Effects of Bit Type on Maximum Torque and Axial Force Using Manual Screwdrivers

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EFFECTS OF BIT TYPE ON MAXIMUM TORQUE AND AXIAL FORCE USING MANUAL SCREWDRIVERS

by
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ABSTRACT

EFFECTS OF BIT TYPE ON MAXIMUM TORQUE AND AXIAL FORCE USING MANUAL SCREWDRIVERS

BY

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The screwdriver is a tool that has been among the most widely used hand tools for decades and continues to be used in the workplace to perform a variety of fastening tasks. Advancements in fastener technology have been complemented by the development of new types of screwdriver bits. While designs may vary, so do the force application requirements placed on the tool user. The primary objective of this experiment is to analyze the relationship between user torque and screwdriver bit design. A further objective is to utilize the results to develop an effort metric by which bits of different designs can be compared.

In this experiment, three types of screwdriver bit designs (straight, Phillips, and combination of straight/Phillips (ECX)) were tested to determine how the design affects the amount and type of force applied by the user when performing a fastening task. The designs were tested to simulate fastener tightening and loosening operations. Sixteen participants were tested in this study. Although there was no significant effect, the data suggest that the Phillips bit design allow subjects to exert the maximum torque and the minimum axial force. This divergence suggests that the Phillips bit may have a higher biomechanical effort ratio, which is greater torque for the same or lower axial force. Finally, the data suggest there is little difference in user torque exertion between the ECX bit and the straight bit designs. Subjective assessment indicated that users overwhelmingly preferred the Phillips bit design.

Bit designs requiring less axial force for the same torque exertion level reduce the overall muscular effort of the user, allowing work to be completed more efficiently and may reduce the risk of musculoskeletal disorder affecting the wrist, elbow, and shoulder. Results may also assist designers by allowing them to select fasteners that provide sufficient mechanical integrity of the design while maximizing user effectiveness.

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Mark D. Hickok, B.S.

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1.0 INTRODUCTION

The screwdriver is among the most widely used hand tools by workers. As the name suggests, it is a tool intended for use in driving screws. However, in recent time the variety of fastening options has increased, which has led to an increase in the number of fastener head styles available. Common to all these fastening options is they require the application of torque in order for them to be secured. When torque is applied by a manually operated, hand-held tool, it is the tool operator's hand that applies a force on the tool, often by repeatedly supinating and pronating the forearm, to turn the fastener.

While many fastening operations may involve a relatively low level of torque application, such as driving sheet metal screws or securing bolts into metal, others require a fairly high level of torque, especially those associated with fastening wood products. Historically, fastener development has shown head style (e.g. straight blade, Philips, square) has an effect on the user's ability to apply torque; a tool should be designed to allow its operators to apply torque in the most efficient way possible for the intended applications.

A recent innovation in screwdriver bit design is the ECX™ bit developed by Milwaukee Electric Tool, which features elements of both the straight blade and Philips head. This combination is intended to allow the bit to have increased retention in the fastener, which may have the added benefit of decreasing the push force required for proper bit retention. This can be significant, as when a driver bit does not stay in the fastener, the user must apply a forward "push" force in an attempt to increase bit retention. Reducing push force will minimize user fatigue and may increase productivity. This may also reduce an operator's risk of being affected by a musculoskeletal disorder affecting the wrist, elbow and shoulder. Additional research is needed to determine the efficacy of bit design advancements that will provide hand tool designers greater insight into the effects bit design may have on the operator.

2.0 LITERATURE REVIEW

2.1 Prior Studies

A comprehensive literature review was conducted prior to initiating the testing phase of this study. Results of the review identify factors shown to affect a person's ability to apply torque; though there may not be consensus as to the extent each factor affects the results. For example, studies conducted by Rhomert (1966), Chaffin (1999), O'Sullivan and Gallway (2001) suggest direction of torque application has an effect. They each report more torque can be applied in supination than in pronation. The fact a majority of the population is right handed, coupled with these findings may, in part, explain why the convention for tightening a screw is clockwise and not counterclockwise. However, studies conducted by Kramer (1994) and Wang and Strasser (1993), in addition to data reported by Woodson (1981), suggest the opposite to be true. When forearm angle is factored in, the ability to apply torque is further affected. Again, the work of O'Sullivan and Gallway (2001) as well as that of Sanchez (2007) demonstrate that as wrist angle increases from the neutral position the ability to apply torque decreases. This has been observed in both supination and pronation.

An additional factor reported to have an effect is handle diameter. Kong et al. (2005) determined that the proper diameter for a hand held screwdriver was in the range of 31.5-37.4 mm (~1.25 -1.47 in.) with the optimal diameter being 35 mm (1.43 in.). Woodson (1981) suggest the proper handle diameter to be between 3.2 to 3.81 cm (1.125 and 1.50 inches). Handle diameter is relevant to this study in as much as it is an important consideration when developing an experiment that includes application of maximum torque under optimal conditions.

Finally, it quickly became obvious the human ability to apply torque has been the subject of numerous studies, including many that involved manually operated screwdrivers. Mital and Sanghavi (1986) suggest the mean torque applied by males using a screwdriver is 3.3 Nm while Kim et al. (2000) observed a mean torque for males of 6.53 Nm. Interestingly, Timm et al. (1992), Wang and Strasser (1993), and Shih et al. (1997) reported maximums in between these values, those being 5.6 Nm, 4.6 Nm, and 4.9 Nm, respectively. Woodson (1981) reports a 50th percentile force value of 285 N (64 lbs.) in supination and 315 N (71 lbs.) in pronation. Using the optimal diameter of the screwdriver handle suggested by Kong et al. (2005), this would equate to output torques of approximately 5 Nm and 5.53 Nm, respectively.

2.2 Human Strength

To generate forearm torque subjects engage a number of muscles in their upper arm. Among those of interests are the flexor digitorum superficialis, extensor digitorum communis, and biceps brachii. Each has a unique function in the generation of this torque and has been shown by Gordon et al. (2004) to provide significant contributions. Anatomica's Body Atlas (2006) describes the function of each as follows:

- Flexor digitorum superficialis – The primary function is to flex the digits. This helps the user achieve the power grip. Tayyari and Smith (1997) have shown that a power grip allows about four times the grip strength that a pinch grip allows. They have a secondary function to assist in the flexing of the hand at the wrist. This may have a small affect to assist in the application of force during supination. Since the reaction force will tend to push the wrist towards extension, the application of wrist flexion force will help to maintain wrist position.

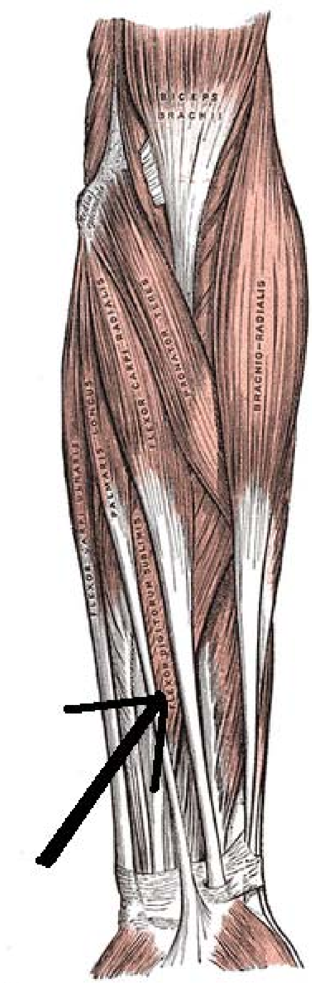

Fig. 2.1: Location of the flexor digitorum superficialis (ref. Gray's Anatomy)

- Extensor digitorum communis – The primarily function is to extend the digits. Of interest to generating forearm torque, the extensor digitorum communis function to assist in the extension of the hand at the wrist, which may assist to apply force during pronation. In a similar manner to the function of the flexor digitorum superficialis, when the hand is moved in pronation, it tends to move the wrist toward flexion. The extensor digitorum communis helps to maintain wrist position.

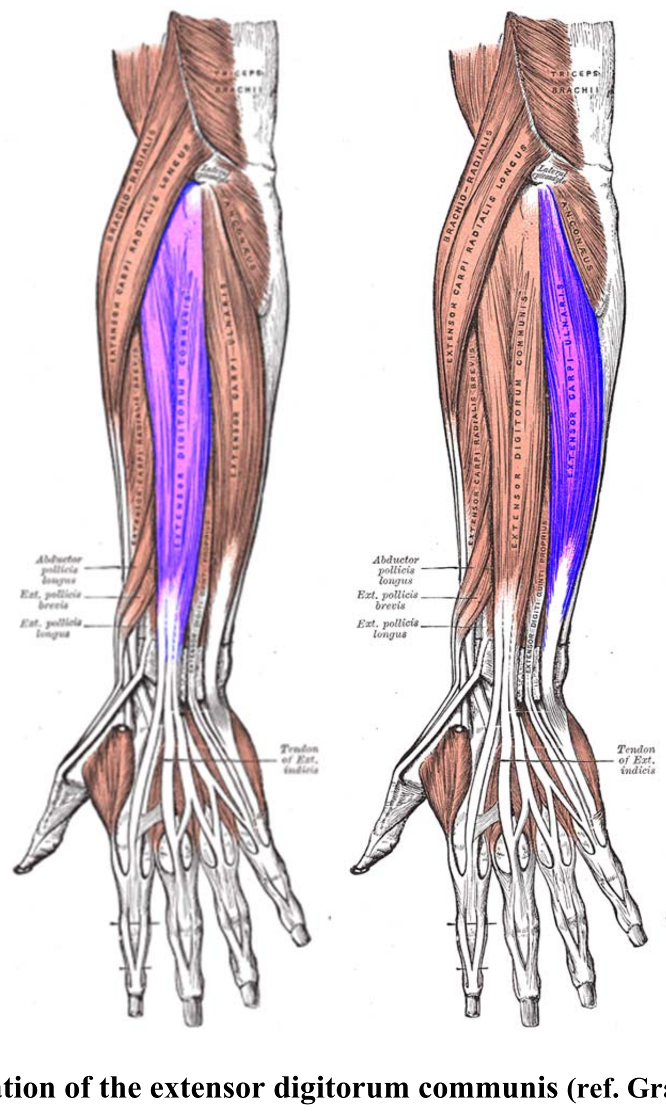

Fig. 2.2: Location of the extensor digitorum communis (ref. Gray's Anatomy)

- Pronator Teres and Pronator Quadratus – Together these muscles act to pronate the forearm. Unlike the extensor digitorum communis, these do not prevent wrist flexion.

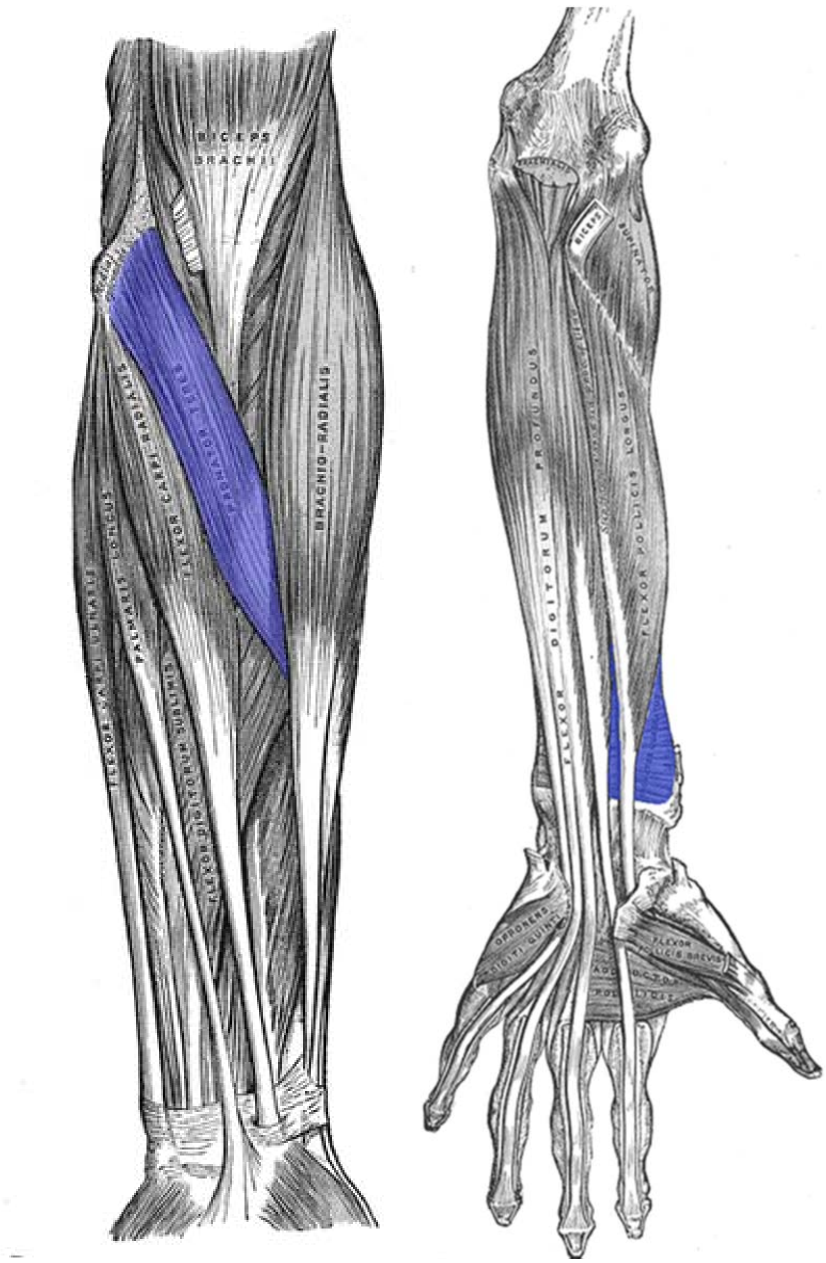

Fig. 2.3: Location of the Pronator Teres and Pronator Quadratus (ref. Gray's Anatomy)

- Biceps brachii – The biceps brachii are a powerful supinator of the forearm, which has a large effect on the generation of torque when supinating. A related function is to flex the forearm, which for this research is relevant since the subjects had to flex their forearms to hold them at the 90 degree position.

