A Mechanical Experiment to Simulate the Nonlinear Hand-Arm Dynamics in Torque Tool Operation

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Abstract

The purpose of this study is to design and test a mechanical DC torque tool testing rig that is capable of simulating dynamic response of the human arm under a torque impulse. The mechanical simulation of the human arm response is based on a nonlinear model derived from human subject testing. The testing rig, which uses both tension and compression springs to provide a bilinear stiffness rate to resist the motion of the torque tool handle, is used to analyze the tool handle angular displacement and reaction force, which has been strongly linked in previous studies to operator discomfort and injury. The mechanical simulation of the human arm response was tested under a number of different conditions, and compared to an analytical nonlinear model. The results showed that the mechanical simulation consistently underestimated the tool handle displacement by up to 16.2% when compared to the nonlinear model predictions. The discrepancy in handle displacement between the nonlinear model and mechanical simulation is likely due the coulomb friction not being included in the nonlinear model. Therefore, this study shows that by suing an offset to compensate for the coulomb friction, the tool testing rig can be used to accurately simulate the nonlinear dynamic response of the human arm under a torque impulse.

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Introduction and Background

The purpose of this study is to simulate the non-linearity of human hand arm dynamics that occur during operation of DC torque tools, using a statistically repeatable mechanical device. The mechanical simulation of the human response will be used on DC torque tools to provide a method for evaluating the ergonomics factors associated with the tools. The response of the mechanical tool testing rig will be compared to a non-linear dynamic model based on studies of human subject responses to torque impulses.

DC torque tools have gained considerable popularity in the manufacturing industry as a primary choice to achieve high repeatability and joint tightening precision during assembly. They are particularly utilized in the automobile manufacturing because of their high accuracy to achieve the desired target torque. Additionally, the DC torque tool nut runners also have a low overall sound level, and do not require a compressed air supply like the previously used pneumatic nut runners.

Despite their contributions to increase torque accuracy and tightening efficiency, powered torque tools are, however, associated with a considerable reaction forces acting on human operators. The high reaction forces of the torque tools subject assembly line workers to repeated muscle stress, fatigue, and discomfort during the joint tightening (Kihlberg, Kjellberg et al. 1995).The repetitive, long term use of the DC torque tools have been linked to increased prevalence of carpal tunnel syndrome, tendinitis, and vibration white fingers (Kihlberg, Kjellberg et al. 1995).While tightening joints, the torque tools build up torque and move the tool handle in the opposite direction of the muscle contraction, which results in an eccentric muscle contraction. Large, repetitive eccentric muscle contractions have also been linked to an increased risk of short term muscle fatigue as well as longer term injury (Lin, Radwin et al. 2003).

Several studies investigated the subjective discomfort of experienced nut runner operators. Kihlberg et al. (Kihlberg, Kjellberg et al. 1995), investigated what are acceptable levels of operator discomfort while using pneumatic torque tools. Although the operation of pneumatic torque tools does differ significantly from that of the DC torque tools, this study provides useful ergonomic information and operator preferences that are relevant to DC torque tools. Kihlberg performed the study with 38 truck assembly plant workers who were experienced in the use of pneumatic nut runners. In particular, this study attempted to investigate the reaction force experienced by the tool operator at the handle, and the subjective rating of operator discomfort at different reaction force levels. Because previous studies had found a strong correlation between tool handle displacement, as well as maximum torque, Kihlberg attempted to determine which predictors were best used to determine operator discomfort. For the experimental setup, a total of four different types of angle nut runners were used, including one tool with a 75 Nm spindle torque and three with spindle torques of 50 Nm and fast, slow, and delayed cut-off mechanisms. The tool was positioned at a height of 124 cm, from 10 cm above the elbow height of the 50th percentile man. A goniometer measured the angular position of the nut runner, and a force platform measured the reaction forces on the tool operator's feet. The test subjects were asked to rate the operation of each tool on a scale from zero to twenty, with zero being no discomfort at all, and twenty being extremely discomforting. The results of the study showed that the average discomfort ratings were strongly related to the total displacement experienced by the tool handle during use. Increases in tool handle displacement increased the discomfort ratings given by the subjects. Additionally, Increases in tool handle reaction force was also linked to an increase in average discomfort ratings given by the test subjects. The study also asked participants what they considered an acceptable level of discomfort for a full 8 hour workday. All of those surveyed said they would work a full day at a discomfort level of 2, while none of the workers would work a full day at a discomfort level of 9. This study provides useful data for torque tool designers who need to know what range of handle displacement and handle force nut runners should have to be acceptable for long term use.

Previous studies have looked at mechanical models for hand-arm-tool interaction during torque tool use. Oh (Oh, Radwin et al. 1997), looked at both a static as well as a dynamic model for the human-tool interaction, and compared the models with experimental data. Oh *et al.* proposed that when there was considerable movement during the operation of the tool, the static model provided a less accurate approximation of hand reaction force. Oh *et al.* (Oh, Radwin et al. 1997) created a dynamic model to be operated with different combinations of target torque and joint hardness. The results from this testing showed that the peak inertial force during torque build-up was highly effected by the torque build-up time. Additionally, it was found that the peak inertial force decreased as the build-up time increased from 35 to 150 ms, although it did not change significantly for durations longer than 300 ms. The results also showed that the increases in target torque magnitude also significantly increased the peak inertial force after the tool had been shut off. This study was the first to attempt to estimate hand force for a right angle torque tool and how the tool's dynamic parameters affect the hand force. The peak and average hand force were smaller for smaller target torques and hard joints with shorter build-up times. This indicated the shortcomings of the static model, which failed to account for the inertial effects of torque rate and build-up time. Additionally, the static model did not account for the hand force due to inertia after the tool shutoff had occurred. A tradeoff was suggested where the increased tool inertia results in reduced angular acceleration, but increasing the mass of the tool to increase the inertia also increased the force required to support the tool. Oh concluded that the upper arm and body mass should contribute to the mass acting on the tool, depending on the working posture of the tool operator. Oh suggested that future models should account for the force components affected by operator posture and orientation.

Lin (Lin, Radwin et al. 2001) also examined the dynamic model of pistol-grip torque hand tool operation and its influence on muscle exertion and ergonomics. The study developed a biomechanical model to help understand the hand and arm response to mechanical shock during torque tool operation. A beam attached to the rotational spring could be displaced and released to provide the system response. Subjects held the mechanical system by a handle as they would a torque tool and resisted the oscillations of the spring and beam.

The human subject testing indicated that the torsional stiffness and damping constant was affected by horizontal distance from the handle, vertical distance to the handle, as well as gender. Handle displacement was then predicted using the stiffness, moment of inertia, and damping constant extracted from each human subject test completed. The handle displacements predicted by this model tended to be 27% lower than the recorded values in model validation experiments carried out with actual pistol-grip tools. However, this study did suggest that an undamped spring and undamped elastic element could effectively represent the mechanical response of muscle. This study also confirmed that the horizontal and vertical distance from the torque tool to the operator affected stiffness, inertia, and damping in the arm.

Lin (Lin, Radwin et al. 2003) further investigated the single-degree-of-freedom dynamic mechanical system model. He used mass, springs, and damping elements to represent the human operator of spindle power hand tools. Lin hypothesized that the mechanical parameters of the system model are vary by work location, posture, and individual tool operators. The goal of this study was to quantify the mechanical model parameters for different work surface locations in a similar way that was done in his previous study (2001). A visual representation of the dynamic model can be seen in Figure 1. By using known values for the test apparatus mechanical elements, the model parameters for the human operator could then be determined. The apparatus applied a harmonic impulse using a torsional mass which was allowed to oscillate about its axis of rotation, at which point the human subjects were instructed to use maximum effort to stop the oscillations by applying force to the apparatus handle.

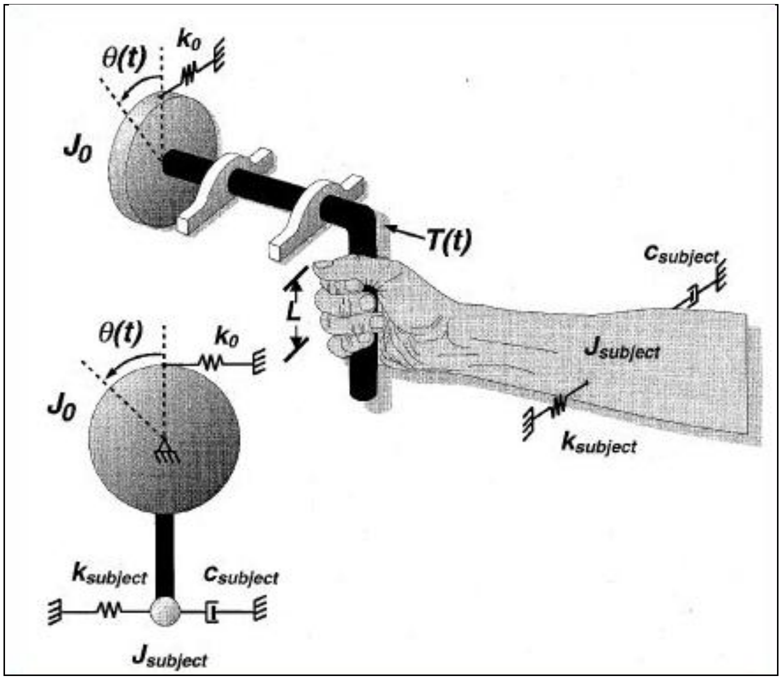

Figure 1: Lin's Dynamic Model of Tool-Task-Operator System (Lin, Radwin et al. 2001)

Lin used the dynamic stiffness of the system, which he defined to be the ratio of peak-to-peak handle torque and angular displacement, to validate the model. The measured stiffness of the subject was used with the angular frequency of the oscillating mass, ω, and the moment of inertia of the subject and apparatus to calculate the ratio of handle torque to displacement.

$$\frac{\Delta T}{\Delta \theta} = k_{subject} - \omega^2 \left(J_{subject} + J_{apparatus} \right) \qquad \text{(Eq 1)}$$

The model error could then be calculated from the difference in the predicted and measured peak-to-peak handle torque and angular displacement ratio. The results from this study found that horizontal position of the tool handle and the gender of the tool operator had a large effect on the effective mass moment of inertia of the human operator. The vertical position of the tool handle with respect to the human operator also had a large effect on the effective stiffness, mass moment of inertia. The study found that for right-angle handles on a horizontal surface, no factors had a statistically significant effect on the damping parameter of the system. This study found that the mechanical parameters of each subject did vary significantly, as was anticipated (Lin 2003).

Lin (Lin, 2005) continued to study the ergonomic factors of power hand tool operation by developing a method to use the dynamic mechanical model to improve tool selection and work design for the reduction of operator stress. The study showed how interpolation could be successfully used to estimate model parameters for different work postures and positions. However, variance due to individual differences in weight, height, and strength, were also predicted.

In Lin’s follow up study into the handle displacement and operator responses to pneumatic nut runner torque build-ups (Lin, Radwin et al. 2005) he again investigated the workstation position and the tool operator reaction forces. The experimental setup included different joint hardnesses to simulate both soft and hard joints using different numbers of Belleville spring washers. Softer joints have longer torque build-up duration than harder joints, and this torque duration may have a potential negative health effect on the human operator in the long term. The results of the study showed that for right angle torque tools used on horizontal surfaces, the tool operator allowed a larger handle displacement when tightening hard joints that when tightening soft joints. These results also indicated that there was a decrease in handle displacement when the torque build-up time increased beyond a certain value. This confirmed observations made during previous studies by Oh and Radwin (Oh, Radwin et al. 1997). They speculated that for longer torque build-up times the torque tool operators had enough time to give a conscious response to resist the torque impulses.

