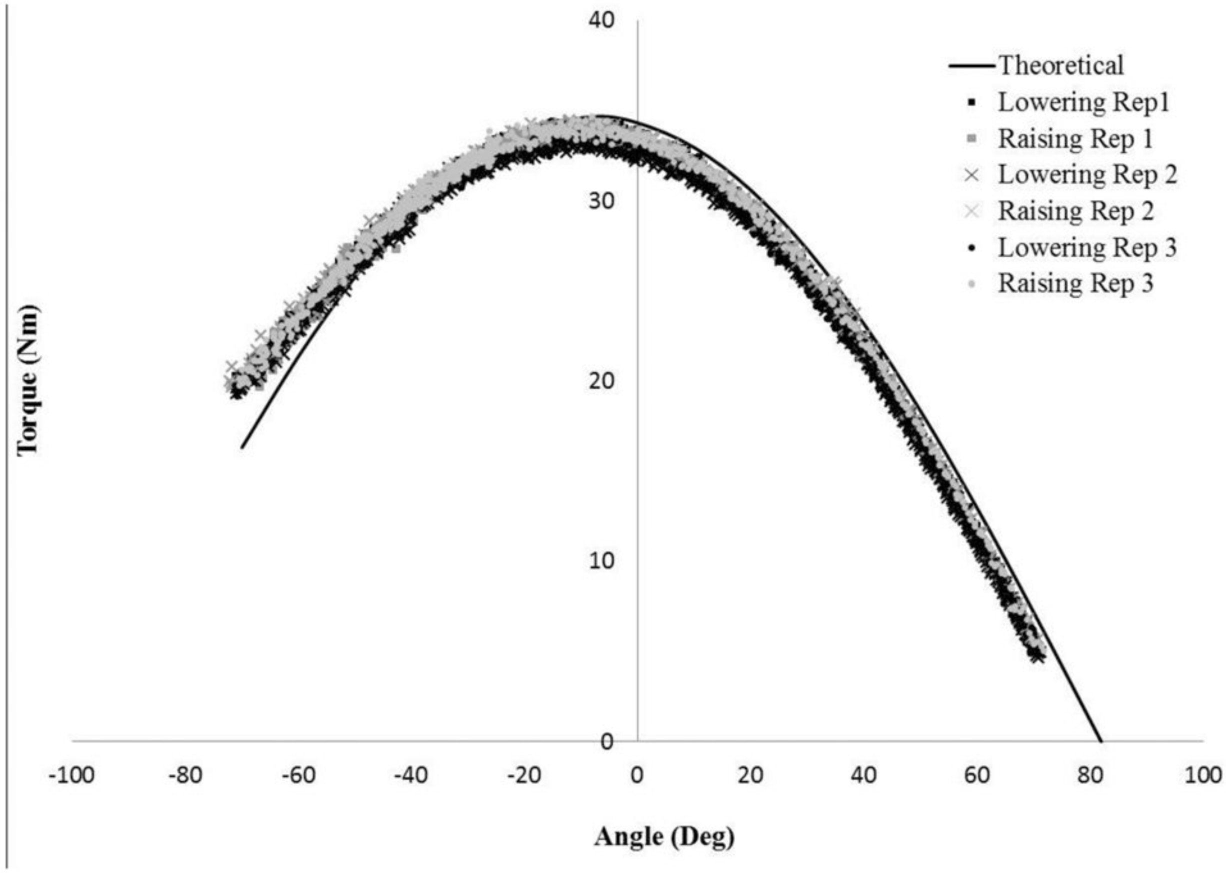

Figure 4.
Actuation torques for raising (speed = 0.9 rpm) and lowering (speed = 0.7 rpm) for three replications with the FEMCO FROPS and the theoretical torque for raising and lowering.