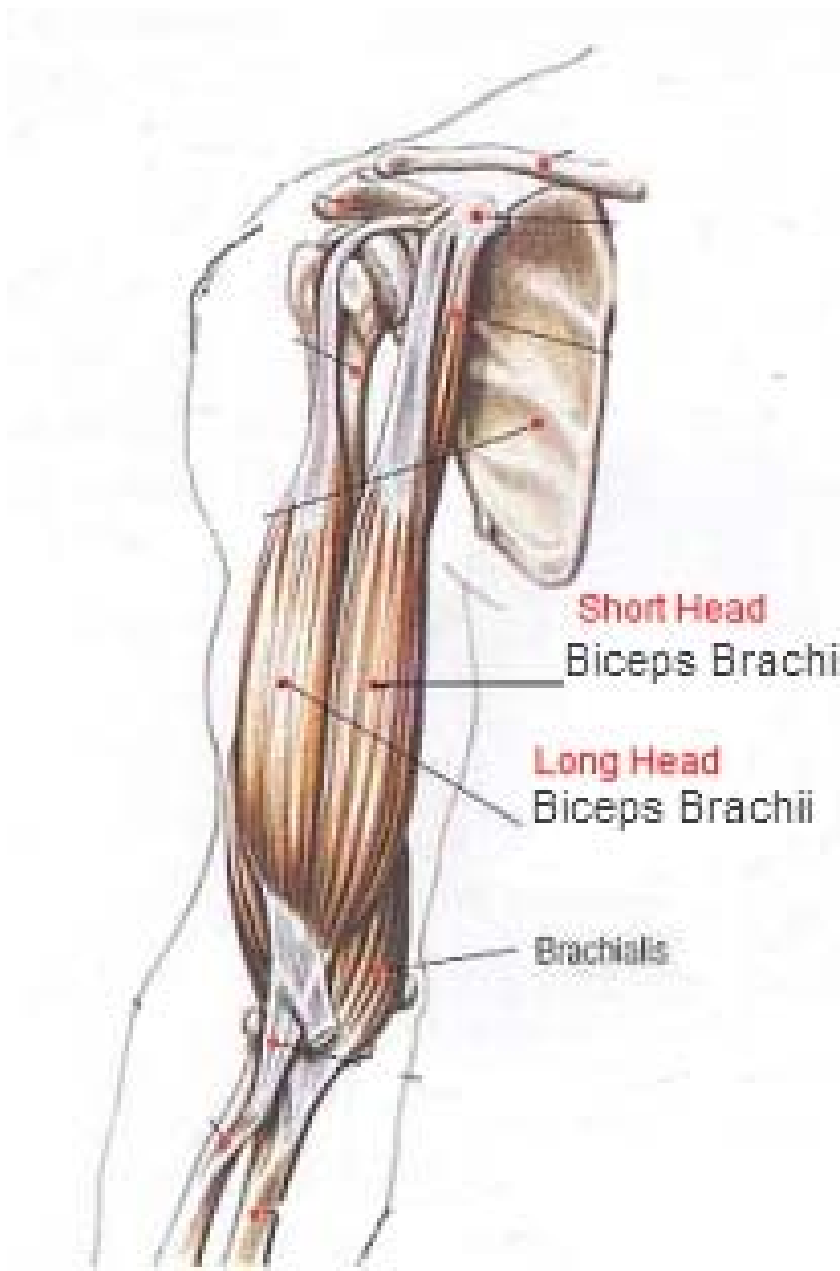

Fig. 2.4: Location of the Biceps Brachii (ref. Gray's Anatomy)

2.3 Screw Head Design

According to Mowins (1991), the introduction of the first "factory" produced screws, those being common wood screws produced by the Wyatt brothers, coincided with the American industrial revolution, cited by many historians to have begun with the development of the steam engine by James Watt in 1765. The design featured a straight slot cut across the diameter of the head that allowed a simple tool (including a coin) to be inserted in the slot that could be used to turn the screw, reference Fig. 2.5. Though simple, the design was not without its problems. The design requires the tool user to precisely place the head of the tool into the slot that may increase time to complete an operation. Additionally, the only mechanism to keep the tool head in contact with the fastener is friction, making the straight design susceptible to slippage and disengagement, especially if the user did not keep the tool perpendicular to the fastener.

Fig. 2.5: Slotted Screw Head Design

In the 1920's and 30's alternate head designs were eventually developed that addressed these shortcomings. This included the Phillips head, see Fig. 2.6, designed by Henry Phillips, a dentist from Oregon, circa 1934 (Mowins, 1991). The Phillips design included a cross-shaped, or cruciform, feature formed into the head of the fastener.

Fig. 2.6: Phillips Screw Head Design

This design required less precision on the part of the tool operator as the tool bit centers itself into the fastener head. This means the operator can work faster with increased work output, especially when performing highly repetitive tasks. The tool head is also more constrained by the fastener head and may make it less likely to slip out. The Phillips, known today as ANSI/ASME B18.6.3 Type 1, was soon joined by other cruciform designs, including the Frearson (or Reed and Prince) that is designated by ANSI/ASME B18.6.3 as Type 2. Details drawings of the Type I and Type II designs are shown in Appendix A. While cruciform designs are improvements over their slotted predecessors, they did allow the tool head to "cam-out" of the fastener under high torque. Due in large part to the fact many domestic applications do not require the application of large tightening torques; the cruciform design continues to be one of the most popular styles currently available.

Many modern cruciform designs, especially those encountered during electrical work, feature geometry combining the self-centering aspect of the Phillips design with the simplicity of the slotted design as shown in Fig. 2.7.

Fig. 2.7: Modern Electrical Screw Head Design

This provides flexibility for workers as either a Phillips or straight blade screwdriver can be used to tighten or loosen the screw. A recent development in screwdriver bit design is the ECX^{TM} bit, a patent pending design from the Milwaukee Electric Tool Corp. The bit features a straight potion to engage the slot feature of the fastener along with a Phillips inspired component. The design intent is to allow greater torque application than the Phillips bit as it would be less prone to allowing the driver to cam-out. This may come with a trade-off though. The slotted portion of the design requires the tool operator to be precise when engaging the tool head with the fastener. This causes the user to work slowly and deliberately, lending itself better to non-repetitive work tasks.

2.4 Research Void

While much of the cited work describes many factors affecting a human's ability to generate forearm torque, there is a need to understand the role the bit style has in relation to the actual use of the screwdriver. There is also a need to understand the overall effort a user put into the application of maximum torque. In other words, the relationship between torque application and push force is not well understood.

2.5 Objectives

The prime objective of this experiment was to analyze the relationship between user torque exertion and screwdriver bit design. An additional objective was to record and analyze the axial (push) force exerted while using the tool under the multiple conditions and determine what, if any relationship exists. The final objective was to utilize the results to develop an effort metric relating the force applied by the user to create torque and axial force that would allow bits of different types to be compared. As part of this analysis, screwdriver bit designs were evaluated under various conditions of use. It was hypothesized the ECX™ bit allows the user to apply greater torque than both the Philips style bits as they were intentionally designed such that the driver head would "cam-out" under strain to prevent over tightening. Since the ECX and straight style bits share the same "blade style" design element, it is expected they will perform essentially the same.

3.0 METHODS

3.1 General Approach

The research goal was to determine the tangential and axial forces applied by the operator to the handle of a manual screwdriver using three commercially available screwdrivers commonly used by tradesman. Each screwdriver sample had the same length and handle diameter, only differing by the style of bit provided on the end. A parametric model of a common electrical screw was created so that test specimens capable of being installed in a torque measurement fixture could be made. Testing was conducted in two directions, supination and pronation, as each is associated with screwdriver use. The study focused on measuring the forces so the levels of user applied torque and axial force could be determined. The data were used for to directly compare torque levels achieved with each bit style. They were also used to calculate the ratio of the tangential and then axial forces applied to the screwdriver handle to compare the overall effort of the user when using each bit style.

3.2 Hypotheses

<u>Hypothesis 1:</u> The ECX bit will allow the user to apply a greater level of torque than the Phillips bit.

<u>Hypothesis 2:</u> There will be difference in the amount of user applied push force between bits.

<u>Hypothesis 3:</u> Users will apply more torque in supination that in pronation.

3.3 Experimental Design

A repeated measures, full factorial design was selected to provide sufficient statistical power. There were 2 independent variables in this experiment and 3 dependent variables, as shown in Table 3.1.

Table 3.1: Experimental variables

Variable	Type
Screwdriver bit design (Philips, straight, ECX^{TM})	Independent
Direction (pronation and supination)	Independent
Forearm torque in Nm	Dependent
Push force in N	Dependent
Effort Ratio	Dependent

The independent variable bit type had 3 levels, ECX, Phillips and Straight, and the independent variable direction had 2 levels, supination and pronation, resulting in 6 possible combinations of factors for which torque and push force data were collected. As subject performed 2 exertions for each condition, each completed a total of 12 exertions as part of this experiment. See Fig. 3.1 for a graphical representation of the experimental design.

Bit Style / Direction of Application	Phillips	Straight	ECX
Pronation	S01 S02 … Sn	S01 S02 … Sn	S01 S02 … Sn
Supination	S01 S02 … Sn	S01 S02 … Sn	S01 S02 … Sn

Fig. 3.1: Experimental Design

3.4 Experimental Controls

To minimize the number of variable associated with this experiment, a number of test conditions were standardized. Each subject was tested in the same environment, that being a laboratory setting where temperature, humidity, lighting, background noise and physical space around the fixture were constant. The screwdriver models, test specimens design, and test specimen orientation in the fixture were also kept constant. During participation, subjects were instructed as to the proper body position and grip on the test screwdriver and asked to maintain that position for each trial of the experiment. The height of the test fixture was adjusted for each participant to ensure they could maintain the prescribed body positioning.

3.5 Sample Size

To calculate the minimum number of participant required to ensure reasonable statistical power, the operating characteristic curves provided by Montgomery (2002) were used. To utilize the curves, three (3) variables need to be determined. The first is Φ, which is determined using equation 1 (Montgomery, 2002).

$$\Phi^2 = \frac{nbD^2}{2a\sigma^2} \qquad (1)$$

Where:

n = observations per level
a = number of levels of primary independent variable
b = number of levels of primary independent variable
D = minimum difference between means
б = standard deviation

Since there are no prior studies relating differences in torque application related to bit type, the work of Sanchez (2007) and work conducted in preparation for this study suggest a standard deviation of 1.5 Nm and a minimum differed D of 1.2 Nm. The primary independent variable (bit type) had 3 levels and the secondary independent variable (direction) had 2 levels.

The next two variables, V_1 and V_2 are calculated using equations 2 and 3, respectively. The variable V_1 represents the degrees of freedoms value of the primary independent variable and V_2 represent the degrees of freedom associated with the error.

$$V_1 = (a-1) \qquad (2)$$

$$V_2 = a*b(n-1) \qquad (3)$$

The value for V_1, which for this experiment equaled 2, was used to select the proper set of curve. Once the proper curves were selected, a value of Φ could be calculated using equation 1 and that along with the value of V_2 used to determined **β** from the chart. To simply the samples size determination, a spreadsheet was created and an initial value of n entered to calculate and an initial value of Φ that could be used to find the **β** associated with that sample size determined. If **β** was too low, a new value of n was chosen and the calculation repeated. This iterative process continued until a sample size having **β** = 0.2 or less was determined, which indicates the Type II error associated with a type I error (α=0.05) of 5% would be less than 20%.

Table 3.2: Iterative Minimum Sample Size Calculation

n	Φ^2	Φ	V_2	β	1-β
5	1.066667	1.032796	24	0.7	0.3
10	2.133333	1.460593	54	0.5	0.5
12	2.56	1.6	66	0.35	0.65
13	2.773333	1.665333	72	0.3	0.7
14	2.986667	1.728198	78	0.25	0.75
15	3.2	1.788854	84	0.15	0.85
16	3.413333	1.847521	90	0.1	0.9

The results of this process indicated a minimum number of subjects needed to be 15.