Previous studies to identify the single degree-of-freedom, linear, second order model for the human arm operating right-angle torque tools were completed by Haluk Ay et al.(Ay, Sommerich et al.). The first study completed built on previous work by Lin, which involved subjects being instructed to stabilize an under damped mechanical system in oscillation. Although Lin’s studies provided a method to characterize the human are as a dynamic system, the human testing was performed with a setup that did not closely mimic the impulsive torque caused by typical DC torque tools. Unlike Lin’s study, Ay’s study aimed to more closely mimic the right-angle torque tool operation. The experimental setup used a handle and tester bar connected to a rotational actuator, as shown in Figure 2 shown below. The tester bar handle was instrumented with a rate gyro to measure angular velocity and strain gages to measure the handle reaction force. The angular displacement and acceleration of the testing handle were obtained by numerically integrating the velocity signal from the rate gyro. The single degree of freedom human arm model was represented with the equation 3 below.

$$T = kL_h^2\theta + cL_h^2\dot{\theta} + (m\dot{L}_h^2 + I_o)\ddot{\theta} \quad \text{(Eq 3)}$$

k, *c*, and *m* are the effective stiffness, damping, and mass of the human arm model, respectively. L_h is the length of the testing apparatus handle, θ is the angular displacement of the apparatus handle, T is the input torque impulse, and I_o is the mass-moment of inertial of the apparatus handle. The least squares method in the time domain was used to determine the model parameters. Validation was done simulating the obtained model and inputting the same torque to determine if the output handle displacement would be identical to that of experiment. Additionally, the handle force was calculated with equation (2).

$$F_r = L_h(k\theta + c\dot{\theta} + m\ddot{\theta}) \quad (2)$$

The calculated F_r from equation (2) was compared to the strain gage measurements from the testing apparatus. Based on this study Ay *et al.* (Ay, Sommerich et al.) hypothesized that it was possible to directly instrument a DC torque tool to determine human arm system parameters during use to achieve more realistic tool operation conditions.

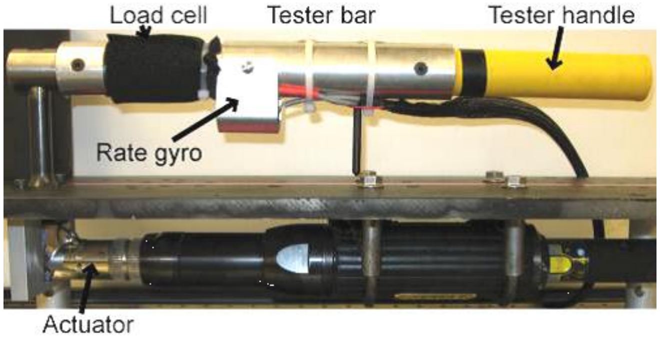

Figure 2: test apparatus for human testing rig

Although many of the studies previously discussed describe single degree-of-freedom, linear, second order models, a study by Gielen and Houk (Houk, 1984) actually showed that the response of the human wrist more closely resembled viscous forces that were not linear, but depended on the low fractional power of viscosity. Although the focus of Gielen and Houk's study was on wrist dynamics, the concept of nonlinear muscle force is also considered relevant to the arm dynamic investigated in the present study.

Honda Tool Evaluation Rig

While the previous studies have primarily focused on identifying the dynamic system parameters of the human arm, other studies have attempted to use that research to further the goal of designing DC torque tools to reduce the number of musculoskeletal injuries in the long term. A right-angle torque tool testing rig was created that could be used to objectively evaluate tools and torque control strategies with respect to target torque, joint rate and simulated operator dynamics. Currently, static testing is required for the measurement of the power tool reaction torque and torque impulse. However, handle displacement and acceleration of the tool handle are also important to the comfort of the tool operator. In order get accurate predictions of how handle displacement and acceleration will be affected by human tool operator dynamics, the tool testing rig must be able to accurately simulate the response of the human arm to a torque impulse. In order to simulate a wide range of the tool operator population, the testing rig must be able to vary the simulated effective human arm stiffness and mass. This means the rig must be able to mimic tool operator response to different tools, tasks, and positions. It must also be able to experimentally measure the handle force and angular displacement of a variety of right angle torque tools.

Several of the early designs to create a tool testing rig were completed by (Mukherji 2008). These first tool rig designs were able to validate the concept as a whole, but they had multiple physical limitations. The most recent tool testing rig, shown in Figure 3, improved on some of the limitations of the previous design to better quantify right angle torque tool performance for the human operators. The frame of the tool testing rig was made of an adjustable rail guide system which allowed tools of different sizes to be accommodated for evaluation. The load cell which measures the reaction force on the tool handle rotates with the tool, remaining normal to the handle while moving along the linear slide. A linear variable displacement transformer located along the linear slide measured the linear displacement of the tool, which was then converted to an angular displacement for the tool handle based on the kinematic model identified for the system. The human arm dynamics were modeled according to a linear, second order model approach similar to Lin’s (Lin et al. 2001). The effective stiffness of the human arm was simulated by an air cylinder with a manually adjustable air pressure. The effective mass of the system was simulated by removable rectangular plates that could be attached to the linear slider. Three different joint hardnesses could be simulated by varying the number of Belleville washers on the fastener head.

Figure 3: DC Torque Tool Ergonomic Evaluation Rig

The identified effective stiffness, damping, and mass obtained from human testing obtained by Ay et al, was used to set the system parameters on the testing rig. The resulting tool handle displacement and peak handle force could then be compared to the values obtained from the human testing. The comparison between the two values indicated that the testing rig consistently underestimated that peak handle force and angular displacement, likely due primarily to the friction in the air cylinder and different damping between the two models. Another drawback to this tool testing rig design is that it requires manual triggering of the torque tool by a human operator, require a light touch to not affect the system response.

Methods

In order to simulate a non-linear model of human arm response to a torque impulse, a new tool testing rig and mechanical model needed to be developed. The repeatability of the testing rig was evaluated using by completing study of the tool handle force and peak displacement at different simulated human arm parameters.

The redesigned torque tool evaluation rig differs significantly from previous designs. Unlike the previous models, the evaluation rig used in this study attempted to simulate a non-linear model of human arm dynamic stiffness to better mimic the response of a human torque tool operator. The evaluation rig, shown in Figure 4, consists of a standard Stanley DC torque nut runner mounted below a fixed steel platform. Torque tools of various dimensions can be accommodated in the testing rig using mounting brackets below the steel platform, as shown in Figure 5 and Figure 6, with the tool nut driver fixed to the tool tester handle located above the platform. The tool tester handle is fastened to a bracket which allows a guide block to slide along a ground steel rod, as shown in Figure 7. Polymer bushings were added between the guide block and steel rod to ensure that friction would be kept to a minimum. As the tool tester handle rotates about its axis of rotation, the steel guide rod swings freely about a reinforced hinge. A torque impulse to the tool tester handle is generated using a motor controller connected to the DC torque tool. The tool evaluation rig uses springs to simulate the stiffness parameter of the human arm model. Unlike previous models, this rig simulates a non-linear model that includes two different stiffness rates. The initial stiffness of the system, which represents the inherent stiffness of the human arm without conscious muscle contraction, is simulated by two tension springs which are attached to the tool handle on each side. While the tool handle is at equilibrium, the springs are each stretched to reduce any potential effects of stiffness nonlinearity near the compressed spring length. The tension springs apply linear spring force to the tool handle if the tool handle is displaced from equilibrium.

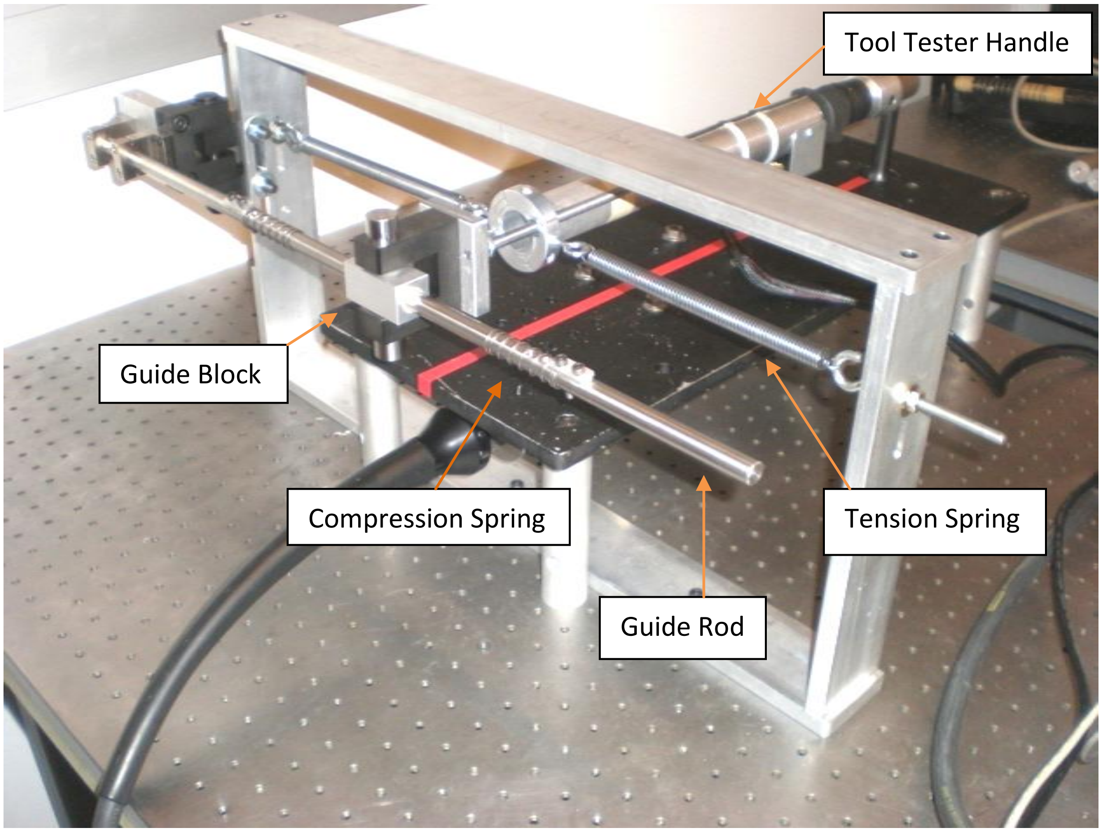

Figure 4: Current Torque Tool Evaluation Rig

A pair of compression springs has been incorporated into the evaluation rig to mimic the nonlinearity of the human arm response to a torque impulse. The nonlinearity is achieved by fixing the compression springs on a ground steel guide rod at a set distance from the end of the torque tool handle guide block. The offset distance between the guide block edge and the start of the compression springs allow the tool handle to move through a portion of its displacement without the additional stiffness of the compression springs. Once the guide block comes into contact with a compression spring on either side, the overall stiffness of the system will change, thus introducing a nonlinear rate of stiffness. The point at which the guide block comes into contact with the compression springs can be adjusted to reduce or increase the time delay before the overall stiffness of the system is increased. As with the previous tool evaluation rig designs, this rig does not have an adjustable damping parameter. Strain gages within the tool tester handle allow the handle reaction force to be recorded during each experimental test run. Additionally, rate gyros within the tool handle measure the handle acceleration, which is then numerically integrated to obtain the tool handle velocity and displacement.