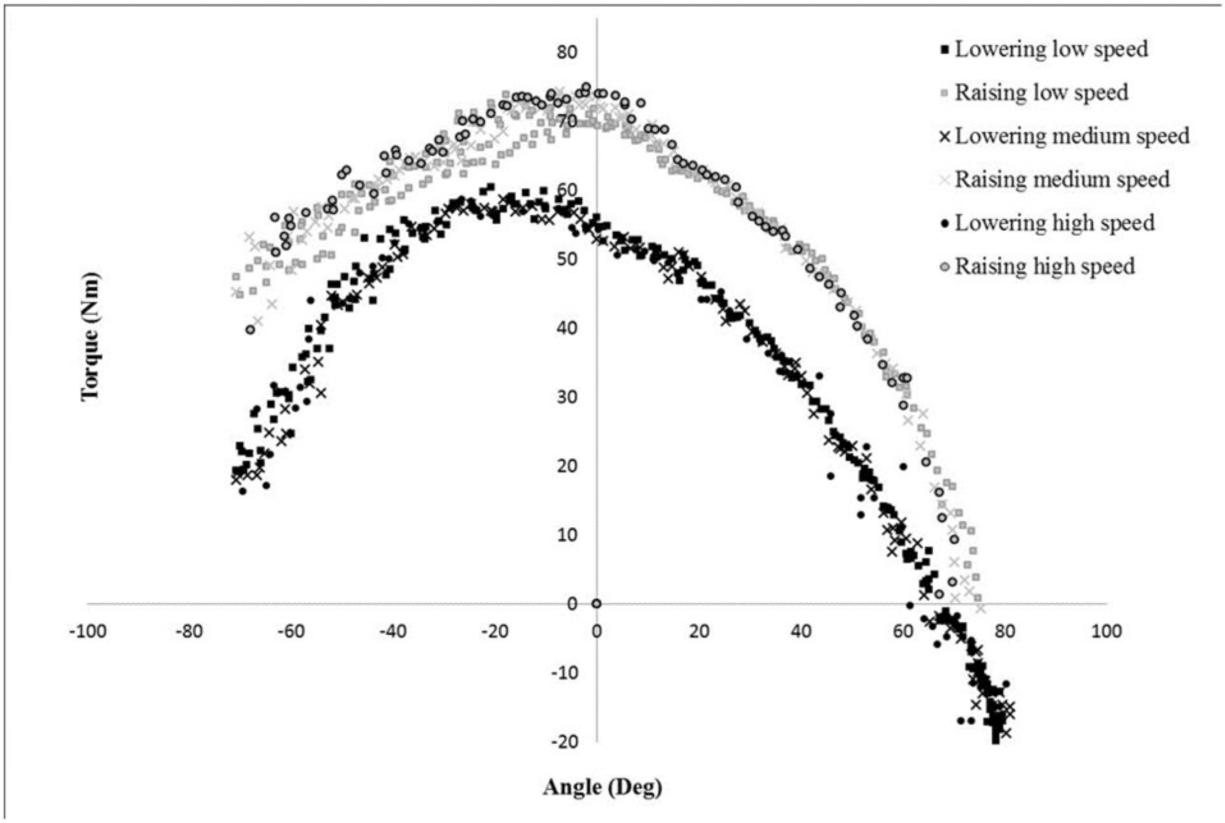

Figure 5.
Actuation torques for raising and lowering the Deere FROPS at three speed levels.