3.6 Test Fixture

A custom-built torque measurement device, as shown in Fig. 3.2, which was previously constructed for a similar experiment, was utilized.

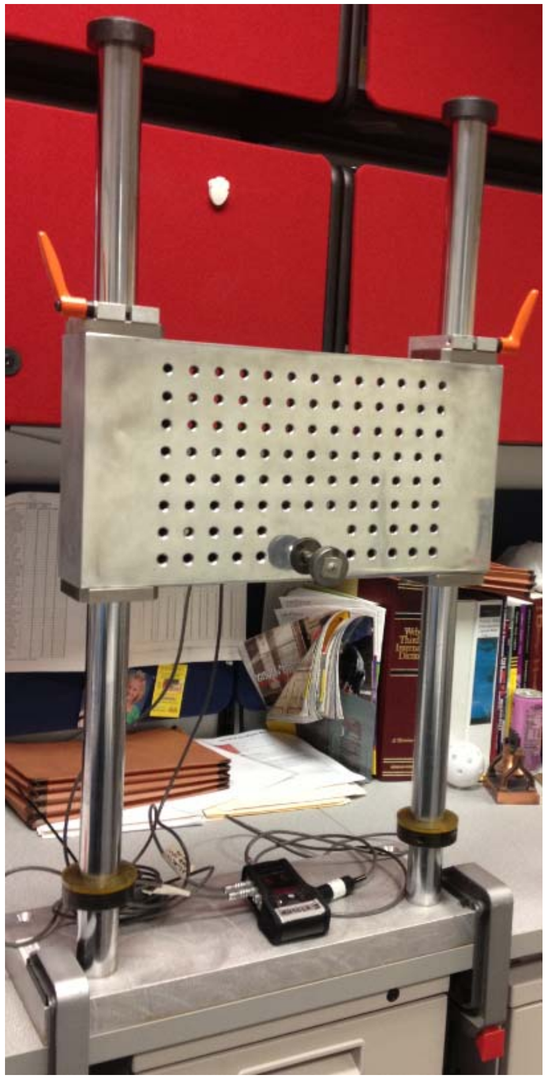

Fig. 3.2: Custom Built Test Fixture

The torque device comprises a metal plate with a plurality of drilled and tapped holes to allow for many possible load application points. The plate is mounted on a set of vertical guides with locking mechanisms that allow the height of the device to be adjusted between 4 and 24 inches above the base to accommodate differences is subject stature and to provide flexibility when investigation a number of different body positions. Two load cells are mounted on the rear portion of the device, one to determine applied torque and one to measure axial force which corresponds to push force. The torque load cell has a range of 0-500 N and is connected to the text fixture by an adjustable linkage provided with holes spaced 2 cm apart. The linkage holes allow the investigator to adjust the fixture based on the levels of torque being measured such that the load cell is operating in a proper portion of its useful range. For this experiment the linkage was set to provide a10 cm moment arm.

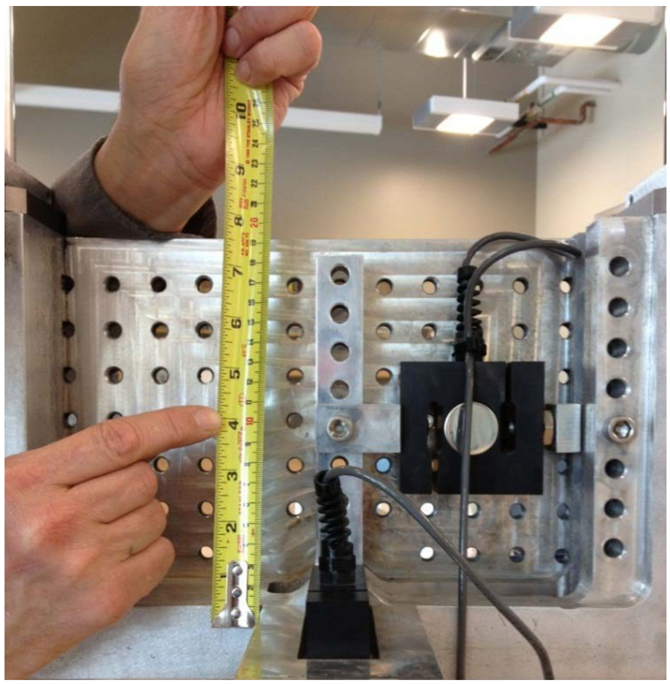

Fig. 3.3: Load Cell Location in Test Fixture

The axial load cell had a range of 0-1000 N and was connected to a ¼" hex shaped input shaft running through the interior and extending outside the front of the test fixture. No means to adjust the location of the axial load cell is provided as the force application is always in-line with the load cell.

Secured to the input shaft is a coupling that connects the subject's torque application device, in this experiment a screwdriver, to the test fixture as shown in Fig. 3.4.

Fig. 3.4: Coupling Assembly Mounted on Test Fixture

The coupling design is based on a ¼" socket with a 3/8" square drive. The coupling features a hole on one end machined to accept the ¼" hex shaft built into the text fixture. The opposite end of the connector has a 3/8" square opening that accepts a custom designed test specimen mounting element. The mounting element is machined from a round bar to have a 3/8" square feature protruding from the rear of the element and a square recess that accepts a custom designed test specimen machined into the front face. Photograph of the mounting system are show in Figs. 3.5 and 3.6.

Fig. 3.5: Coupling Assembly

Fig. 3.6: Disassembled View of Coupling Assembly

The test specimen for this experiment is a custom made metal part designed to replicate a screw head commonly encounter by tradesmen. In this case, the screw from a commercial electrical outlet, which is equivalent to an ANSI/ASME #10 machine screw. This size was chosen based on its prevalence in both residential and industrial construction.

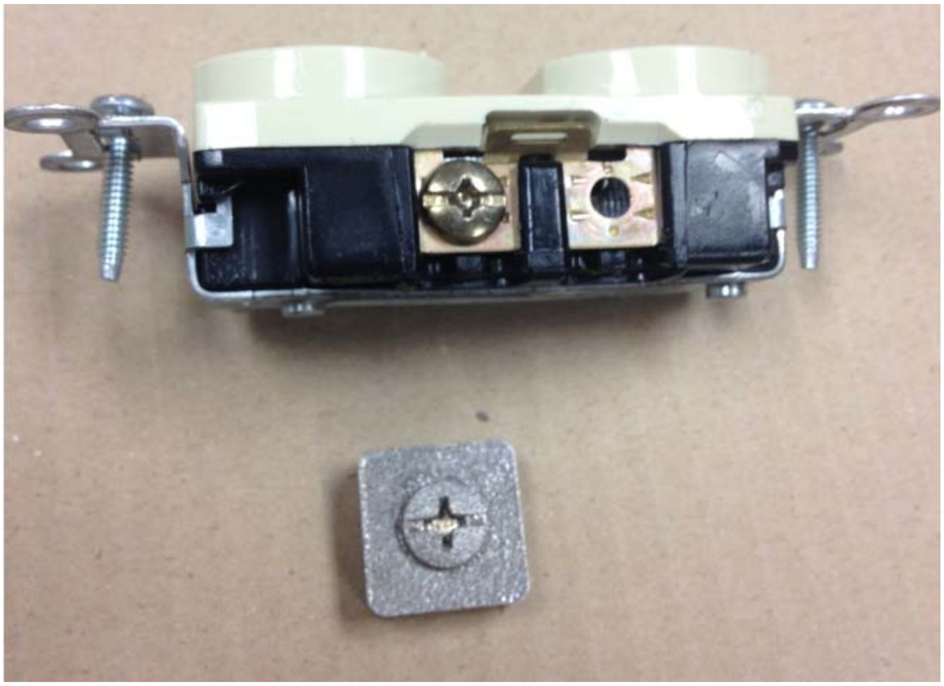

Fig. 3.7: Comparison of Electric Screw and Test Specimen

The screw was removed from the outlet and measured to determine the head diameter, head height, and the bit reception geometry. The values were compared to those provided by ANSI/ASME B18.6.3, *Machine Screws, Tapping Screws, and Metallic Drive Screws (Inch Series),* to ensure accuracy.

The dimensions were used to create a three dimensional, parametric model of the screw head using Pro/Engineer ("Pro/E") software (PTC, Needham, MA). The screw head model was added to a square base model to form the test specimen's final design. The Pro/E model was sent to a Selective Laser Sintering ("SLS") machine that created a nylon plastic prototype, ref. Fig. 3.8.

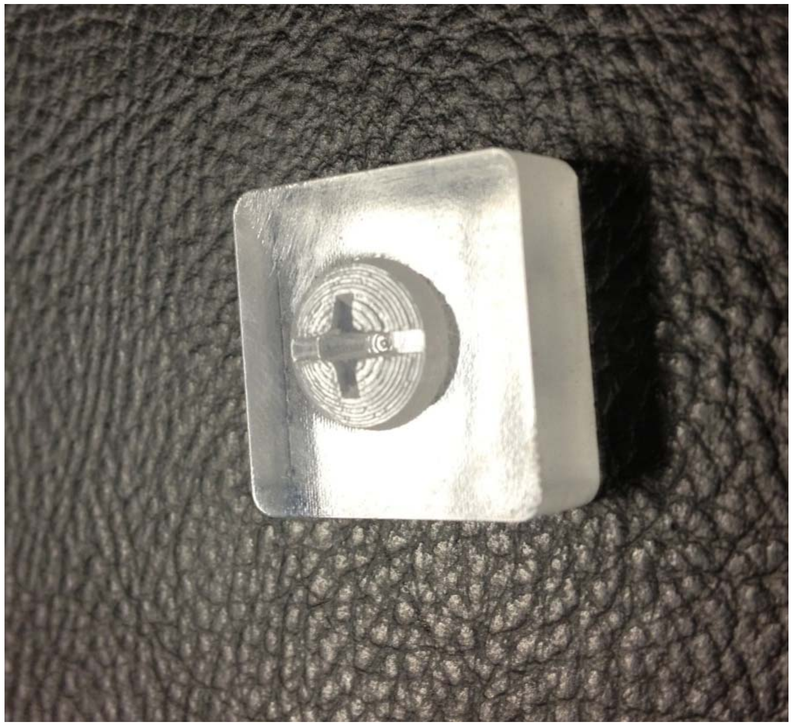

Fig. 3.8: SLS Model of Test Specimen

The SLS prototype was measured and the dimensions compared to those of the electrical screw. The base was also measured to ensure it would fit properly into the mounting element. Adjustments to the model to account for tolerance and shrinkage were made and another prototype was made. Once the prototype design was finalized, the Pro/E model was sent to a metal fabricator where sintered parts made from 420 stainless steel were made.

3.7 Data Recording

Each load cell is connected to the Biometrics Ltd (Gwent, UK) Datalog Wireless Bluetooth Data Unit, model MWX8. Also connected to the data unit was a manually operated triggering device that was used to start and stop the data recording of the unit. Data was transmitted wirelessly to a laptop computer operating the Biometrics DataLog Management and Analysis Software, version 8.0, which was used to configure the data unit and provide graphical representations of the data being recorded. Channel sensitively, sampling rate, excitation voltage and full-scale range were all set via the software. The software also allowed data to be analyzed and exported to Microsoft Excel for further analysis and data presentation preparation. For this experiment, the sampling rate was set to 100Hz and the scale was set to display 0-100% of full-scale range.

Fig. 3.9: Biometrics Datalog Wireless Data Unit

3.8 Screwdrivers

To apply torque, a screwdriver design having a straight (conventional) handle was used. The design is comprised of a thermoplastic handle secured to a steel shank having the specified bit style machined into one end. This creates what is referred to as an "in-line" style screwdriver since that the handle has the same long axis as the bit shank. Three screwdriver bit styles were evaluated in this experiment: a Phillips head that engages screws and bolts having a cross shaped depression when viewed from the front, a straight of slotted head having a flat blade head that engages a slot on the top of a fastener, and the ECX^{TM} bit, which is essentially a combination of the Philips bit and a straight blade.

The screwdrivers chosen for this experiment were the Milwaukee 48-22-2012 (Phillips), the Milwaukee 48-22-2041 (ECX), and the 48-22-2021 (straight blade). Each was identical in size, having overall lengths of approximately 210 mm, handle lengths of approximately 104 mm, and handle diameters of approximately 31 mm. Detailed engineering drawings of each screwdriver are shown in Appendix A. Important to their selection was that the handle diameter was within the range suggested by Kong et al. (2005) of 31.5 mm to 37.4 mm.

Fig. 3.10: Photo of Screwdrivers used in this Study

3.9 Calibration

Calibration of both the torque and axial load cells was needed to ensure the data recorded during the experiment was proper. The load cells were calibrated before each test session using the same calibration procedures.