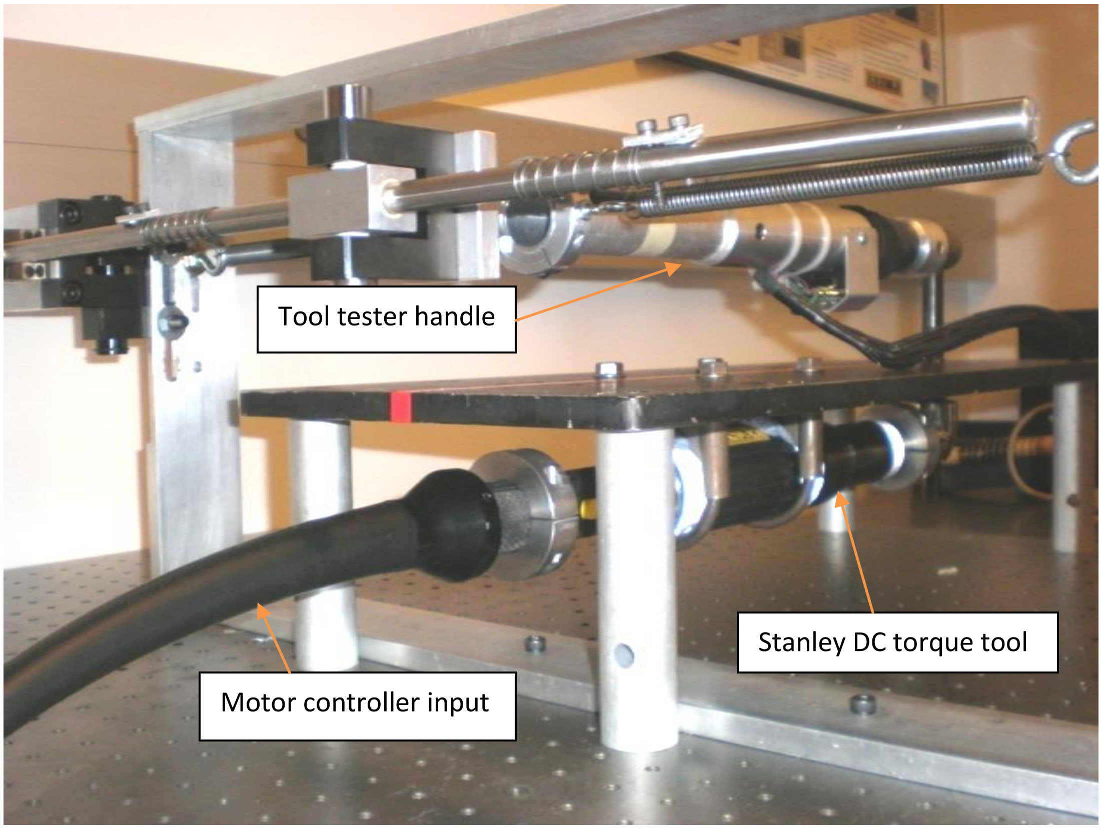

Figure 5: Tool Evaluation Rig Tool Mount.

Figure 6 shows the Stanley DC torque tool and the mounting brackets that hold the tool to the underside of the tool testing rig. The DC torque tool buildup time and magnitude is adjusted by using an external motor controller. Figure 7 show the connection between the between the DC torque tool and the tool tester handle.

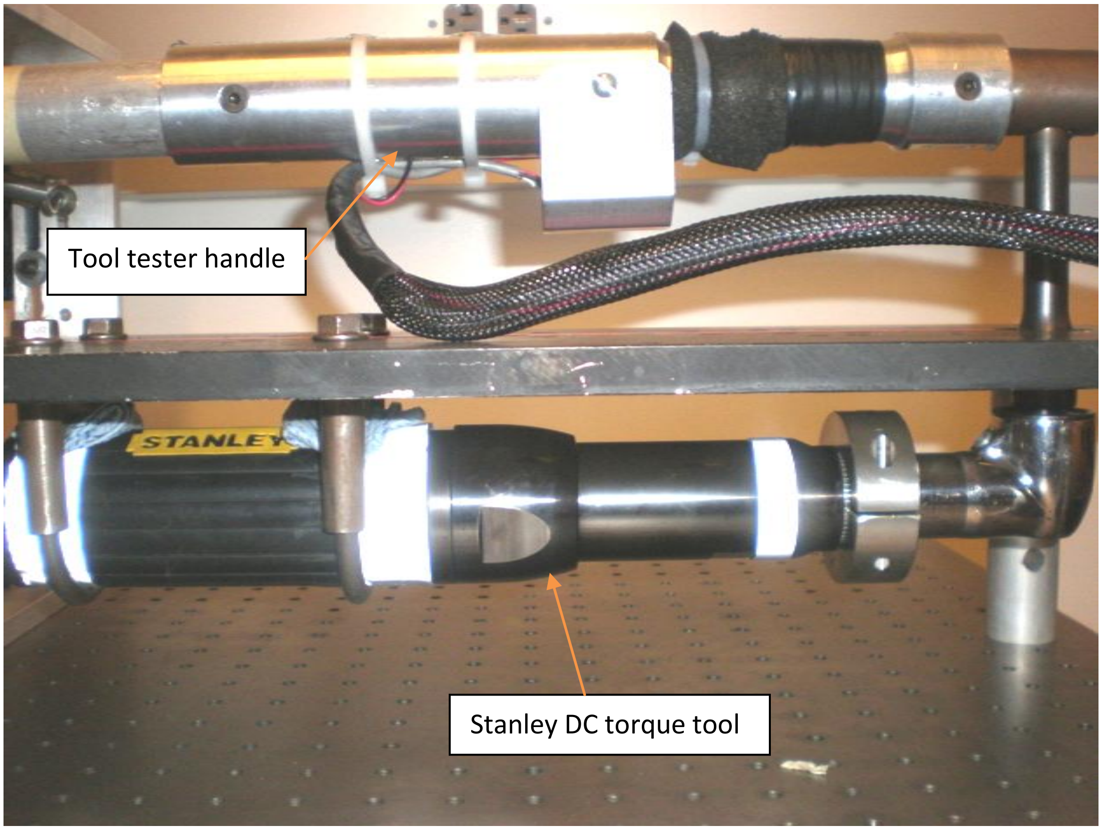

Figure 6: Connection between Tool Tester Handle and Torque Tool

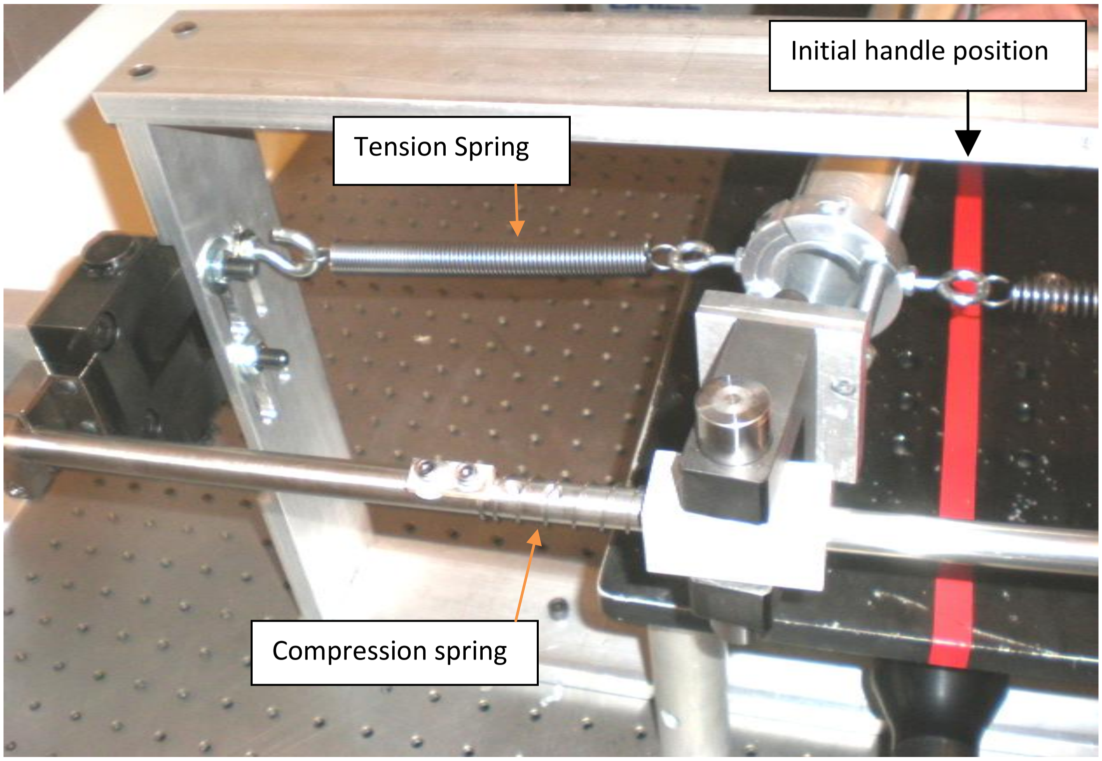

Figure 7: Tool Handle Tester While Displaced to Compression Spring

This experiment examines how the output handle displacement and handle reaction force are affected by changes in the simulated arm model parameters. The handle displacement and handle reaction force are the focus of this study because previous work has shown that these are the tool conditions that are linked most to tool operator discomfort and injury. Three mechanical model parameters were adjusted during this study. Two tension springs of different spring rates were tested, along with three compression springs of different spring rates. Additionally, the distance the compressions springs were offset from the guide block was adjusted to three different positions, each half an inch apart. Each of the model parameters were tested under several tool operating conditions. Three torque tool buildup times of 200, 450, and 700 ms were used to simulate soft, medium and hard joint stiffnesses. The torque tool torque magnitude was also tested at 20, 28, and 36 Nm. A full factorial study was completed to test each combination of different model parameters, with three repetitions completed for each condition to reduce the effect of outliers.

In addition to the tests to determine the effect of changing model parameters on tool output conditions, Ay (Ay, H. 2011) used his nonlinear system model to show how repeatable the tool evaluation rig is with respect to the input torque, output force, and displacement. The results from Ay’s repeatability analysis are shown in Tables 2 and 4, and Figures 8, 9, 10, and 11. This repeatability test was completed by performing twenty repetitions of the testing conditions with respect to both the mechanical model parameters and the tool input torque.

Results

The results from the repeatibility tests were anaylsed based on which variables were adjusted. Figure 8 and Figure 9 show the variance of the tool handle angular displacement and handle force with respect to mechanical parameters of the system. With the input torque magnitude set at 28Nm, and the torque duration set at 450 ms for each test, the mechanical system parameters were adjusted to 17 different testing conditions with different combinations of tension spring stiffness, compression spring stiffness, and bilinearity starting position, as shown in

Table 1 . The results indicate that the tool testing rig is repeatible across the entire range of mechanical testing parameters.

Table 1: Testing Conditions for Repeatability Testing With Respect to System Parameters.