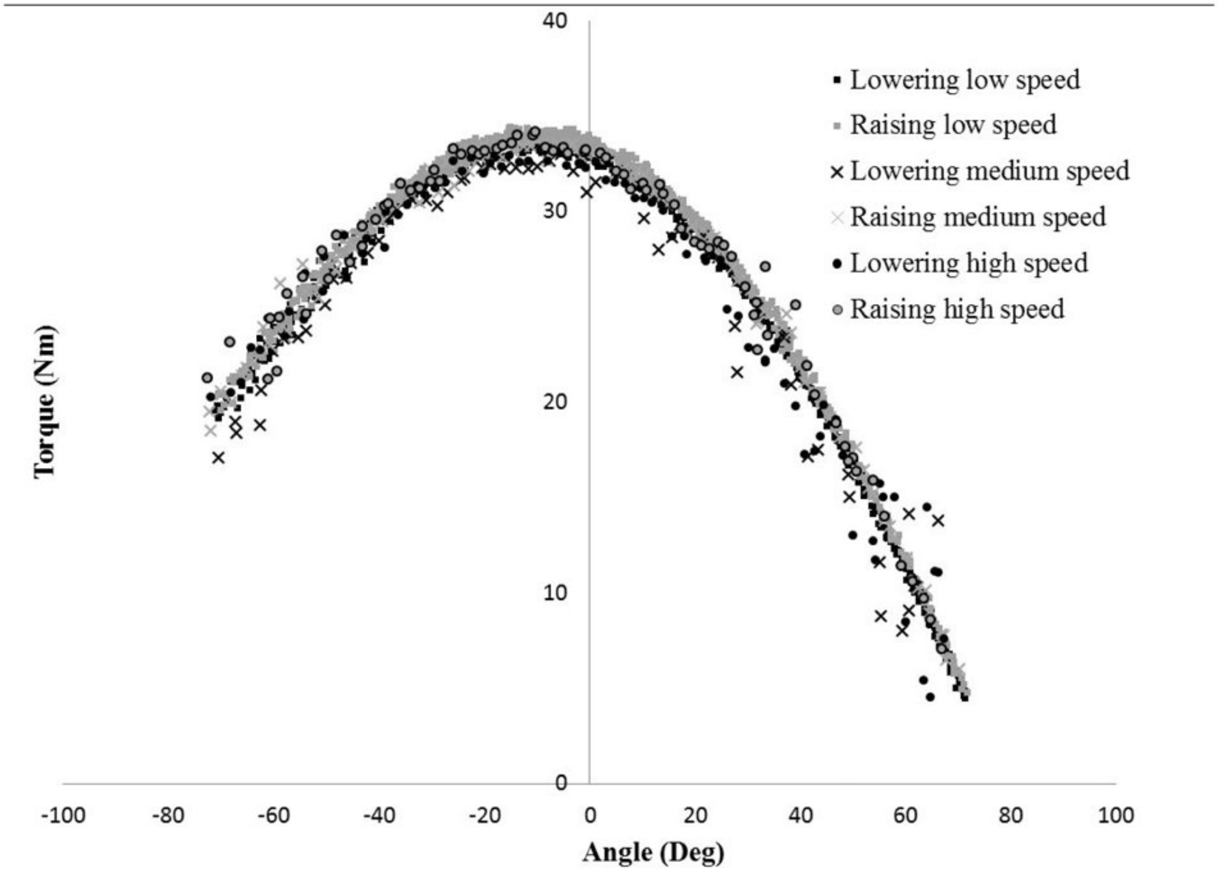

Figure 6.
Actuation torques (Nm) for raising and lowering the FEMCO FROPS at three speed levels.