3.9.1 Torque Load Cell Calibration

The torque load cell was calibrated by means of a custom designed calibration bar that could be connected to the test fixture. The bar is approx. 40 cm long and has machined lines every 1 cm across which correspond to the distance the line is from the centerline of the test fixture's input shaft. The bar was installed and a small bubble level was placed on the top of the bar to ensure that it was parallel the surface was level as shown in Fig. 3.11.

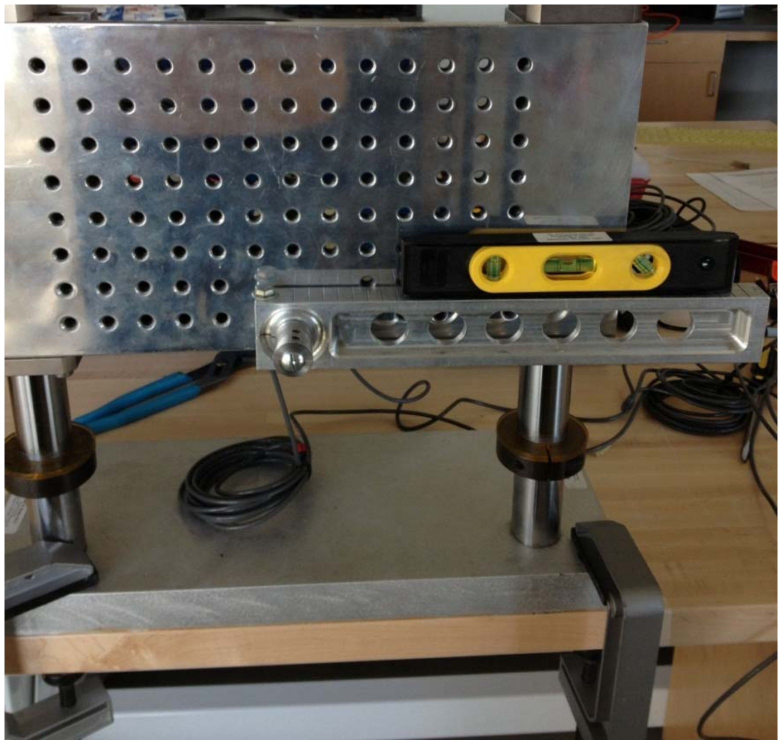

Fig. 3.11: Calibration Bar being Leveled on Test Fixture

A calibrated 1 kg weight was hung from the bar, as shown in Fig. 3.12, at various distances so a calibration curve could be generated. Utilizing equation 4, the torque resulting from the weight was determined.

$$T=F*d \qquad (4)$$

Where T = torque (Nm)

F = force (N)

d = distance from then fixture center (m)

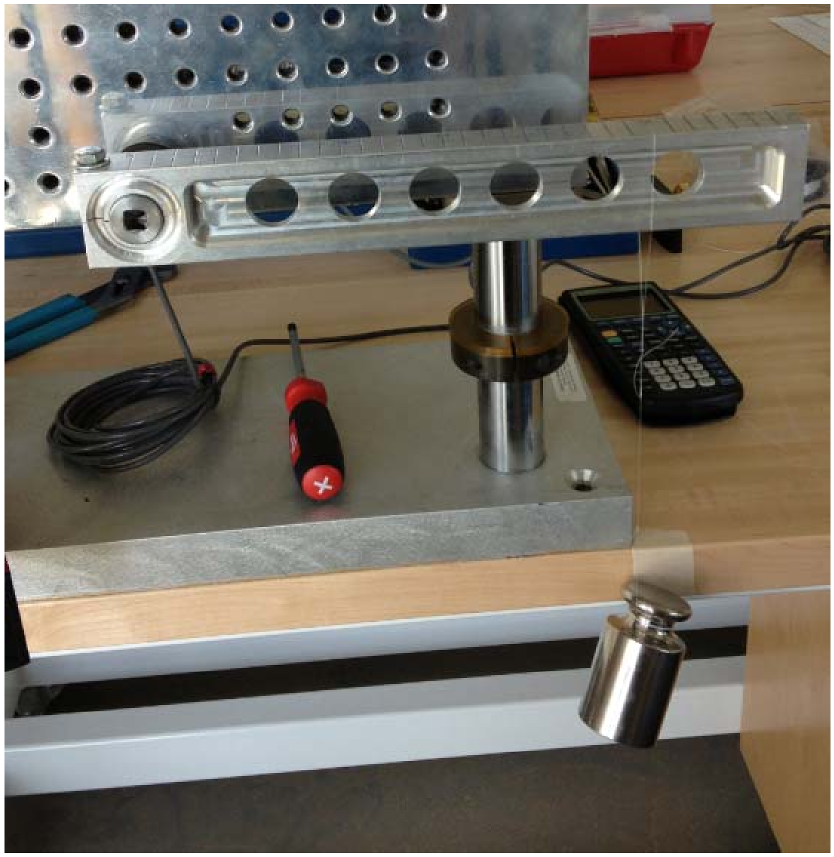

Fig. 3.12: Torque Load Cell Calibration.

As related to the calibration, the torque (T) would be that caused by the hanging weight. Since the weight had a mass of 1 kg mass, the resulting force (F) applied by the weight on the bar was approximately 9.81N. The distance (d) is then the distance from then fixture center to the location of the hanging weight. After the weight was hung, it was allowed to come to rest and the Biometric system used to record the output of the load cell. The value indicated by the load cell and the calculated torque were entered into a Microsoft Excel table. The weight was hung at distance of 5 cm, 10, cm, 15 cm, 20 cm, 25 cm and 30 cm and the above mentioned data enter into the table. Two applications were made at each distance resulting in 12 data points for the calibration.

The resulting calibration data was plotted on a graph and a curve fit was created, ref. fig. 3.13.

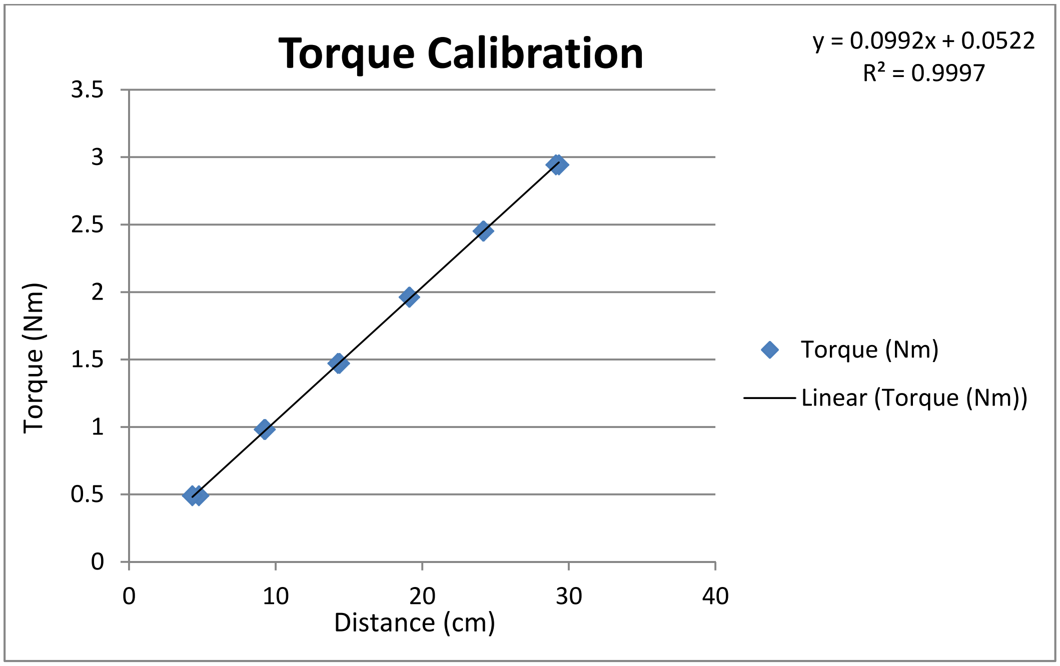

Fig. 3.13: Torque Load Cell Calibration Curve

3.9.2 – Axial Load Cell Calibration

The axial load cell was calibrated by means of a hand-held force gauge (Imada DPS-44). The gauge was set to read N and configured to display the Peak value observed during a measurement. The gauge was applied directly to the input shaft of the test fixture and the experimentor attempted to apply certain value of push force, ref. Fig. 3.14.

Fig. 3.14: Axial Load Cell Calibration

The application of the force was recorded using the Biometrics system. The peak value recorded by the gauge and the max value indicated by the Biometrics software were entered into a Microsoft Excel table. The gauge was used to apply forces of ranging from 4.5N to 135N. In total 17 measurements were taken. The resulting calibration data was plotted on a graph and a curve fit was created, ref. Fig. 3.15.

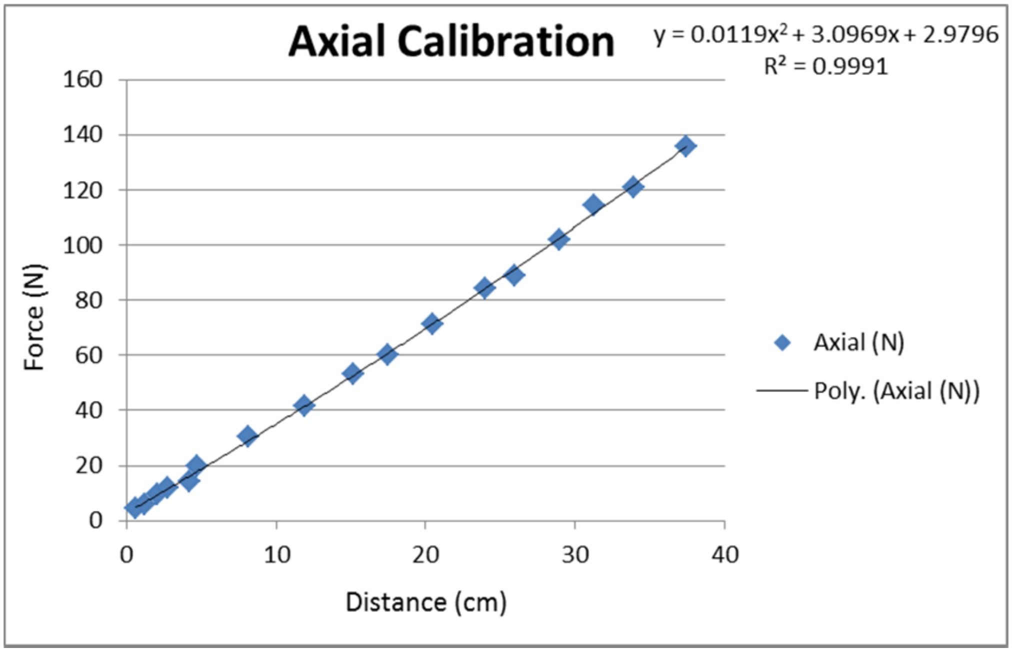

Fig. 3.15: Axial Load Cell Calibration Curve

Each of the calibration curve equations was used to condition the data output form the Biometrics software to detemine the torque and push force applied by the users.

3.9 Subjects

Professionals responsible for hand tool design volunteered to be subjects of this study. A total of 8 men and 8 women participated in the study. Prior to participation in the study, each volunteer was asked to read and sign a consent form which had previously been approved by the Institutional Review Board of Marquette University, ref. Appendix B.

The investigator went through participation requirements with each subject prior to their inclusion in the study. Items discussed included the test procedure, the purpose of the study and it benefits, confidentiality requirements and reviewed any risks associated with the study. For this study it was stated there were no risks beyond those encountered in normal life. If the volunteer was willing to participate, they signed and dated the consent form and were asked to complete an Occupational Health Background Information Form, ref Appendix B. In order to participate, volunteers were required to be between 18 and 65 years of age and physically able to complete all of the trials with minimal rest using the specified methods. In addition, subjects could not have any past or present physical injuries that could be exacerbated by participation in this study such as, but not limited to, upper extremity pain or injury, back or neck pain or injury, or lower extremity pain or injury that prevents the subject from standing for the entire experiment.

4.0 PROCEDURE

The experiment was broken into 2 parts. One part focused on determining the anthropometric dimensions of each subject with respect to certain aspects of the dominant upper extremity, body parts of interest, and grip strength. The second part focused on recording the torque applied by the screwdriver and the axial force when performing a screw-driving task. Typically, 4 test subjects would participate during a test session, the length of which was normally 1 to 1-1/2hrs.

4.1 Anthropometry

To measure a subject's body dimensions, standard anthropometric tools were employed. The following anthropometric measurements were recorded for each subject along with a recording of the subject's gender and dominant upper extremity (R or L):

- **Stature**
- **Acromial Height**
- **Acromion to Dactylion Length**
- **Hand Length**
- **Hand Breadth**
- **Wrist Circumference**
- **Forearm Circumference**
- **Arm Circumference**
- **Grip Strength**
- **Weight**

All data were measured using metric dimensions with length and circumference being recorded in centimeters and weight in kilograms, respectively. Measurements were performed in accordance with the methods described by Van Cott and Kinkade (1972) and NASA (1978). Examples of the location at which each measurement was taken can be found in Annex D. An investigator using the anthropometric measuring tool measured each subject. In some cases, an observer who ensured the test subjects assumed the proper position for the measurement of interest assisted the investigator. Data were recorded on a data sheet, a sample of which is shown in Annex B.