Testing Condition #	Tension spring	Compression spring	Bilinearity position
1	High Stiffness	Low Stiffness	Close
2	High Stiffness	Low Stiffness	Medium
3	High Stiffness	Low Stiffness	Far
4	High Stiffness	High Stiffness	Close
5	High Stiffness	High Stiffness	Medium
6	High Stiffness	High Stiffness	Far
7	High Stiffness	Medium Stiffness	Medium
8	High Stiffness	Medium Stiffness	Far
9	Low Stiffness	Low Stiffness	Close
10	Low Stiffness	Low Stiffness	Medium
11	Low Stiffness	Low Stiffness	Far
12	Low Stiffness	High Stiffness	Close
13	Low Stiffness	High Stiffness	Medium
14	Low Stiffness	High Stiffness	Far
15	Low Stiffness	Medium Stiffness	Close
16	Low Stiffness	Medium Stiffness	Medium
17	Low Stiffness	Medium Stiffness	Far

Table 2: Standard Deviation of Handle Force and Angular Displacement for 17 Testing Conditions With Respect to System Parameters (Ay, H. 2011).

Testing Condition	Handle Force Standard Deviation (N)	Handle Displacement Standard Deviation (Rad)
1	0.78	1.48E-03
2	0.69	1.44E-03
3	0.48	2.15E-03
4	1.21	5.56E-04
5	1.07	1.17E-03
6	0.75	1.45E-03
7	1.48	1.41E-03
8	0.93	7.61E-04
9	0.88	1.56E-03
10	0.69	5.36E-04
11	1.71	4.76E-03
12	0.86	5.10E-04
13	0.90	6.21E-04
14	1.40	1.20E-03
15	0.64	4.09E-04
16	1.41	3.22E-04
17	2.13	1.23E-03

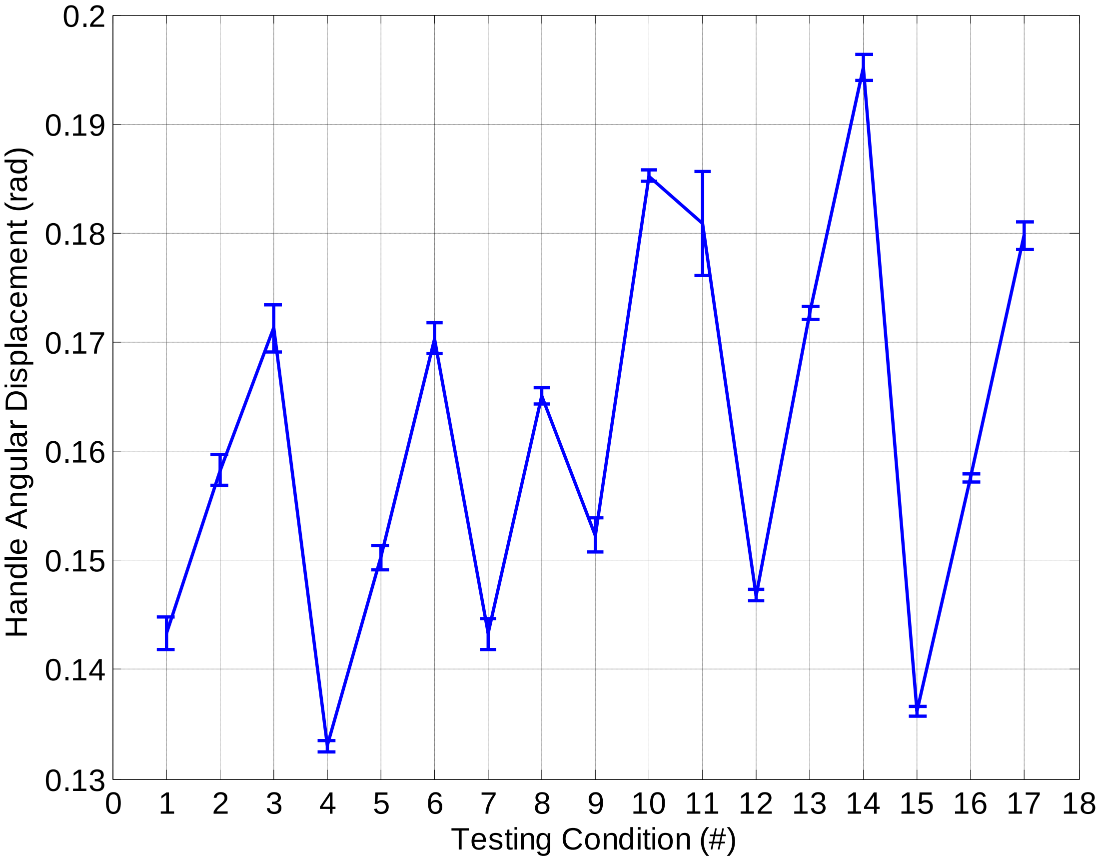

Figure 8: Handle Angular Displacement Repeatability With Respect to System Variables (Ay, H. 2011).

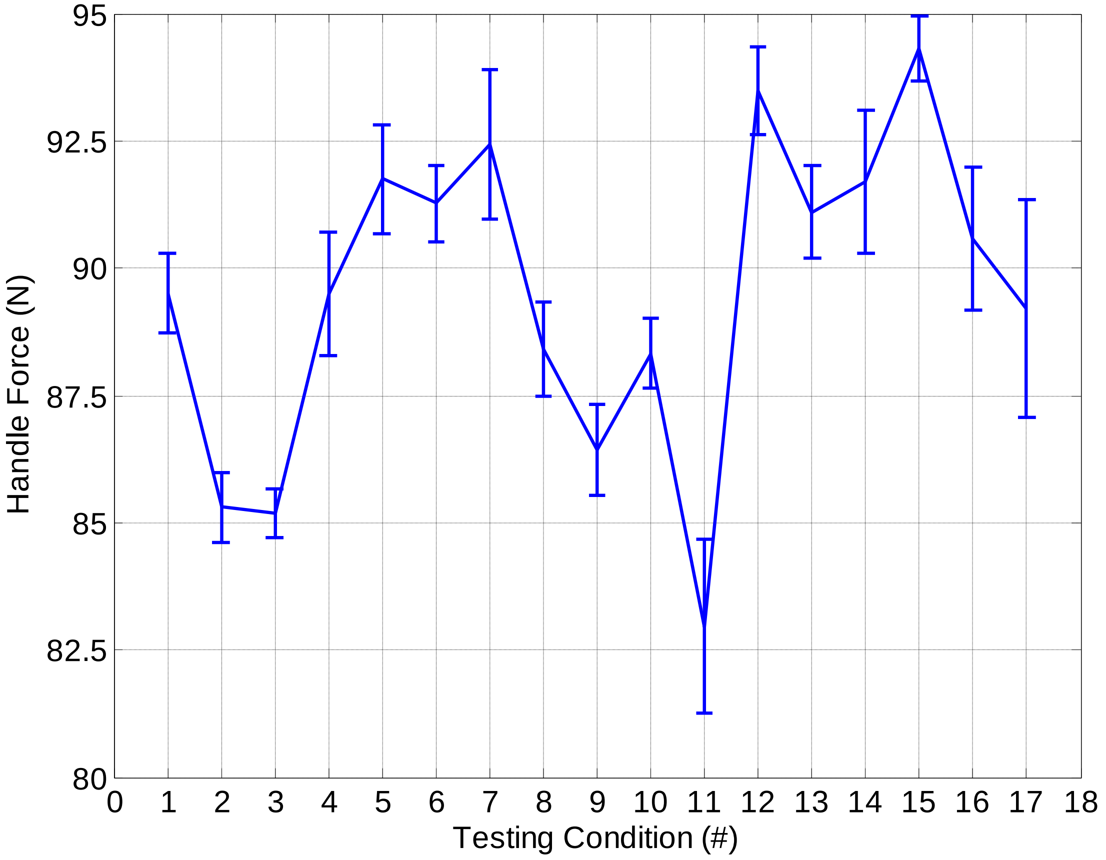

Figure 9: Handle Force Repeatability With Respect to System Variables (Ay, H. 2011).

The repeatibility of the handle angular dispalcement and handle force are also shown in Figure 10 and Figure 11, this time with respect to changing input torque values. A total of nine testing conditions were completed, with the torque magnitude varying between 20 and 36 Nm and the torque duration varying between 200 and 700 ms. The testing conditions for the input torque values are shown in Table 3. The repeatibility testing with respect to the input torque shows that the tool evaluation rig is also repeatible over the range of 20 to 36 Nm and 200 to 700 ms.

Table 3: Testing Conditions for Repeatability Testing with Respect to System Inputs.

Testing Condition #	Torque Pulse Amplitude (Nm)	Torque Pulse Duration (ms)
1	20	200
2	20	450
3	20	700
4	28	200
5	28	450
6	28	700
7	36	200
8	36	450
9	36	700

Table 4: Standard Deviation of Handle Force and Angular Displacement for 9 Testing Conditions With Respect to the System Inputs (Ay, H. 2011).

Testing Condition	Handle Force Standard Deviation (N)	Handle Displacement Standard Deviation (Rad)
1	0.60	1.42E-03
2	0.92	6.71E-04
3	0.98	6.82E-04
4	1.77	9.44E-04
5	1.07	1.17E-03
6	0.76	5.42E-04
7	2.09	1.09E-03
8	0.81	1.38E-03
9	0.69	8.11E-04

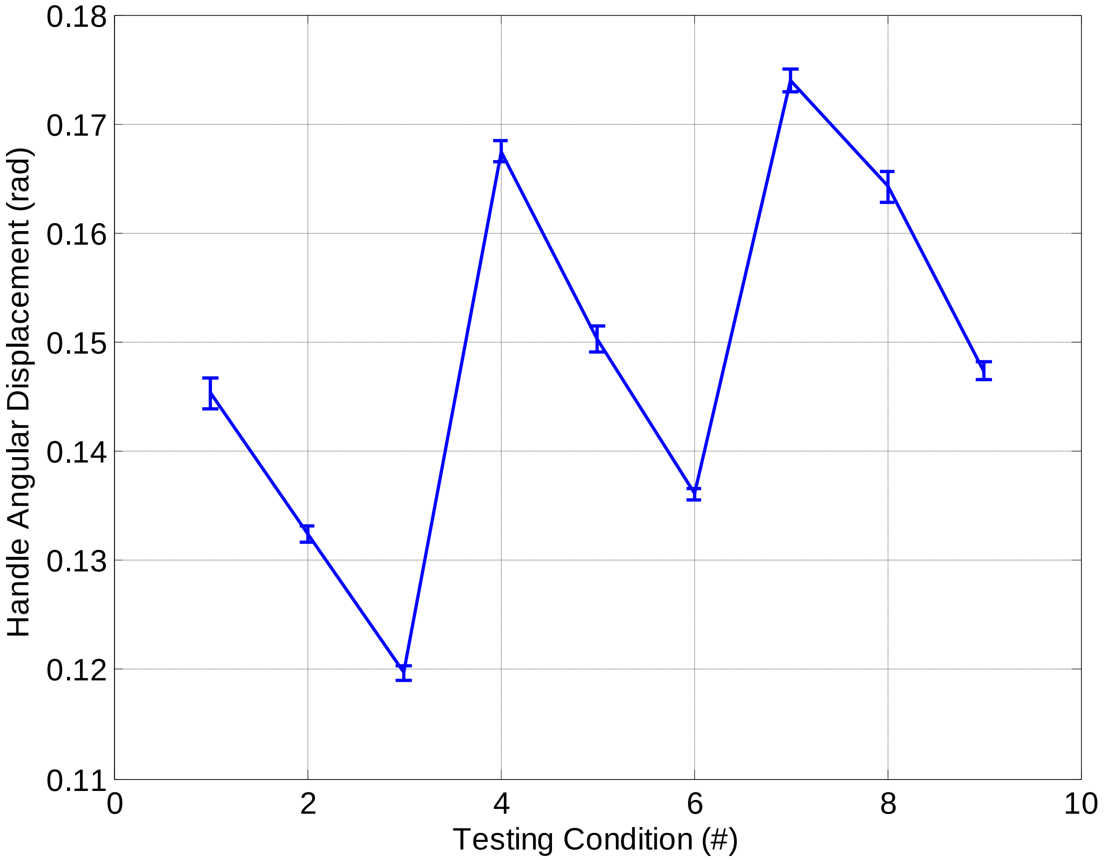

Figure 10: Tool Handle Angle Displacement Repeatability With Respect to System Inputs (Ay, H. 2011).