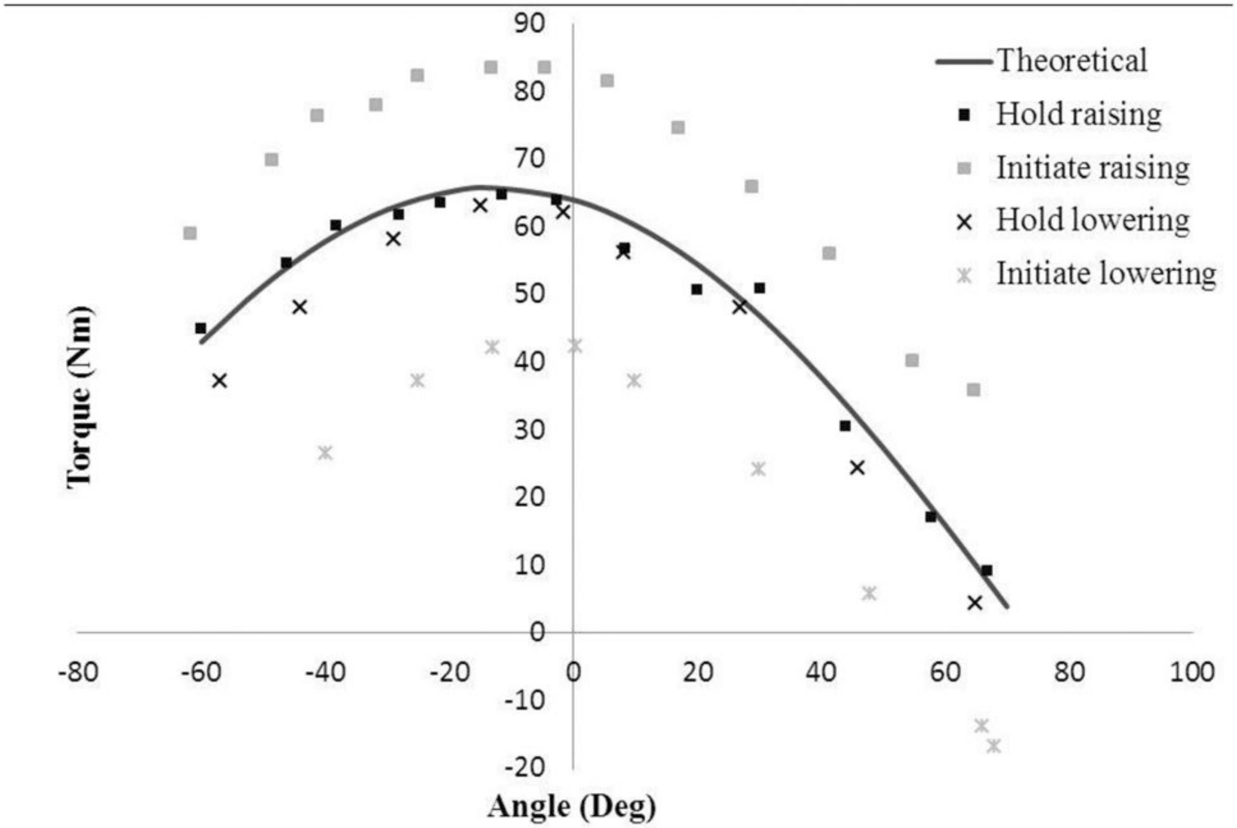

Figure 7.
Static holding and static transient torques for raising and lowering the Deere FROPS.