A Jamar hand dynamometer was used to measure each subject's grip strength. The device features a fixed handle and an adjustable handle that could be installed into one of five preset positions.   A gauge is located on the top of the device that has a movable pointer that can be used to indicate maximum force, which is read in kg. The handle was set for a 6.0 cm, grip span. The subjects were instructed to stand tall, facing straight ahead with their dominate arm positioned with the elbow at a 90 degree angle, making the forearm parallel to floor. The wrist was held in the neutral position. Two trials were conducted and the mean of the trials reported.

4.2 Force Testing

The second part of this experiment involved the measurements of the torque and the push force exerted by the subject on the test fixture with a screwdriver. After the text fixture was calibration, which occurred outside the presence of test subjects, the investigator had subjects prepare for participation by providing protocol instruction and what the subject would be asked to do as part of this experiment, including the number of trials to be completed. Each subject was shown how to grasp the handle of the tool with a neutral grip, how to position their arms to form a 90^{o} angle between the forearm and upper arm, how to keep the elbow tucked near the body, and where to stand when addressing the test fixture. They were also instructed as to the commands that would be given by the investigator to ensure they would perform each trial in the proper direction and for the requisite length of time.

Fig. 4.1: Subject's Test Postion

Once trained, the subject was asked to move towards the test fixture and assume the experimental position. To ensure the subject's arm was in the correct position, the lateral epicondyle, which is located near the subject's elbow, was marked representing one end point of the humerous bone in the forearm. The opposite end of the humerous bone, which is located by palpating the depression near the center of the wrist, was also marked. A level was placed between these points and the wrist end of the subject's arm was moved up or down until the bubble indicated the arm was level.

Fig. 4.2: Test Subject's Arm being Leveled

The subject was advised to maintain that position and the height of the test fixture was adjusted to the proper height, which was recorded for that subject to ensure the fixture could be returned to the correct position during subsequent trials. After the fixture height was set, a test specimen was installed in the test fixture and the subject was allowed to perform 2 practice trials to get familiar with the commands of the investigator and to get comfortable using the test fixture. The subject was then given a rest period and the process repeated for the next subject. After all test subjects had been trained and had a chance to complete their practice, the collection of experimental data was initiated.

Fig. 4.3: Test Subject Conducting Experiment.

To begin the data collection phase of the experiment, the subject was provided a screwdriver and asked to address the test fixture and again assume the experimental position so the test fixture could be adjusted to the proper height. The subject then was instructed by the investigator regarding which direction, supination (clockwise for a right handed subject) or pronation (counterclockwise for a right handed subject), to apply torque.

The investigator started the collection of data by first installing a test specimen into the test fixture and then setting each data collection channel to zero using the Biometric software. The subject was instructed to place the screwdriver into the test specimen and wait for the command to begin. The investigator pressed the manual switch connected to the Datalog system to being data collection, waited a second, and then instructed the subject to exert their maximum torque on the handle of the screwdriver in the prescribed direction. The subject applied torque for approximately 5 seconds, at the end of which the investigator advised the subject to stop. Data continued to be recorded for an additional second after which the investigator again operated the switch to stop data collection. The subject was then allowed to rest for a period of at least 2 minutes in accordance with the recommendation of Caldwell et al. (1974) to prevent fatigue before repeating the experiment under the same conditions.

The data collected were saved to the laptop computer into a folder for that subject and labeled such that the subject number, bit type, direction of torque application, and trial number were able to be identified. A sample of the naming convention is below for subject 3 using an ECX bit, apply torque in pronation, first trial:

S3	ECX	PRO	1	.log
Subject Number	Bit Type	Direction	Trial	File Type

After the subject completed the second trial in the initial direction, the average of 2 data points was calculated and the data reviewed to ensure each was point was reasonable. Data points found to be too dispersed were rejected and replaced with a new measurement.

The experimental was then repeated using the next test sequence. Once all trials pertaining to a particular bit style were complete, the subject was asked to complete the portion of the subjective assessment relevant to that bit style.

The experiment was repeated for all other sequences until 2 trials under each of the 6 possible combinations of bit type and direction had been completed. This resulted in a total of 12 torque exertions for each subject (3 head designs x 2 torque directions x 2 trials). Once all trials were complete, and the user answered all question in the subjective assessment for the each bit types, they were asked to complete the ranking portion of the subjective assessment.

4.3 Subjective Assessment

A subject assessment form in the style of a questionnaire was developed. The questions included in the form were designed to illicit feedback as to how easy the user felt he/she could apply torque using each bit. The questions asked for each bit type tested were:

1. **Please rate the ease of applying torque in a counterclockwise direction**
2. **Please rate the ease of applying torque in a clockwise direction**

At the end of the document the subjects were asked rank each bit in order of which they liked best on a 1-3 scale with 1 being the best. The subjective assessment form is shown in Appendix B.

4.4 Presentation Order

To control for order and carryover effects, the sequence in which the different combinations of independent variables were adjusted as recommended by D'Amato (1970). Essentially, the order in which the different screwdriver bit types was given to the subject, and the direction of applied effort to begin the experiment, were varied as indicated in Table 4.1.

Table 4.1: List of Test Sequences

Sequence	Bit type	Direction of Torque Application
1	ECX	Supination
2	Phillips	Pronation
3	Straight	Supination
4	ECX	Pronation
5	Phillips	Supination
6	Straight	Pronation

This method allows the sequence to be repeated every 6 subjects per Table 4.2. The layout of this method would cause each condition to precede each of the others only once in the whole sequence.

Table 4.2: Presentation Order

Subject	Presentation Order					
S01	1	2	6	3	5	4
S02	2	3	1	4	6	5
S03	3	4	2	5	1	6
S04	4	5	3	6	2	1
S05	5	6	4	1	3	2
S06	6	1	5	2	4	3
S07	1	2	6	3	5	4
S08	2	3	1	4	6	5
S09	3	4	2	5	1	6
S10	4	5	3	6	2	1
S11	5	6	4	1	3	2
S12	6	1	5	2	4	3
S13	1	2	6	3	5	4
S14	2	3	1	4	6	5
S15	3	4	2	5	1	6
S16	4	5	3	6	2	1

4.5 Data Conditioning and Analysis

First, the data for anthropometry of all subjects was placed into a table and a summary of statistics, including mean, standard deviation, minimum and maximum for each measurement was created. Next, the data output from the Biometric system was analyzed to obtain the torque applied and the axial force for each trial. Each data file (192 total) was opened and the mean value of the central 2 seconds of data for both torque and axial force was determined. Since both torque and axial force data graphs were parallel and essentially steady, the maximums for each occurred during the time period. An example of a data collection file along with the 2-second selection is shown in Fig. 4.4.

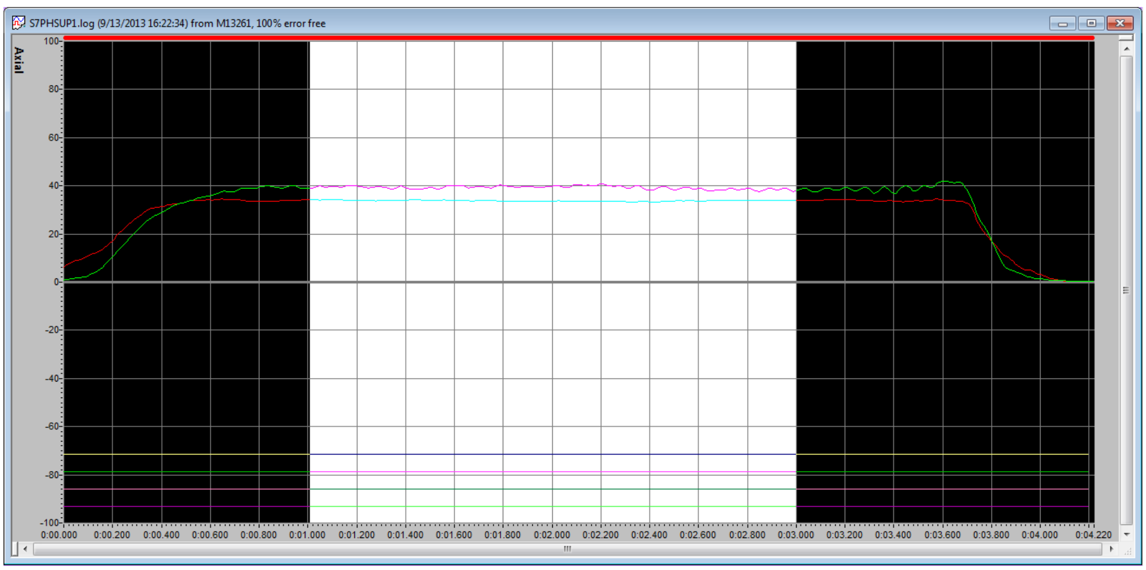

Fig. 4.4: Screen Capture of Exemplar Data Collection File.

The actual value of the torque and axial force applied for a that trial was calculated using the equations determined during the calbibration process, ref Figs. 3.13 and 3.15. The data for each of the 2 trials were averaged to determine the actual torque and axial force applied by that subject and entered into the data table. This was done for each of the 12 trial performed for all subjects. A summary of statistics was created for the torque and axial force data that included mean, standard deviation, minimum value and maximum value. An analysis of variance (ANOVA) was also perfomed to analyze the main effects, any interactions, and their significance.

To calculate an effort metric, the torque value for a particular condition was divided by the diameter of the screwdriver handle to determine the tangential force applied to the tool handle. This along with the axial force applied under that condition was used to calculate an "effort ratio" per equation 5. The ratio relates overall effort of the user for that condition. The effort ratio for each of the 6 condition was calculated for each subject.

$$\text{Effort Ratio} = \frac{\text{Force}_{\text{Tangential}}}{\text{Force}_{\text{Axial}}} \qquad \text{(eq 5)}$$

Finally, the results of the subjective assessment were tabulated and the percentage of responses for each level of the 6 questions regarding ease of use. The data were then analyzed using a non-parametric analysis tool, the Friedman's ANOVA Test. The results of the overall rating of each bit style were also tabulated. To determine the bit most preferred by users, points were assigned to each the ranking levels with 3 being awarded for each number 1 ranking, 2 being assigned to each number 2 ranking and 1 being assigned to each number 3 ranking. The values were then totaled and the bit having the highest number of points was considered the most preferred. The bit having the least number of points was the least preferred.

5.0 RESULTS

5.1 Anthropometry

A summary of the data for the anthropometric data collected is shown in Table 5.1. The descriptive statistics for the experiment, including mean, standard deviation, and maximum and minimum values for each body dimension are also included. For the upper extremity data, the subject's dominant hand was indicated as either R (right) or L (left). The complete set of data recorded for all subjects is shown in Annex D.

Table 5.1: Summary of Statistics for Anthropometry Data (n=16)

Subject #	Stature (cm)	Acromion Height (cm)	Acromion to Dactylion Length (cm)	Hand Length (cm)	Hand Breadth (cm)	Wrist Circ. (cm)	Fore-arm Circ. (cm)	Arm Circ. (cm)	Hand Dyno. (kg)	Weight (kg)
Mean:	**167.6**	**140.2**	**73.9**	**18.7**	**8.4**	**16.6**	**26.9**	**30.3**	**42.8**	**65.7**
SD:	**11.3**	**9.5**	**5.5**	**1.2**	**0.8**	**1.3**	**3.4**	**4.6**	**19.8**	**20.4**
Max:	**185.8**	**153.3**	**83.6**	**20.5**	**9.7**	**18.1**	**31.2**	**40.0**	**88.5**	**104.5**
Min:	**155.6**	**129.3**	**68.6**	**17.2**	**7.4**	**13.9**	**21.5**	**24.2**	**19.5**	**42.9**

5.2 Torque

A summary statistics of data recorded for the maximum user applied torque is shown in Table 5.2 and Figure 5.1. The complete set of torque data recorded for all subjects is shown in Appendix E. An analysis of variance (ANOVA) was performed to determine whether there were any significant effects. The results suggest neither bit, direction, nor their interaction has a significant effect. A summary of the ANOVA is shown in Table 5.3.

Although there were no significant effects for bit design and direction and their interaction, the data suggest that subjects may be able to exert more torque in pronation than supination.