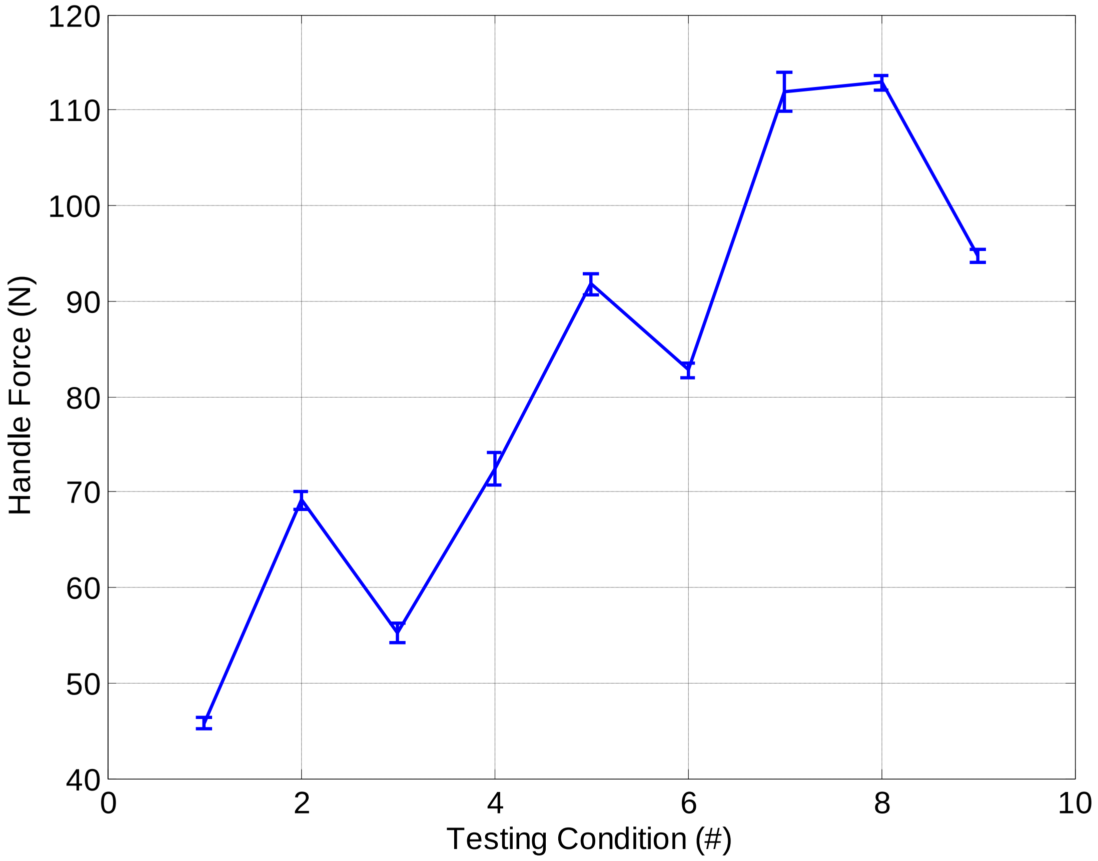

Figure 11: Tool Handle Force Repeatability With Respect to System Inputs (Ay, H. 2011).

The nonlinear model for human arm dynamic under a torque impulse currently being developed by Ay (Ay, 2011) was compared to the values collected experimentally using the tool evaluation rig. Two mechanical testing conditions were analyzed here in depth. Testing condition 1 includes the tool evaluation rig with a low stiffness compression spring with a rate of 667 N/m, a low stiffness tension spring with a rate of 250 N/m, and a bilinear offset of 4.125” from the edge of the guide block. Testing condition 2 includes the evaluation rig with a high stiffness compression spring with a rate of 1581 N/m, a high stiffness tension spring with a rate of 325

N/m, and a bilinear offset of 5.125” from the edge of the guide block. Both mechanical test setups were evaluated at several input torque durations and magnitudes, as shown in Table 5 and Table 6. The static measurements for the spring rates and bilinear offsets were also used with the nonlinear model to predict the behavior of the torque tool handle angular displacement at each testing condition. The maximum angular handle displacement as predicted by the nonlinear model and the experimental results from the mechanical testing, as well as the percent error for the nonlinear model can also be seen in Table 5 and Table 6. Figures 13 through 15 show the experimental testing rig data and non-linear model predicted tool handle angular displacement for each torque input duration and magnitude for testing condition 1. Figures 16 through 18 show the experimental testing rig data and nonlinear model predicted tool handle angular displacement based on Ay’s study (Ay, 2011) for each torque input duration and magnitude for testing condition 2.

Table 5: Max Handle Displacement for Nonlinear Model and Experimental Results with Low Stiffness Compression Spring, Low Stiffness Tension Springs, and Close Bilinear Start Position.

Torque Input Duration (ms)	Torque Input Magnitude (Nm)	Nonlinear Model Peak Displacement (rad)	Experimental Peak Displacement (rad)	% Error for Model
200	20	0.151	0.135	11.79
200	28	0.167	0.150	11.84
200	36	0.174	0.150	16.20
450	20	0.130	0.125	3.82
450	28	0.151	0.148	2.19
450	36	0.168	0.152	10.57
700	20	0.117	0.113	3.80
700	28	0.134	0.135	0.77
700	36	0.147	0.147	0.00

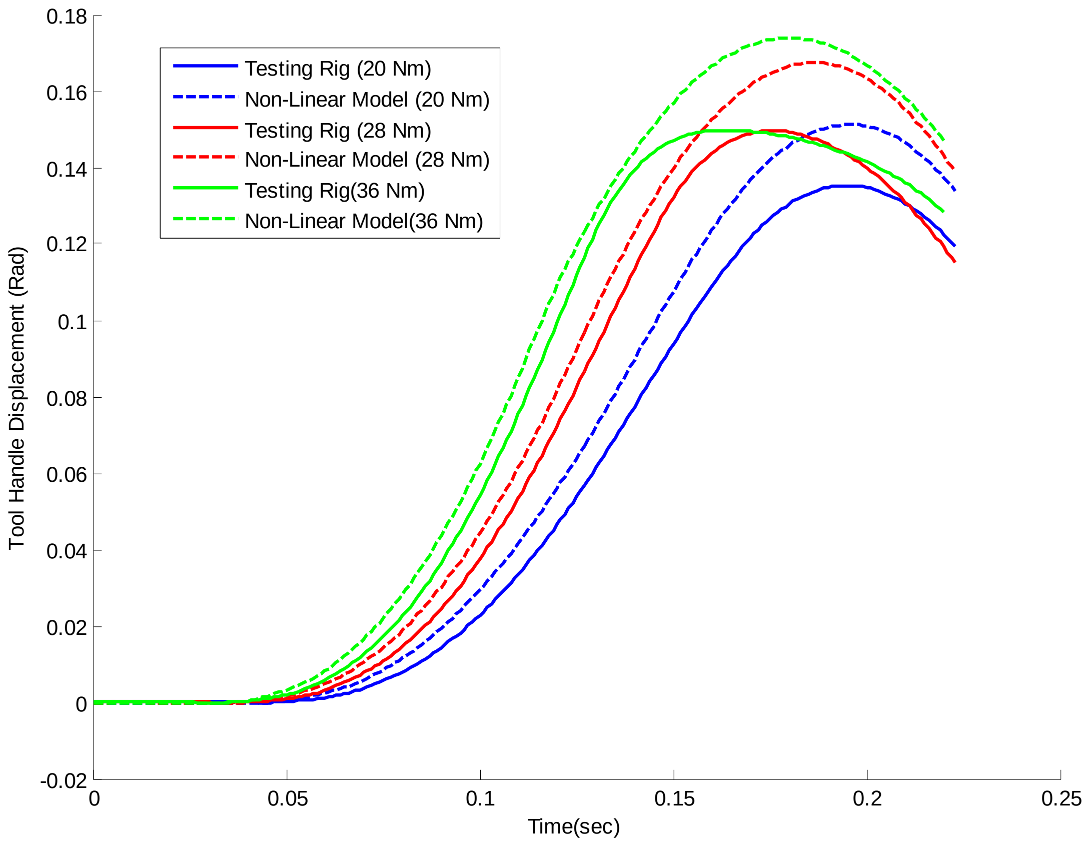

Figure 12: Tool Handle Angular Displacements for 200 ms Torque Impulses with Testing Condition 1.

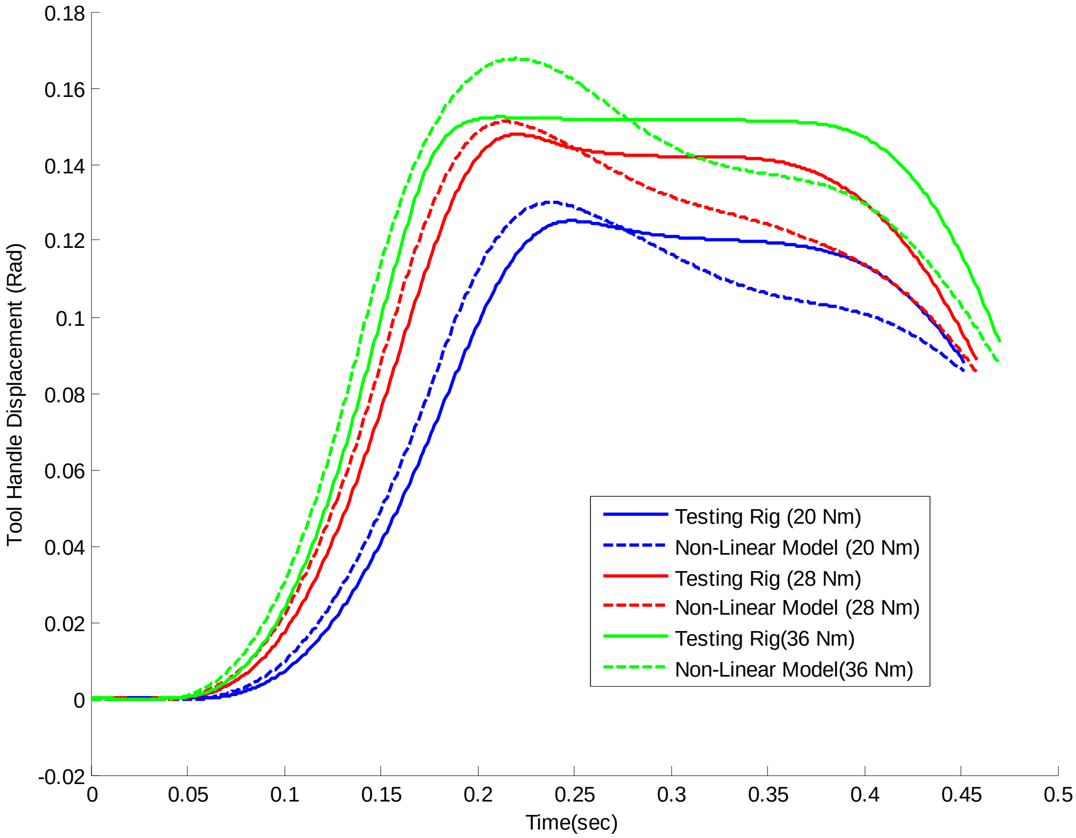

Figure 13: Tool Handle Angular Displacements for 450 ms Torque Impulses with Testing Condition 1.