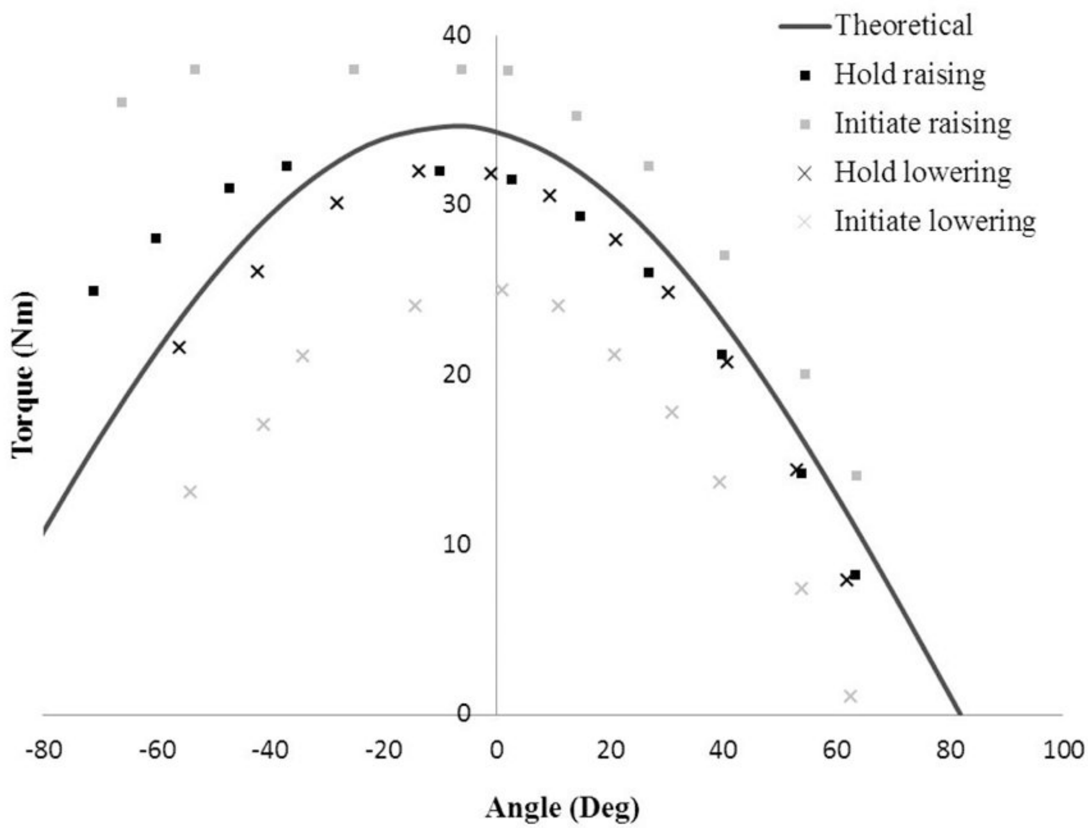

Figure 8.
Static holding and static transient torques for raising and lowering the FEMCO FROPS.