Table 5.2: Summary of Statistics for Maximum Forearm Torque (Nm) (n=16)

Bit Type	ECX		Philips		Straight	
Direction	Pro	Pro	Sup	Pro	Sup	Sup
Mean	2.850	2.973	2.641	2.873	2.636	2.617
SD	1.170	1.325	1.175	1.128	1.106	1.134
Max	5.715	5.828	4.732	4.931	4.837	5.049
Min	1.256	1.158	1.163	0.887	1.106	0.938

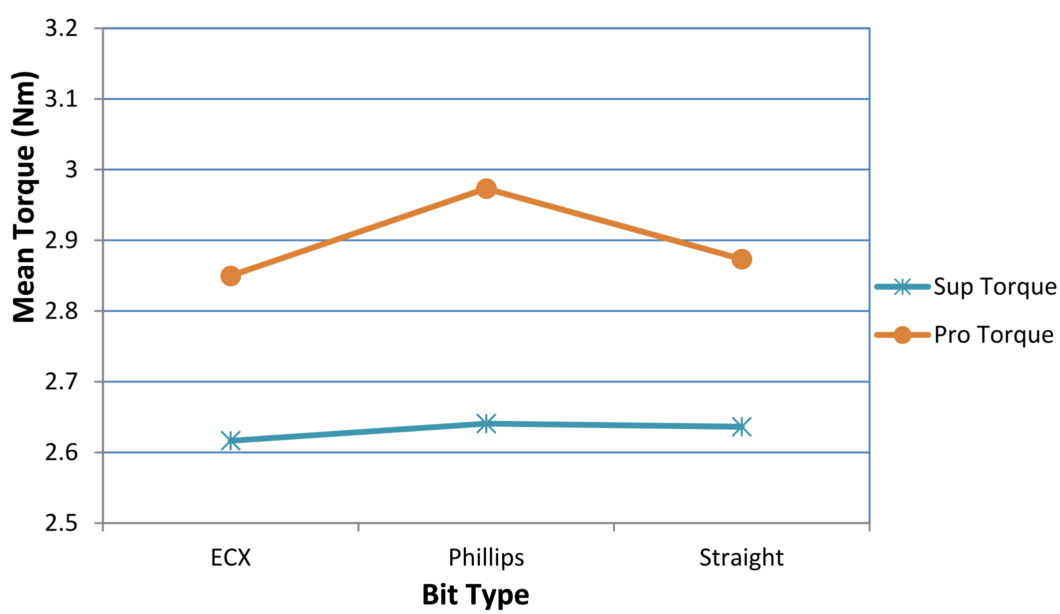

Fig 5.1: Average of Maximum Torque (n=16)

To simplify the analysis of the data, the data were split into two types: that recorded when the subjects applied torque through supination and when they applied it through pronation. A bar chart was chosen to display the data as it lends itself nicely to quick visual analysis. Fig 5.2 shows the data for pronation plotted next to supination .bit.

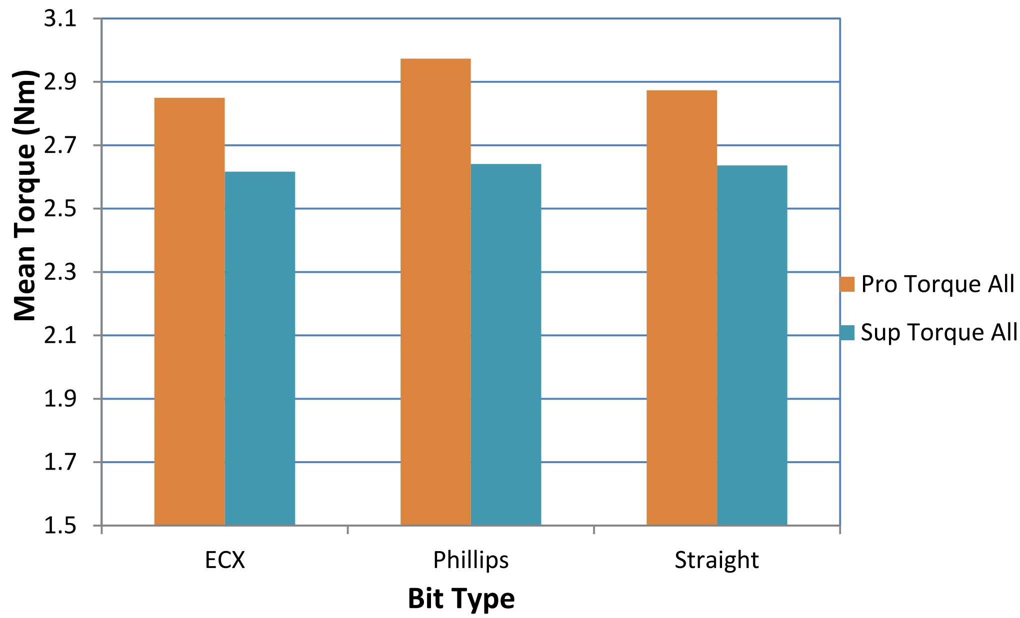

Fig 5.2: Average of Maximum Torque (n=16)

Table 5.3: Summary Table of ANOVA for Torque Data (n=16)

		SS	d.f.	MS	F	P
Total SS		126.165	95			
Subjects		1.861	15	0.124	0.075	1.000
	Bit	0.092	2	0.046	0.028	0.973
	Dir.	1.719	1	1.719	1.037	0.312
	DxB	0.050	2	0.025	0.015	0.985
Error		124.304	75	1.657		

5.3 Axial Force

A summary statistics of data recorded for the maximum user applied axial force is shown in Table 5.4. The complete set of axial force data recorded for all subjects is shown in Annex E. The data shows subjects applied more axial, or push force, using the ECX bit than with both the straight and Phillips bits. The data also suggests users will apply more axial force while pronating than when supinating for all bits, though the difference is relatively small.

Table 5.4: Summary of Statistics for Axial Force (N) (n=16)

Bit Type	ECX		Philips		Straight	
Direction	Pro	Pro	Sup	Pro	Sup	Sup
Mean	**81.001**	**67.482**	**65.798**	**76.722**	**72.922**	**79.942**
SD	**54.255**	**51.015**	**50.512**	**54.664**	**51.195**	**60.755**
Max	**196.355**	**191.277**	**181.939**	**204.843**	**187.463**	**224.502**
Min	**20.895**	**12.921**	**12.065**	**24.215**	**18.472**	**17.480**

The means of the data for all subjects under each condition were plotted in Fig. 5.3. The shape of each line is approximately the same for both a pronation and supination, suggesting there is no interaction between bit type and direction. The difference is demonstrated graphically by the bar chart show in Fig. 5.4.

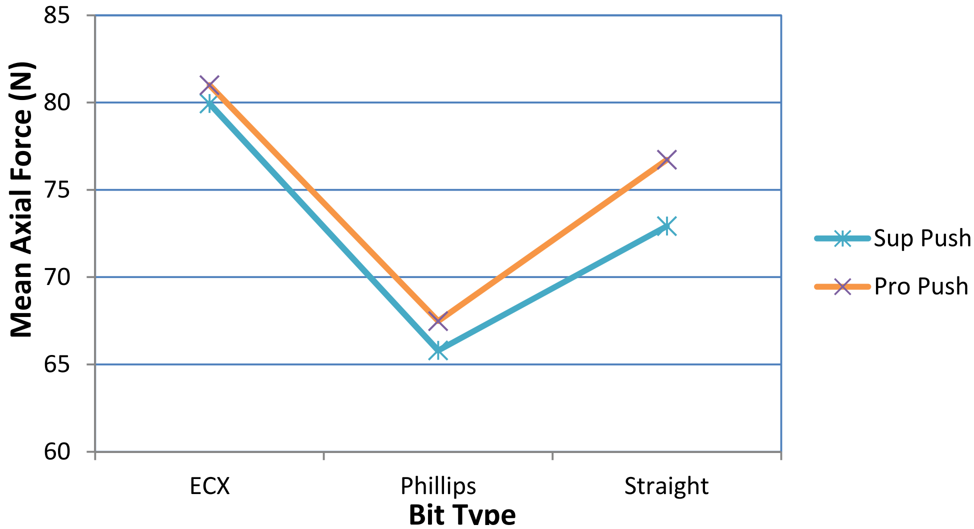

Fig 5.3: Mean Axial Force for All Subjects (n=16)

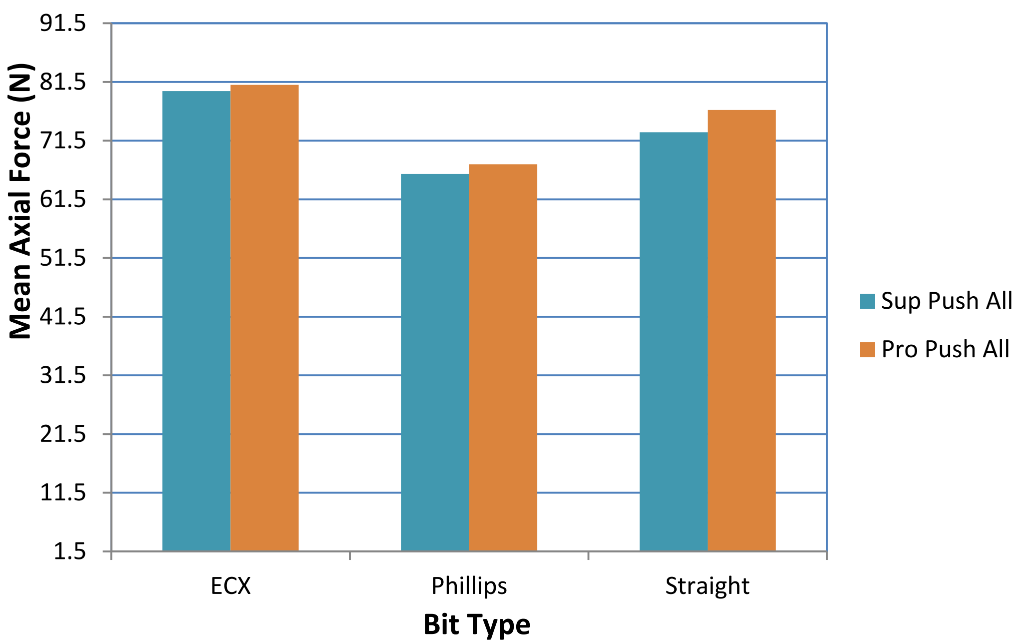

Fig 5.4: Average of Mean Axial Force (n=16)

The results of the ANOVA suggest bits have a significant effect. Neither direction nor the interaction of direction and bit were shown to have a significant effect. A summary of the ANOVA is shown in Table 5.5.

Table 5.5: Summary Table for ANOVA of Axial Force (n=16)

		SS	d.f.	MS	F	P
Total SS		317131.335	95			
Subjects		151363.744	15	10090.916	4.566	0.000
	Bit	151248.450	2	75624.225	34.215	0.000
	Dir.	49.148	1	49.148	0.022	0.882
	DxB	66.147	2	33.073	0.015	0.965
Error		165767.591	75	2210.235		

5.4 Effort Ratio

To investigate the existence of a relationship between screwdriver head design and user effort, an effort ratio was calculated. For the purpose of this experiment, the effort ratio was a dimensionless value calculated by dividing the tangential force causing the maximum applied torque and the axial force applied by the subject. A summary statistics of data recorded for the effort ratio is shown in Table 5.6. The complete set of effort ratio data recorded for all subjects is shown in Annex E.

Table 5.6: Summary of Statistics for Effort Ratio (N/N) (n=16)

Bit Type	ECX		Philips		Straight	
Direction	Pro	Pro	Sup	Pro	Sup	Sup
Mean	**2.870**	**4.006**	**3.636**	**3.051**	**3.114**	**2.969**
SD	**1.287**	**2.616**	**2.116**	**1.261**	**1.741**	**1.623**
Max	**6.048**	**10.295**	**8.731**	**4.968**	**7.010**	**6.666**
Min	**0.950**	**1.742**	**1.526**	**1.199**	**1.407**	**0.995**

A higher value of the ratio indicates more of the overall effort exerted by the subject went into the application of torque and less into pushing the screwdriver bit into the fastener. The data shows subjects had the greatest effort ratio using the Phillips bit. The data also suggests users will have a higher effort ratio while pronating than when supinating with the Phillips bit. However, the opposite was observed for the straight and ECX bits, though the difference of the means is small. The effort ratio values for all subjects were plotted as shown in Fig 5.5.