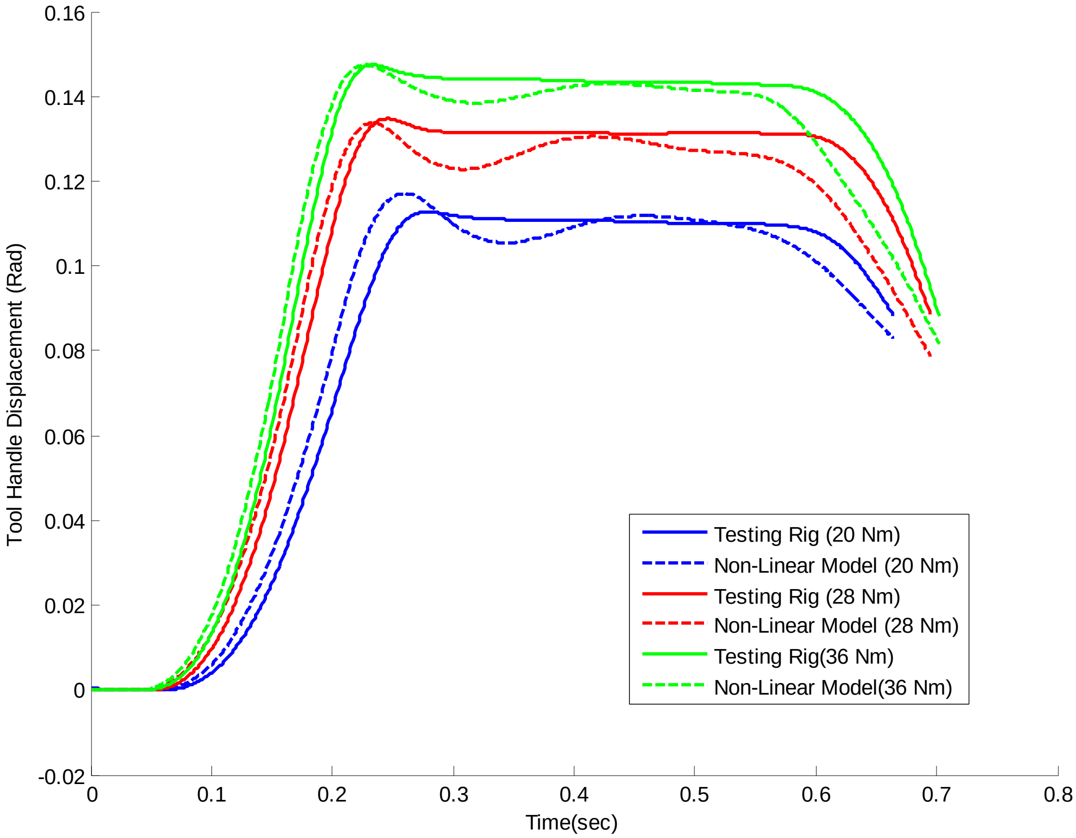

Figure 14: Tool Handle Angular Displacements for 700 ms Torque Impulses with Testing Condition 1.

Table 6: Max Handle Displacement for Nonlinear Model and Experimental Results with High Stiffness Compression Spring, High Stiffness Tension Springs, and Far Bilinear Start Position.

Torque Input Duration (ms)	Torque Input Magnitude (Nm)	Nonlinear Model Peak Displacement (rad)	Experimental Peak Displacement (rad)	% Error for Model
200	20	0.159	0.151	5.17
200	28	0.187	0.173	8.03
200	36	0.205	0.185	10.77
450	20	0.152	0.143	6.71
450	28	0.170	0.166	2.50
450	36	0.183	0.180	1.75
700	20	0.132	0.120	9.89
700	28	0.153	0.145	5.53
700	36	0.163	0.157	3.84

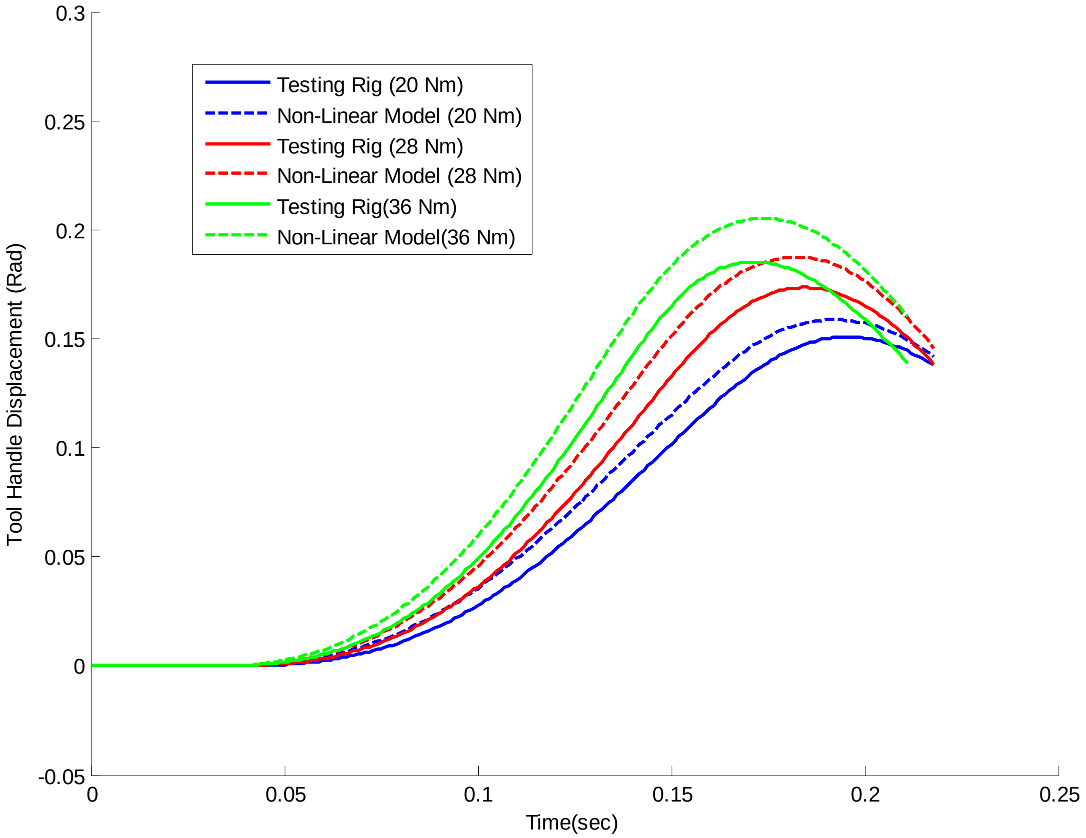

Figure 15: Tool Handle Angular Displacements for 200 ms Torque Impulses with Testing Condition 2.

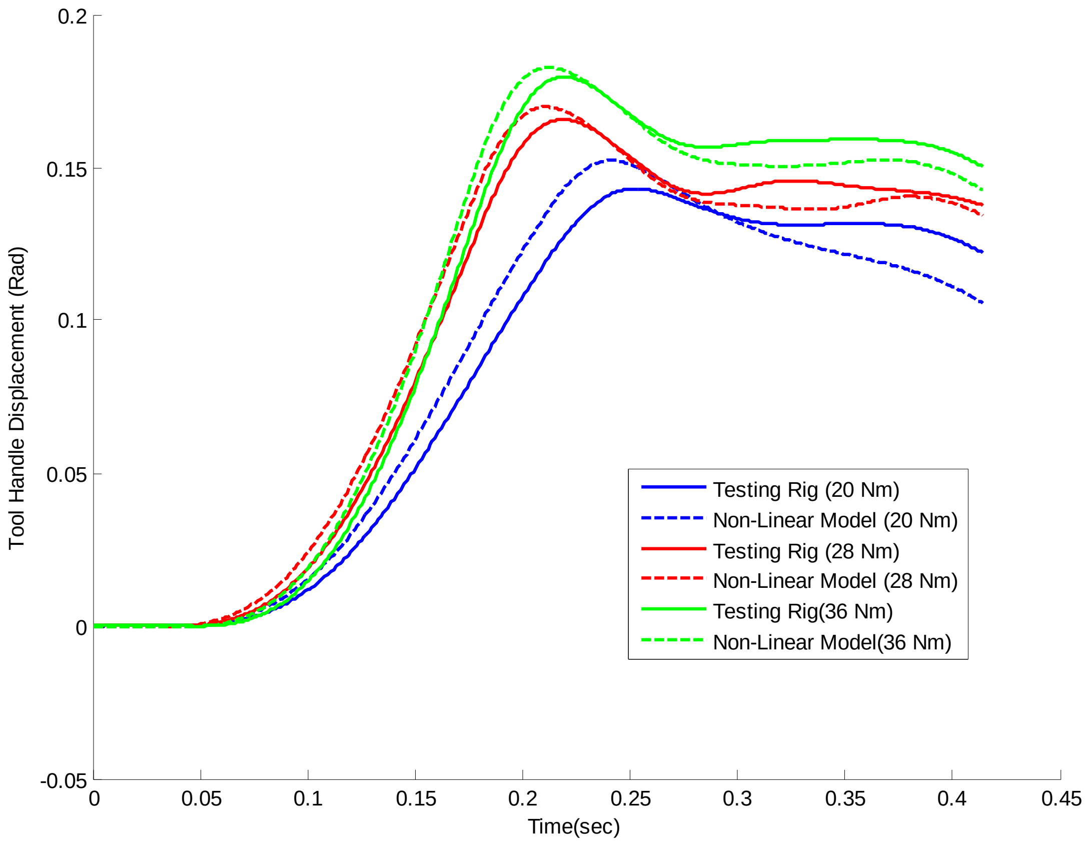

Figure 16: Tool Handle Angular Displacements for 450 ms Torque Impulses with Testing Condition 2.