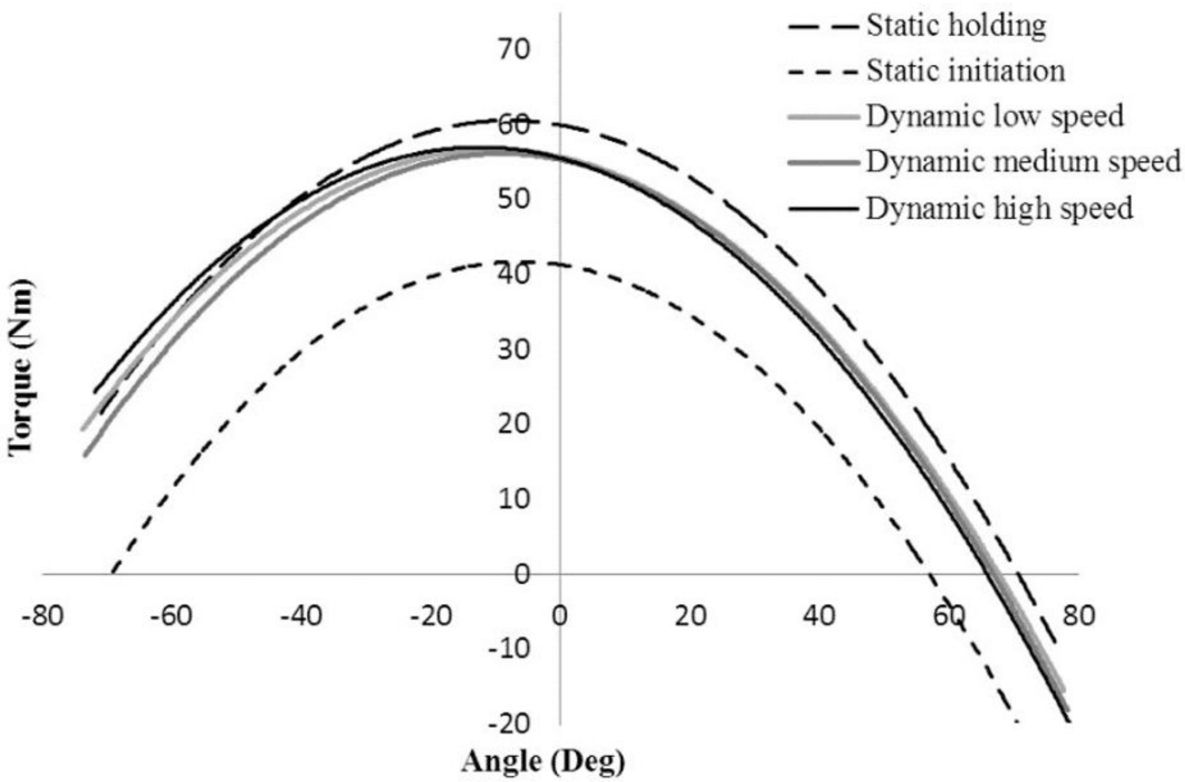

Figure 9.
Regression lines for lowering the Deere FROPS

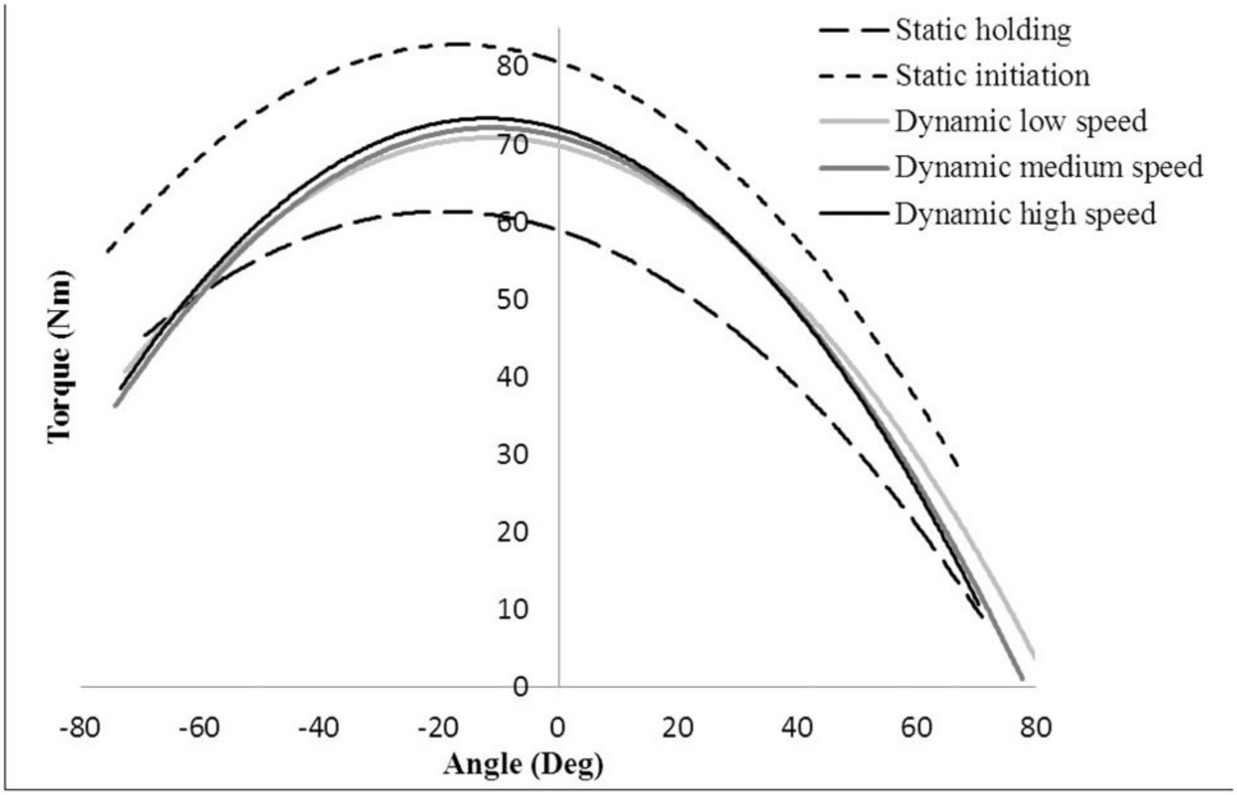

Figure 10.
Regression lines for raising the Deere FROPS.