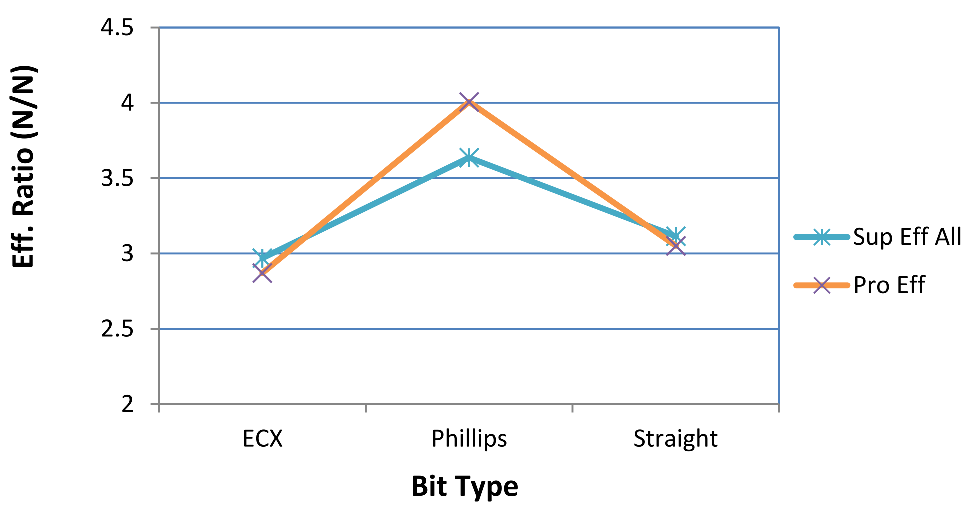

Fig. 5.5: Graph for Effort Ratio

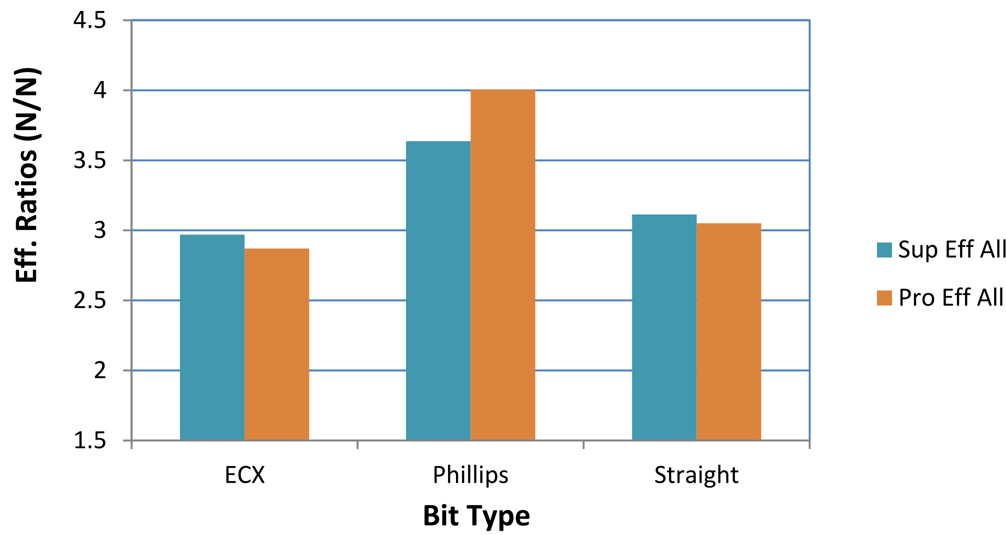

Fig. 5.6: Average Effort Ratio (n=16)

The results of the ANOVA suggest neither bits, direction, or their interaction has a significant effect. A summary of the ANOVA is shown in Table 5.6.

Table 5.6: Summary Table for ANOVA of Effort Ratio (n=16)

		SS	d.f.	MS	F	P
Total SS		319.544	95			
Among Cells		15.965	15	1.064	0.263	0.997
	Bit	14.760893	2	7.380	1.823	0.169
	Dir.	0.1150655	1	0.115	0.028	0.867
	DxB	1.089	2	0.544	0.135	0.874
Within cells		303.579	75	4.048		

5.5 Subjective Assessment

After testing with each bit was complete, the subjects used a 7-point Likert scale to rate the ease of use for that bit. The median rank data for all subjects are presented in Fig. 5.7 were within a close range (5 to 6). The Friedman's non-parametric (ANOVA) test revealed s bit type did not have a systematic effect on the ratings. Results of the Friedman's test are shown in Appendix F.

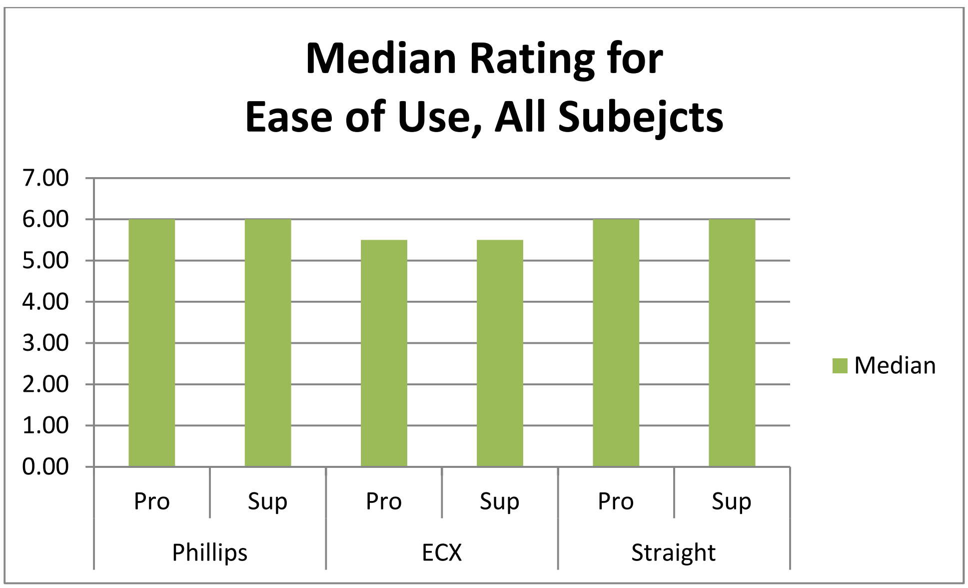

Fig. 5.7: Bar Chart for Median Ease of Use Ratings

Analysis of the subjective rankings where a rating of 1 indicates the bit subjects liked best and 3 the bit they liked least, subjects ranked the Phillips bit as being the best more often than any other bit tested. The data shows the Phillips bit was rated as the best by 56.2% of all subjects. A summary of the result for all subjects is show in Fig. 5.8.

Table 5.8: Bit Rankings (n=16)

Ranking	1	2	3	Points
Phillips	**9 (56.2%)**	**7 (43.8%)**	**0 (0%)**	**41**
ECX	**4 (25%)**	**2 (12.5%)**	**10 (62.5%)**	**26**
Straight	**3 (18.7%)**	**7 (43.8%)**	**6 (37.5%)**	**29**

6.0 DISCUSSION

6.1 General

This study was designed to determine what, if any, effect bit type had on the ability to a user to apply maximum torque to a fastener using a conventional screwdriver. The study also endeavored to analyze the relationship between torque application and axial force as a way to relate the user's overall effort to the task being completed. With the large variety of fastener styles available, there is little data regarding full user effort available to product designers. Such data would make it possible to consider not only a user's ability to apply torque, but also their overall effort when making fastener choices. These data may lead to a reduction in musculoskeletal injuries.

6.2 Torque exertion

At the start of this experiment, it was hypothesized that the bit design would have an effect on maximum torque. The data did not show a significant effect.

6.3 Torque levels

The levels of torque applied by test subjects were consistent with the literature, though on the lower end of the reported values from relevant studies. A factor that differentiates many previously conducted studies and this study is the fact those subjects performed simulated work tasks using tools that were not actually engaging a fastener. When using the screwdriver handle purely as a connecting device to a torque measurement fixture, the subject is actually being tested more for their physical ability to apply torque using that connection and less on their ability to apply torque to a fastener. For example, Kim et al. (2000) employed a screwdriver handle connected to work task simulator as part of their study yielding a mean applied torque reported was 6.53 Nm (S.D 1.22) with a range of 5.2 Nm to 9.8 Nm. These values are much higher than the mean value of 3.3 Nm (SD 1.2) and range of 1.9 Nm to 5.8 Nm measured as part of this study where an actual work task was performed. The results of this study are consistent with those of Sanchez (2007) who reported between 3.33 Nm (SD 1.15) and 4.06 Nm (SD 1.51) for college males using a conventional screwdriver while turning an actual screw.

The difference between simulated work tasks and actual work tasks may appear subtle but values of torque can be substantially different between actual tool use and maximal human ability. It is important to recognize the difference may be important to those developing a product or making a fastener selection. Using data from a simulated work task may not accurately replicate a fastening operation and could overestimate a person's ability to complete the operation with an actual tool. Having access to data that more accurately represent the actual user experience will be a benefit to both the designer and the worker.

During torque application, it was observations the screwdriver bit would "cam-out" or disengagement from the fastener on 13 of 192 (6.8%) trials. The fact tools disengage from the fastener at this rate implies a self-limiting factor associated with the fastener/driver interface design relevant to this work. Cam-out is a well-known issue in the field of fastener design and plays an important role in fastener selection. For example, when assembling a joint that requires high clamping force, the fabricator of the joint may be required to apply a high level of torque to meet the design specification.

Choosing a fastener prone to cam-out at low torque would cause a fabricator to have difficulty applying sufficient torque to assemble the joint properly. In contrast, to prevent a fastener from being over-tightened, a fastener prone to cam-out at high torque may be desirable. The data recorded as part of this study may be more helpful to a designer than pure human strength data as one could more closely predict the field conditions under which a fabricator would be working, allowing additional insight into their design.

6.4 Direction

It was hypothesized that subjects would produce more torque in supination that in pronation. This hypothesis was based, in part, by the fact the biceps brachii is known to be a strong supinator. There is even a suggestion that the tightening direction of a screw is clockwise, or supination for a right handed user, due to the fact that for a majority of the population is right handed and supinating the right hand would allow a user to apply their maximum torque output. While this may be anecdotal evidence, it may not be without merit as the Scientific American website (2013) states between 70 and 90% of the population is right handed, a contention supported by Bhattacharya and McGlothlin (1996) who report approximately 90% of the population is right handed. Coupled with the human strength literature, a circumstantial argument can be made.

While many factors including, but not limited to, posture of the user, the fastener/bit interface design and overall effort to exert torque, direction was not found to be a significant factor. When compared to the work of Rhomert (1966), Chaffin (1999), O'Sullivan and Gallway (2001) who all suggest more torque can be applied in supination, the results of this study may seem inconsistent as it suggest the opposite. However, those studies were human strength studies and not work task specific, the difference between which was previously discussed. Taking those differences into account, chiefly the relationship between torque application and axial force related to cam-out or bit disengagement, may help explain the results. As shown in figs. 5.3 and 5.4, axial force was highest for conditions where torque applied was lowest, which includes those in supination. This suggests higher torque output may be expected under conditions where subjects apply lower levels of axial force as less effort is exerted keeping the bit in contact with the fastener head leaving more available to generating torque. This research suggests this to be the case in pronation. This issue is further discussed under Effort Ratio.

6.5 Axial Force

Another hypothesis was there would be a difference in the amount of user applied push force between bits, which did have a significant effect. However, the results did not support an initial expectation that axial force would be greatest for the Phillips bit and lowest for the ECX bit. The data indicate the opposite to be true. A review of the fastener/bit interface may explain this result. While the intended design of the ECX bit was to combine the length of the straight bit with the self-centering aspects of the Phillips bit, it does not provide the same level of surface contact between the tool head and the screw when compared to a Phillips bit. As such, the tool head is more likely to ride-out of the screw head, which means less energy, is transmitted to torque the screw and more axial force applied by the user to keep the tool engaged. This may be due to the fact the Phillips portion of the design does not penetrate the fastener head to the same depth a true Phillips bit does. Similarly, the straight bit has a tendency of "sliding" out of the screw head, either from the front of the rear of the fastener, also causing the user to increase axial force to prevent movement.

6.6 Effort Ratio

For the purpose of this study, the ratio of tangential force applied to the tool handle causing torque and axial force is called the Effort Ratio. The purpose is to develop a metric by which overall user effort can be determined, allowing comparisons between bit designs to be made. The principle is simple, if a user applied less axial force when applying the same level of torque, the ratio goes up and they are exerting less overall energy. This would suggest that employing a design requiring less axial force to keep the bit engaged in the screw head would increase worker effectiveness by reducing muscle fatigue.

6.7 Sources of Error

There are a few sources of error identified during this experiment. With respect to human error, anthropometric data are sensitive to investigators technique, especially identifying landmarks and being consistent, subject-to-subject. With respect to procedural error, having the subject obtain proper posture during the test, and maintain for the duration of the test trial is important. The subject is to remain vertical with the wrist in the neutral position. Tayyari and Smith (1997) have shown that wrist deviation in any direction has an effect on the maximum force a subject can apply. As a result, measurements made with subjects in different posture may produce results that are lower than expected. Providing a tool with a higher coefficient of friction and with a better system for adjustment may reduce the slipping, improve posture and increase the torque values. Visual gauges the investigator could use to ensure proper posture is maintained could help reduce this affect.

6.8 Limitations

The nature of this study required a number of variables to be controlled in order to limit their effects on results. The number of fastener heads was one of those variables. Because the development of the effort metric is in its infancy it was decided to limit the study to just the one fastener type to determine if the concept had merit.

Similarly, the type of screwdriver handle utilized in this study was limited to one style, the conventional handle, and one size of that style. While Kong et al. (2005) showed that handle size does have an effect on grip force and torque application, this study was limited to the one size to simplify the analysis of how torque application and axial force may be related.

This study had subjects applying torque in only one body posture. O'Sullivan and Gallway (2001), Kim et al. (2002), and Sanchez (2007) have all shown that body posture does have a significant effect on a person's ability to apply maximum torque. However, the objective of this research was not to analyze posture but to more clearly understand the relationship between forces applied by the user, so it was limited to one posture.