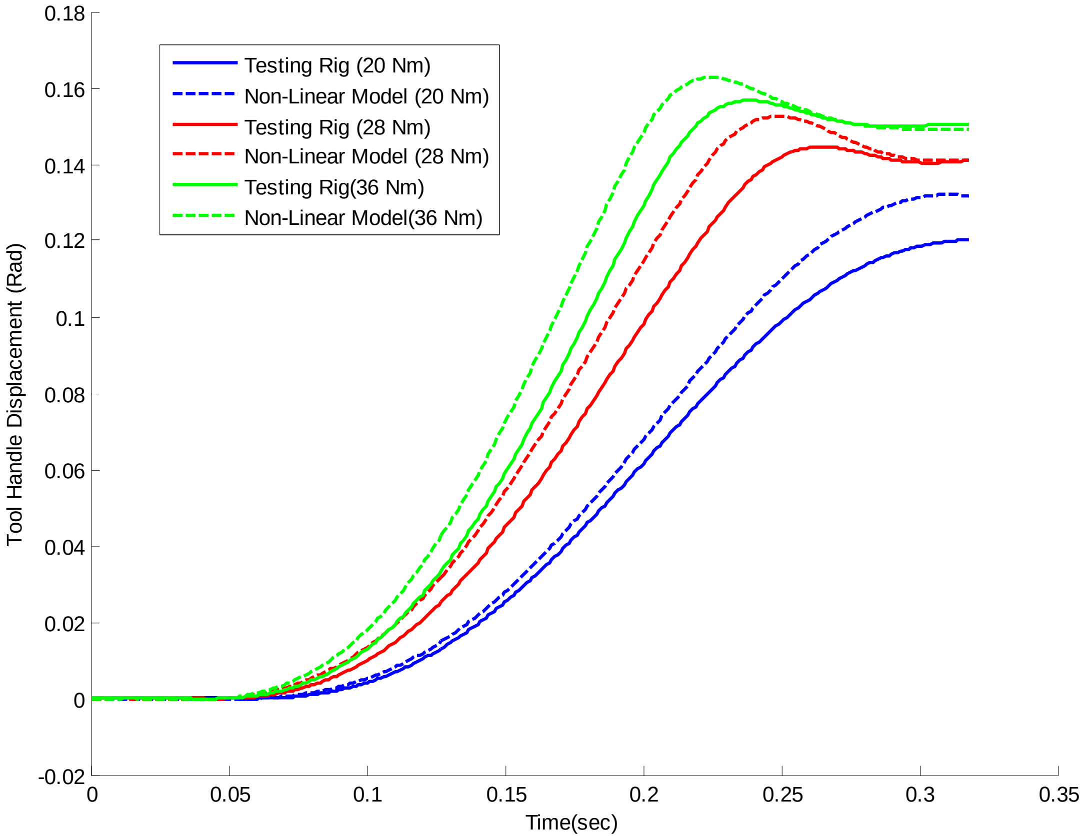

Figure 17: Tool Handle Angular Displacements for 700 ms Torque Impulses with Testing Condition 2.

In addition to the comparison of the nonlinear model and experimental results, this study also examines the relationship of tool handle angular displacement and handles reaction force with respect to the mechanical parameters of the system. Table 7 below show the torque input testing conditions used. Figure 18 shows the peak handle displacement for the 250 N/m and 350 N/m tension spring rates. Figure 19 shows the peak handle displacement for the low, medium, and high compression spring stiffnesses of 667 N/m, 1337 N/m, and 1581 N/m. Finally, Figure 20 shows the peak handle displacement for three different bilinear stiffness offset positions for the compression springs relative to the guide block. The closest bilinear offset position is 4.125”, the middle position is 4.625”, and the farthest offset position is 5.125” from the guide block’s edge.

Table 7: Testing Conditions for Mechanical Parameter Testing.

Testing Condition	Torque Duration (ms)	Torque Magnitude (Nm)
1	200	20
2	200	28
3	200	36
4	450	20
5	450	28
6	450	36
7	700	20
8	700	28
9	700	36

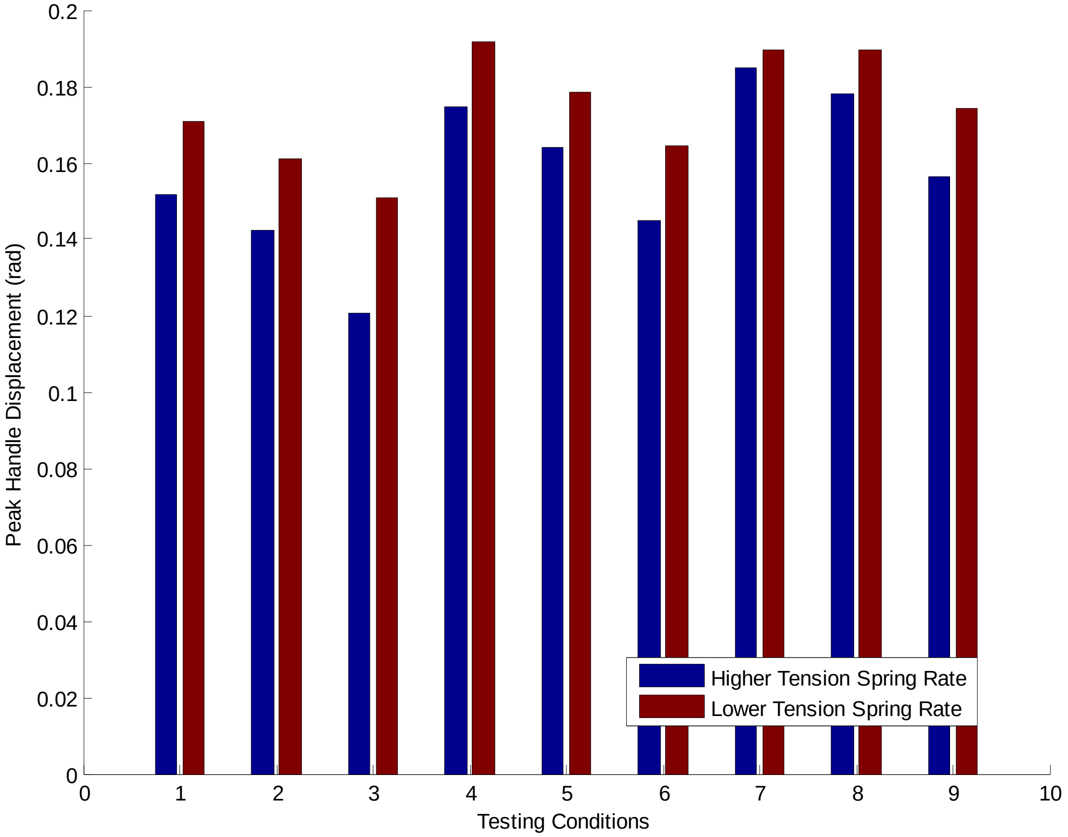

Figure 18: Peak Handle Displacement for Two Tension Spring Stiffnesses.

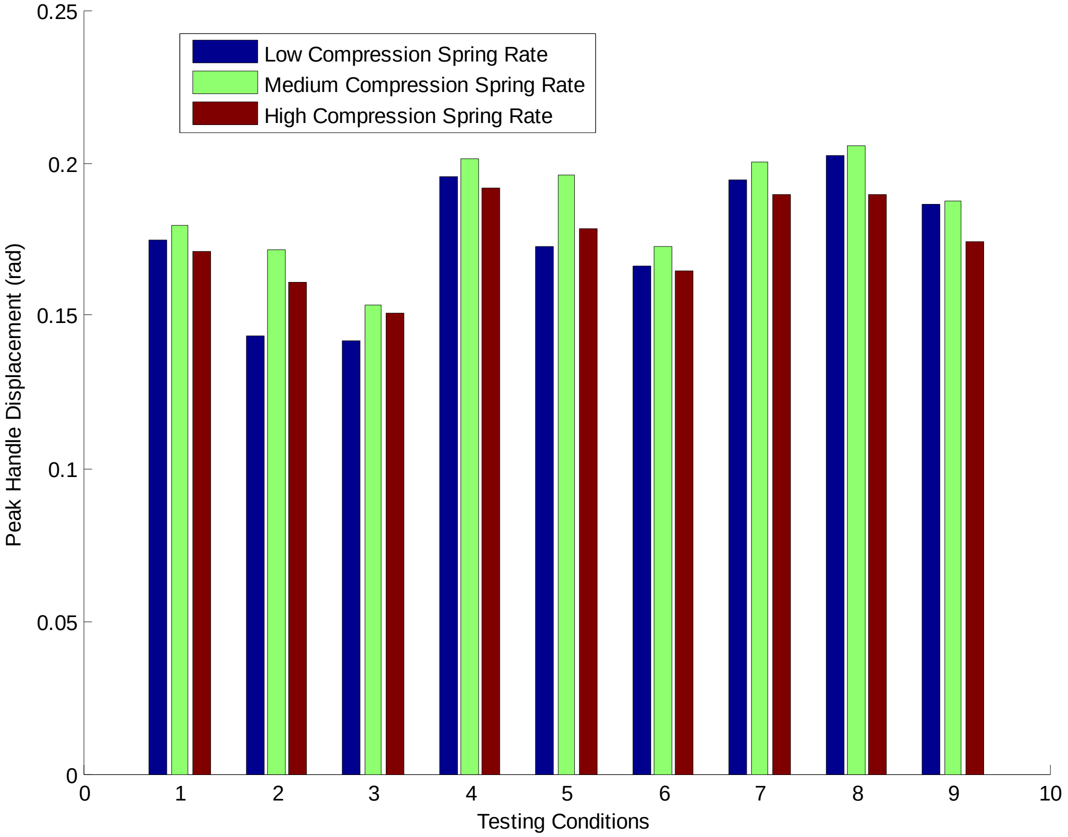

Figure 19: Peak Handle Displacement for Three Different Compression Spring Stiffnesses.

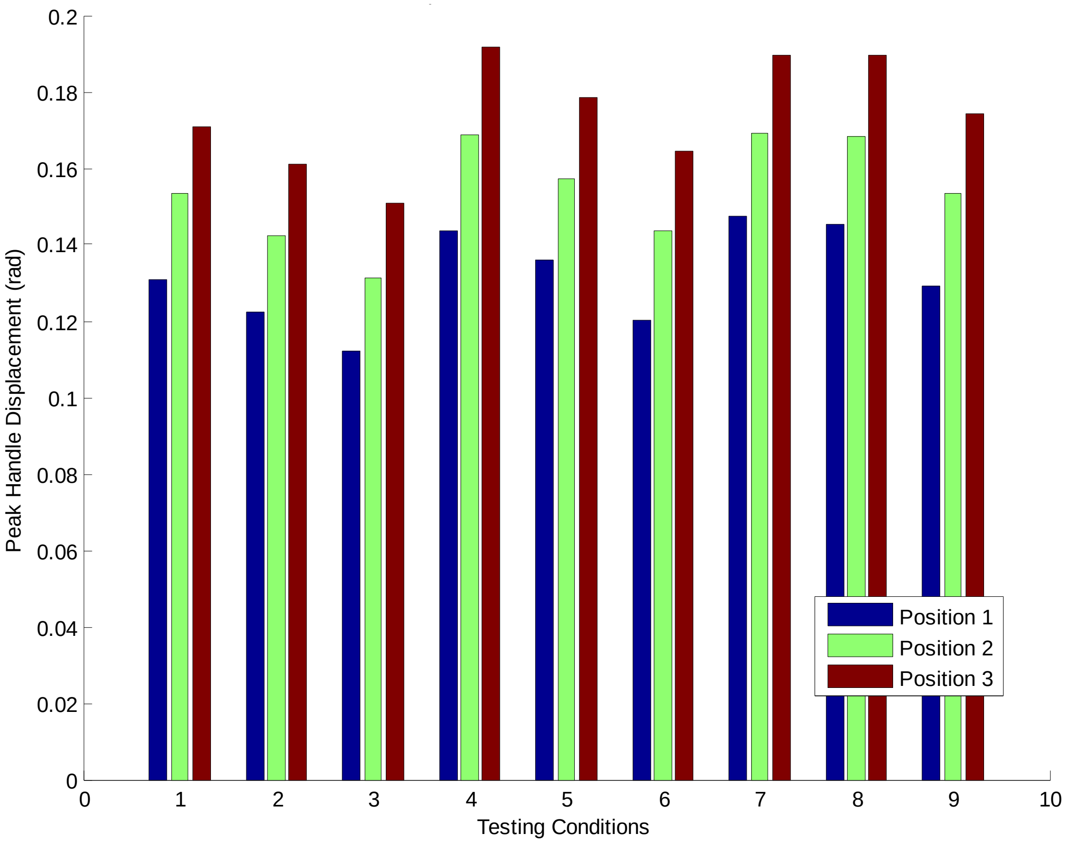

Figure 20: Peak Handle Displacement for Three Different Bilinear Start Positions.