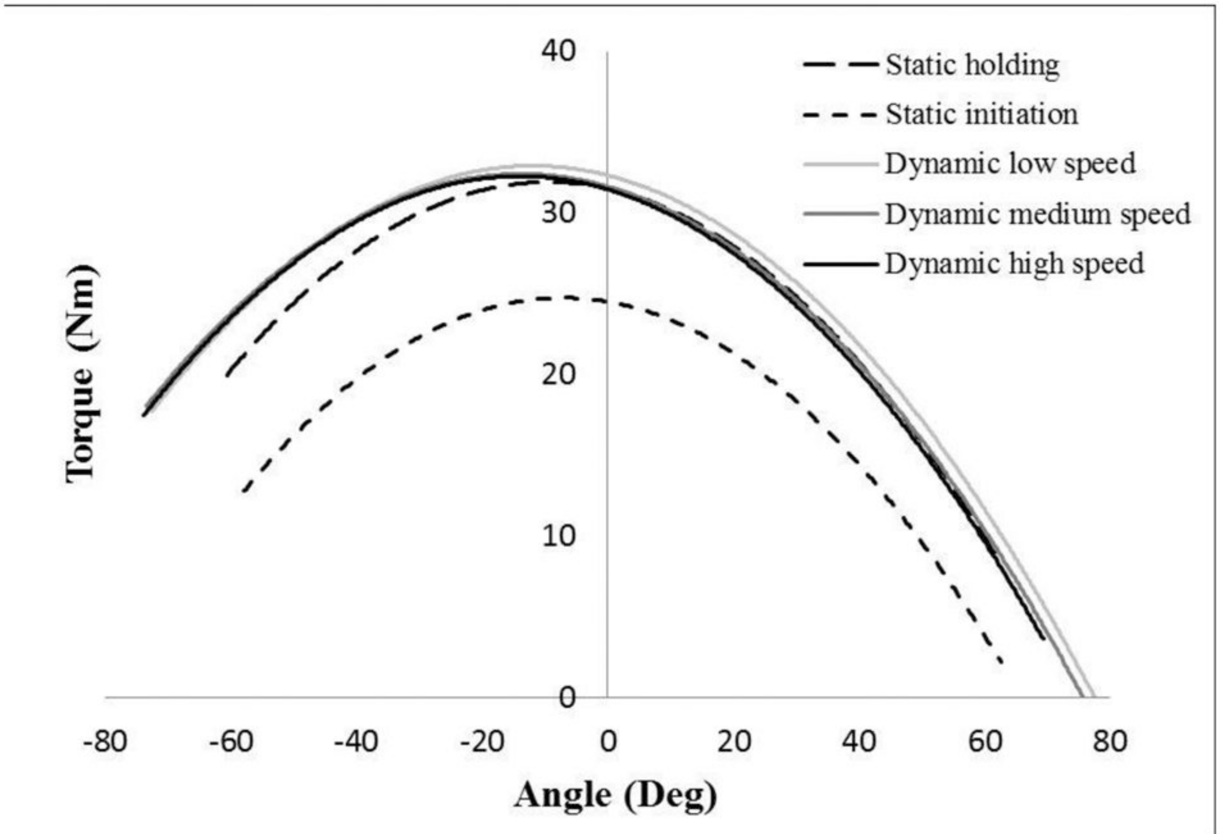

Figure 11.

Regression lines for lowering the FEMCO FROPS.