Figure 21, 22 and 23 below show the tool handle force versus time for the 200ms, 450 ms, and 700 ms torque buildup. Additionally, the time at which the guide block impacts the compression spring has been labeled for the 450 ms and 700 torque buildups in order better illustrate the nonlinearity of the system.

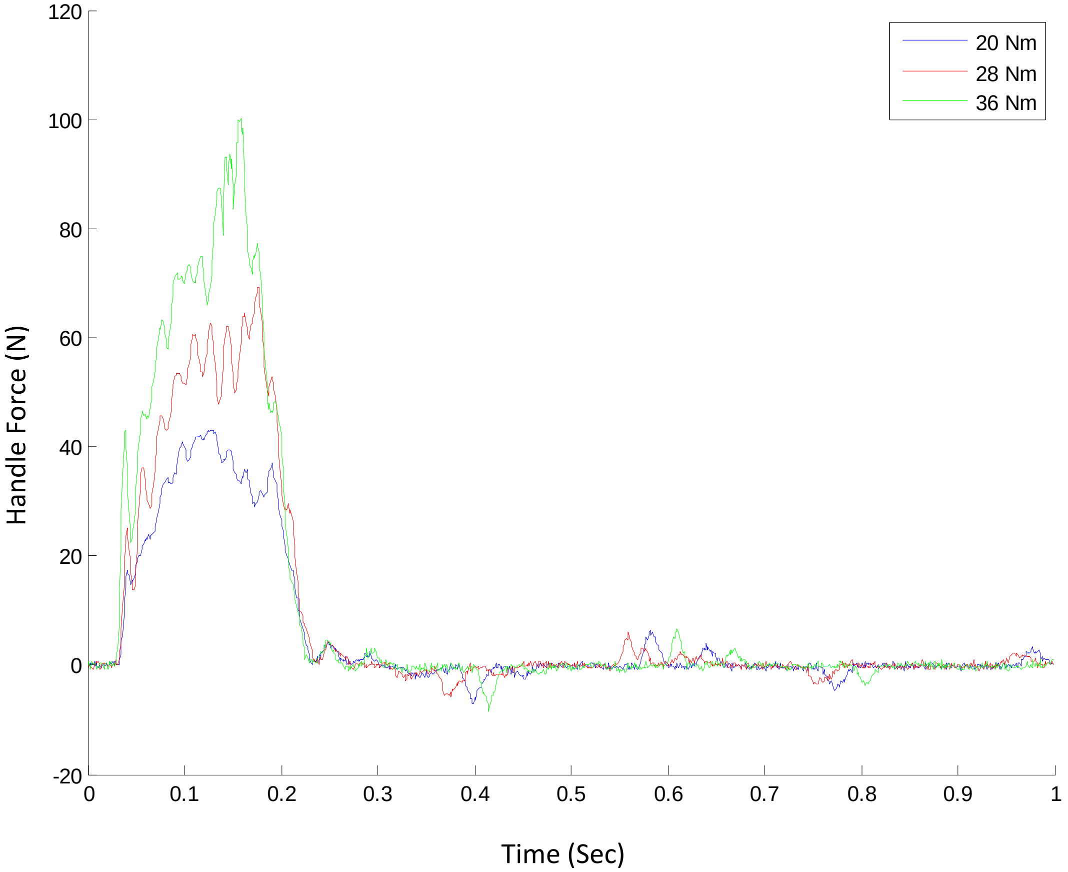

Figure 21: Handle Force vs. Time for 200 ms Torque Buildup.

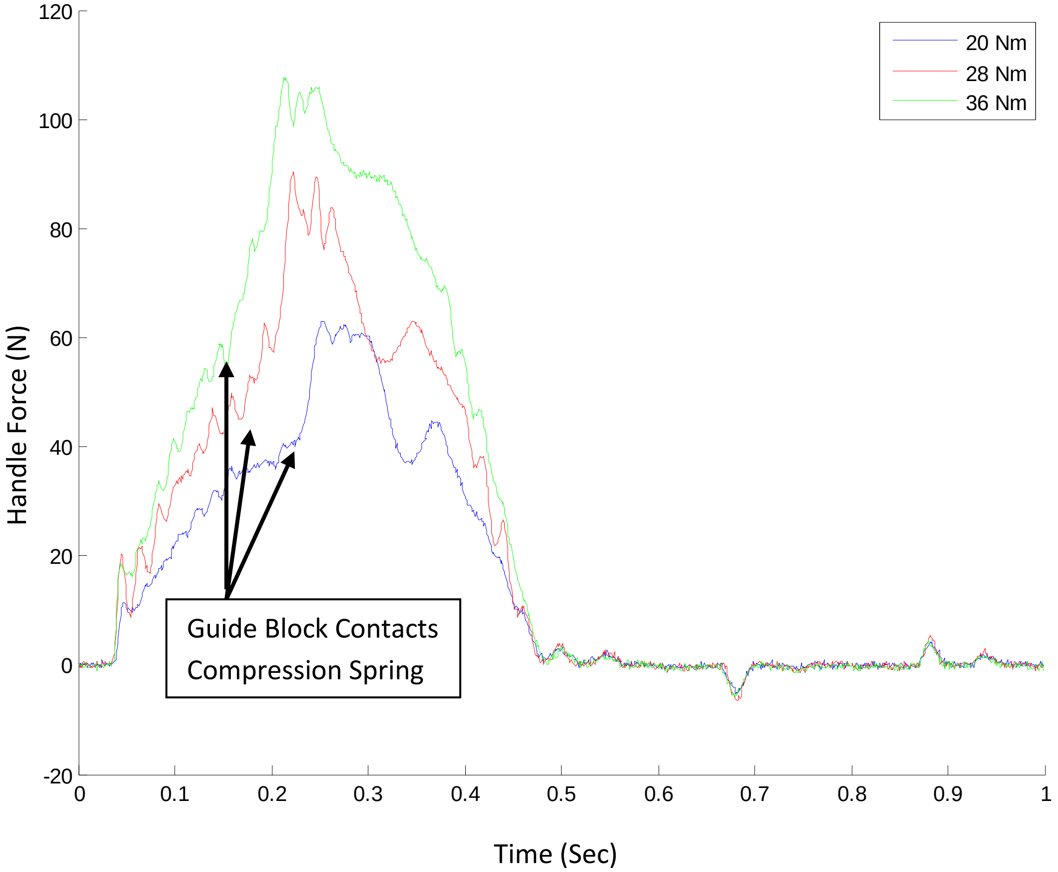

Figure 22: Handle Force vs. Time for 450 ms Torque Buildup.

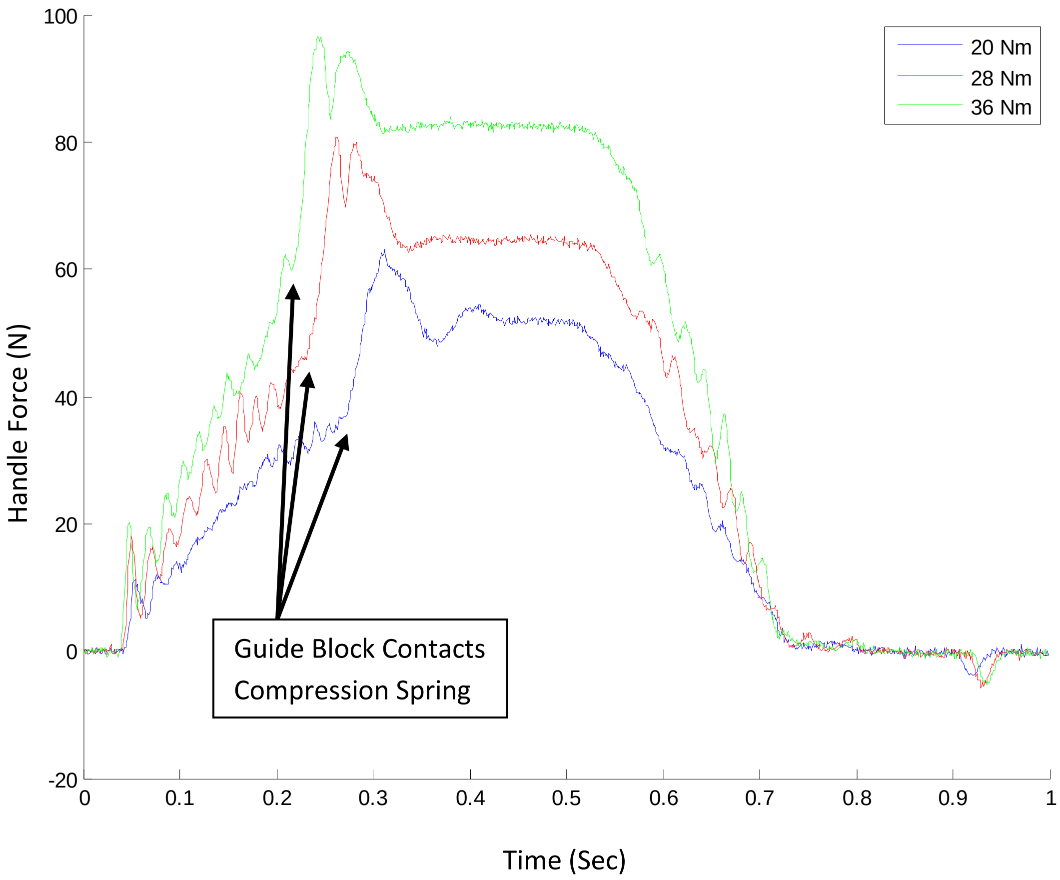

Figure 23: Handle Force vs. Time for 700 ms Torque Buildup.

Discussion

The comparison between the nonlinear model prediction and the experimentally measure results for tool handle displacement show several trends. Firstly, the nonlinear model consistently overestimated the handle displacement during the torque buildup period. Although the percent error of the nonlinear model remained below 10 percent for many of the testing conditions, it did reach as high as 16.2% for the 200 ms, 36 Nm torque impulse. Additionally, the percent error tended to decrease as the torque buildup time increased from 200ms, to 450 ms, to 700 ms. The torque impulse magnitude did not affect the model error to the same extent that the torque duration did. The tendency of the nonlinear model to overestimate the handle displacement may be attributed to the lack of coulomb friction in the nonlinear model prediction. Although the viscous friction within the system is accounted for in the model, the static and kinetic friction of the guide rod and other mechanical components within the test rig were not included in the model, causing the mechanical simulation to yield handle displacements lower than predicted by the nonlinear model.

This study shows that, although the tool testing rig tends to underestimate the handle displacement when compared to the nonlinear model prediction, the rig can still be used to accurately evaluate tools for ergonomic purposes. By including an offset in the mechanical testing rig data to compensate for the coulomb friction, the rig can accurately simulate the nonlinear dynamic human arm response to a torque impulse from a DC torque tool.

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