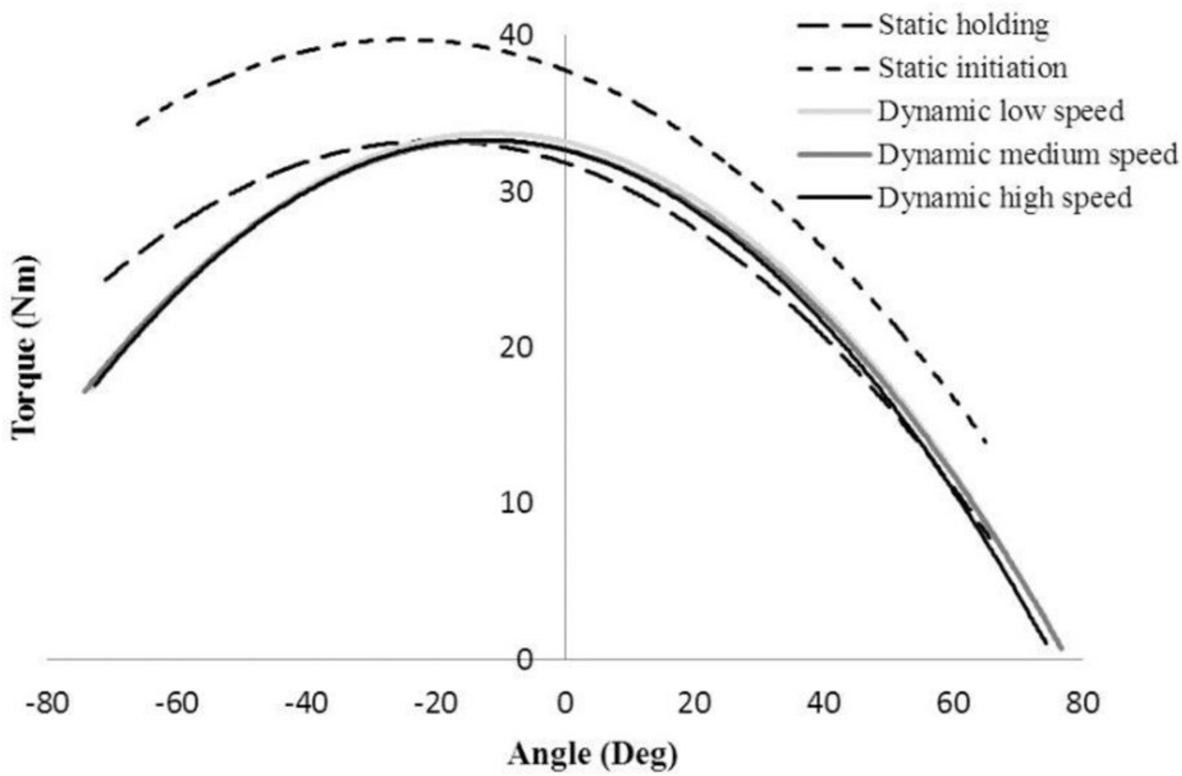

Figure 12.
Regression lines for raising the FEMCO FROPS.

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Table 1.

Three levels of actuation speed (rpm) for raising and lowering the Deere and FEMCO FROPS. Values are means (standard deviations are shown in parentheses).

FROPS	Raising			Lowering		
	Low	**Medium**	**High**	**Low**	**Medium**	**High**
Deere	2.6 (0.4)	4.7 (0.1)	6.7 (0.7)	2.5 (0.2)	4.4 (0.1)	6.1 (0.9)
FEMCO	0.9 (0.3)	7.1 (0.7)	9.3 (0.3)	0.7 (0.3)	4.6 (0.1)	7.3 (0.3)

Table 2.

Mean comparison of peak torques values.[a]

Dynamic Speed	Deere		FEMCO	
	Lowering	Raising	Lowering	Raising
Low	57.4 a	70.7 b	33.3 a	33.9 a
Medium	56.7 a	72.4 a	32.5 b	33.2 b
High	57.3 a	73.0 a	31.9 c	33.4 b

[a]Values followed by the same letter are not significantly different (p > 0.05).

Table 3.

Regression equations for lowering the Deere FROPS.

Treatment	**Equation**	R^2
Static holding	$T = -0.0098?^2 - 0.1547? + 59.95$	0.96
Static initiation	$T = -0.0105?^2 - 0.1290? + 41.33$	0.98
Dynamic low speed	$T = -0.0093?^2 - 0.1928? + 55.69$	0.98
Dynamic medium speed	$T = -0.0097?^2 - 0.1768? + 55.33$	0.97
Dynamic high speed	$T = -0.0093?^2 - 0.2317? + 55.54$	0.98

Table 4.

Regression equations for raising the Deere FROPS.

Treatment	**Equation**	**R^2**
Static holding	$T = -0.0079?^2$ - 0.240? + 61.565	0.98
Static initiation	$T = -0.0077?^2$ - 0.2614? + 80.574	0.95
Dynamic low speed	$T = -0.0081?^2$ - 0.1826? + 69.743	0.96
Dynamic medium speed	$T = -0.0090?^2$ - 0.2007? + 70.954	0.93
Dynamic high speed	$T = -0.0092?^2$ - 0.2217? + 71.949	0.95

Table 5.

Regression equations for lowering the FEMCO FROPS.

Treatment	**Equation**	R^2
Static holding	$T = -0.0045?^2 - 0.0862? + 31.51$	0.99
Static initiation	$T = -0.0046?^2 - 0.0663? + 24.51$	0.96
Dynamic low speed	$T = -0.0041?^2 - 0.0979? + 32.34$	0.99
Dynamic medium speed	$T = -0.0040?^2 - 0.1120? + 31.64$	0.95
Dynamic high speed	$T = -0.0041?^2 - 0.1157? + 31.46$	0.93

Table 6.

Regression equations for raising the FEMCO FROPS.

Treatment	**Equation**	**R^2**
Static holding	$T = -0.0035?^2 - 0.1397? + 31.80$	0.99
Static initiation	$T = -0.0032?^2 - 0.1584? + 37.74$	0.97
Dynamic low speed	$T = -0.0043?^2 - 0.0959? + 33.14$	0.99
Dynamic medium speed	$T = -0.0041?^2 - 0.0987? + 32.63$	0.98
Dynamic high speed	$T = -0.0043?^2 - 0.1053? + 32.63$	0.96