A limitation related to the statistical power of the results is the small sample size. Ideally, a larger sample would have been taken that would have allowed for more statistical power and an analysis of the effects of gender. Again, since one of the objectives of this study was the initial development of the effort metric concept, a smaller sample was acceptable to determine whether additional research was indicated.

7.0 FUTURE WORK

A number of future studies should be conducted to further investigate the concept of the effort ratio. This would include performing the study described herein to determine of the results are consistent.

The inclusion of additional bit and/or handle styles in a similar study may allow an investigator to determine if bit types or handle styles affect the relationship between torque application and axial force to a greater level than torque.

Performing a study that includes a variety of postures may provide insight into whether axial force would be affected by body position in the same it has been shown to affect torque application. This certainly would be valuable to the overall development of the effort ratio concept.

Eventually the compilation of data from these studies may be used to develop recommendations for tool designers to improve the user experience and possibly reduce the likelihood of workers to suffer musculoskeletal injuries.

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9.0 APPENDIX A: DRAWINGS

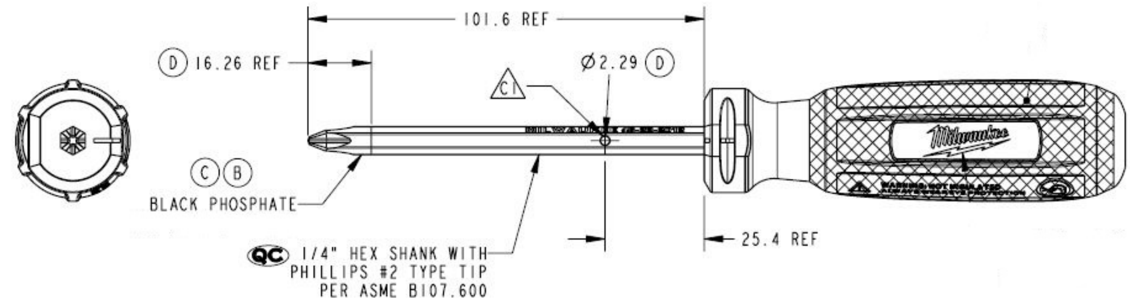


Fig. 9.1: Engineering Drawing of Phillips Screwdriver

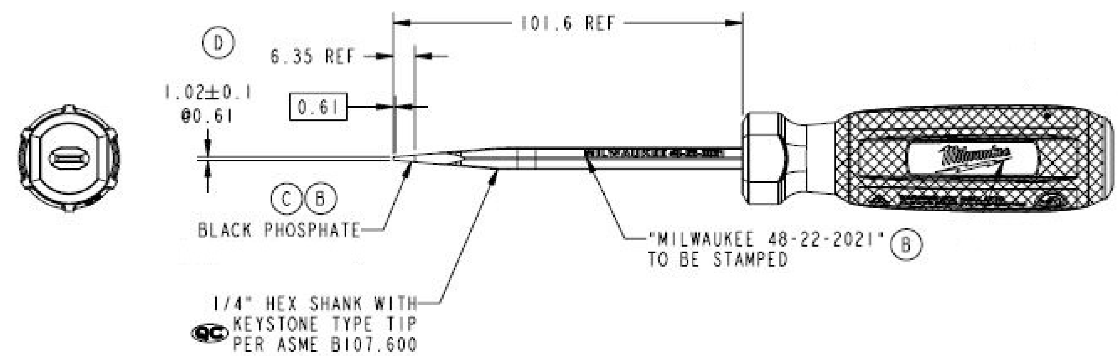


Fig. 9.2: Engineering Drawing of Straight Screwdriver

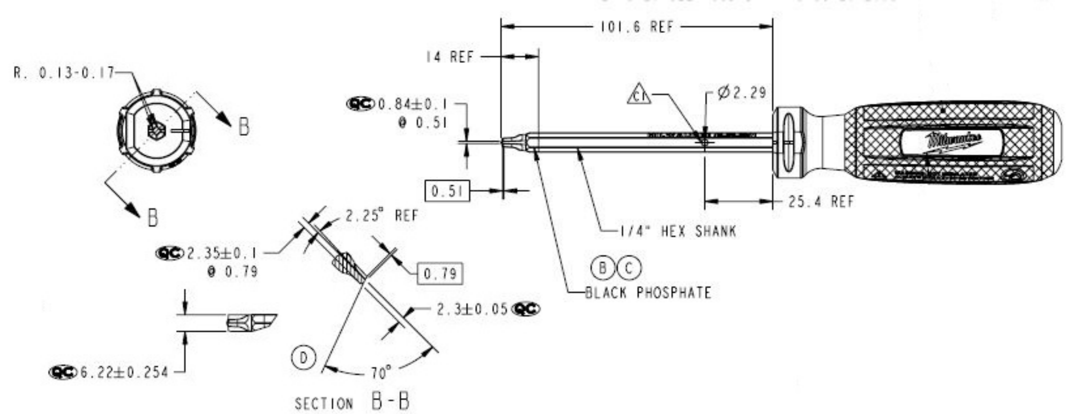
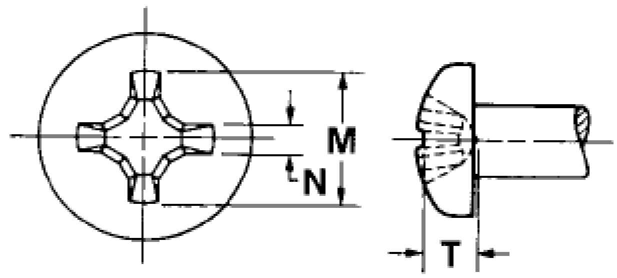


Fig. 9.3: Engineering Drawing of ECX^{TM} Screwdriver

TYPE 1

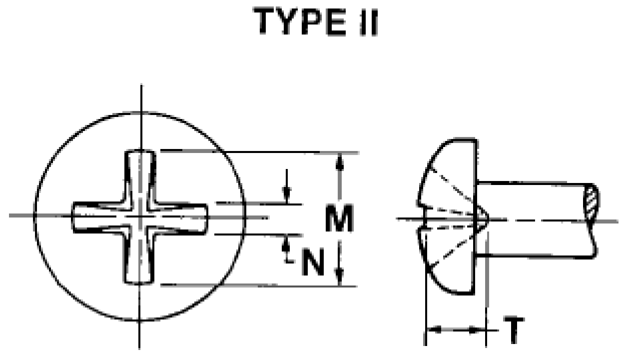


This type of recess has a large center opening, tapered wings, and blunt bottom, with all edges relieved or rounded.

Fig. 9.4: Engineering Drawing of ANSI/ASME B18.6.3 Type 1 Screw

Nominal Size or Basic Screw Diameter		H_1 Head Height		R_1 Head Radius	Type 1 M Recess Diameter		T Recess Depth		N Recess Width	Driver Size	Recess Penetration Gaging Depth	
		Max	Min	Min	Max	Min	Max	Min	Min		Max	Min
0	0.0600	0.044	0.036	0.005	0.067	0.054	0.039	0.021	0.013	0	0.032	0.014
1	0.0730	0.053	0.044	0.005	0.074	0.061	0.045	0.025	0.014	0	0.040	0.022
2	0.0860	0.062	0.053	0.010	0.104	0.091	0.059	0.041	0.017	1	0.052	0.034
3	0.0990	0.071	0.062	0.010	0.112	0.099	0.068	0.050	0.019	1	0.061	0.043
4	0.1120	0.080	0.070	0.010	0.122	0.109	0.078	0.060	0.019	1	0.071	0.053
5	0.1250	0.089	0.079	0.015	0.158	0.145	0.083	0.057	0.028	2	0.072	0.046
6	0.1380	0.097	0.087	0.015	0.166	0.153	0.091	0.066	0.028	2	0.080	0.055
8	0.1640	0.115	0.105	0.015	0.182	0.169	0.108	0.082	0.030	2	0.097	0.071
10	0.1900	0.133	0.122	0.020	0.199	0.186	0.124	0.100	0.031	2	0.113	0.089
12	0.2160	0.151	0.139	0.025	0.259	0.246	0.141	0.115	0.034	3	0.124	0.098
1/4	0.2500	0.175	0.162	0.035	0.281	0.268	0.161	0.135	0.036	3	0.144	0.118
5/16	0.3125	0.218	0.203	0.040	0.350	0.337	0.193	0.169	0.059	4	0.173	0.149
3/8	0.3750	0.261	0.244	0.040	0.389	0.376	0.233	0.210	0.065	4	0.213	0.190
7/16	0.4375	0.305	0.284	0.050	0.413	0.400	0.259	0.234	0.068	4	0.239	0.214
1/2	0.5000	0.348	0.325	0.055	0.435	0.422	0.280	0.255	0.071	4	0.260	0.235
9/16	0.5625	0.391	0.366	0.065	0.470	0.447	0.312	0.288	0.076	4	0.292	0.268
5/8	0.6250	0.434	0.406	0.075	0.587	0.564	0.343	0.314	0.081	5	0.310	0.281
3/4	0.7500	0.521	0.488	0.085	0.633	0.610	0.382	0.355	0.086	5	0.349	0.322
See Note 1		2			4						3	

Fig. 9.5: Dimension Table for ANSI/ASME B18.6.1 Type I Screw



This type of recess consists of two intersecting slots with parallel sides converging to a slightly truncated apex at bottom of recess.

Fig. 9.6: Engineering Drawing of ANSI/ASME B18.6.3 Type II Screw

Nominal Size or Basic Screw Diameter		H_1 Head Height		R_1 Head Radius	Type II M Recess Diameter		T Recess Depth		N Recess Width	Driver Size	Recess Penetration Gaging Depth	
		Max	Min	Min	Max	Min	Max	Min	Min		Max	Min
0	0.0600	0.044	0.036	0.005	0.076	0.066	0.038	0.026	0.022	Point same on all drivers	—	—
1	0.0730	0.053	0.044	0.005	0.089	0.079	0.046	0.034	0.024		—	—
2	0.0860	0.062	0.053	0.010	0.109	0.097	0.059	0.046	0.027		0.033	0.022
3	0.0990	0.071	0.062	0.010	0.125	0.113	0.069	0.056	0.029		0.043	0.032
4	0.1120	0.080	0.070	0.010	0.142	0.130	0.079	0.066	0.032		0.055	0.043
5	0.1250	0.089	0.079	0.015	0.159	0.145	0.090	0.076	0.034		0.066	0.052
6	0.1380	0.097	0.087	0.015	0.176	0.162	0.096	0.082	0.037		0.077	0.064
8	0.1640	0.115	0.105	0.015	0.207	0.192	0.116	0.101	0.041		0.097	0.083
10	0.1900	0.133	0.122	0.020	0.240	0.224	0.137	0.122	0.046		0.118	0.104
12	0.2160	0.151	0.139	0.025	0.272	0.254	0.158	0.142	0.051		0.139	0.124
1/4	0.2500	0.175	0.162	0.035	0.318	0.300	0.180	0.163	0.058		0.169	0.153
5/16	0.3125	0.218	0.203	0.040	0.396	0.375	0.231	0.212	0.069		0.220	0.202
3/8	0.3750	0.261	0.244	0.040	0.480	0.457	0.286	0.266	0.081		0.275	0.256
7/16	0.4375	0.305	0.284	0.050	0.557	0.531	0.336	0.314	0.093		0.325	0.304
1/2	0.5000	0.348	0.325	0.055	0.630	0.604	0.384	0.362	0.104		0.373	0.352
9/16	0.5625	0.391	0.366	0.065	0.638	0.612	0.389	0.367	0.105		0.378	0.357
5/8	0.6250	0.434	0.406	0.075	0.638	0.612	0.389	0.367	0.105		0.378	0.357
3/4	0.7500	0.521	0.488	0.085	0.638	0.612	0.389	0.367	0.105		0.378	0.357
See Note 1		2			4						3, 5	

Fig. 9.7: Dimension Table for ANSI/ASME B18.6.1 Type II Screw

10.0 APPENDIX B: FORMS

10.1: Marquette University IRB Approved Consent Form

Protocol Number : **HR-2538**

MARQUETTE UNIVERSITY
AGREEMENT OF CONSENT FOR RESEARCH PARTICIPANTS
Laboratory Study of Effects of Bit Type on Maximum Torque and Axial Force Application
While Using Manual Screwdrivers
Mark D. Hickok
Department of Mechanical Engineering

You have been invited to participate in this research study. Before you agree to participate, it is important that you read and understand the following information. Participation is completely voluntary. Please ask questions about anything you do not understand before deciding whether or not to participate.

PURPOSE: The purpose of this research study is to analyze the relationship between user force application and screwdriver bit design. A further objective is to utilize the results to develop an efficiency metric by which bits of different designs can be compared. These will be determined by measuring force and torque while operating various manual screwdrivers, each having a different bit design. You will be one of approximately 70 participants in this research study.

PROCEDURES: You will perform twelve (12) simulated screwdriver tasks where you will exert your maximum forearm torque on a screwdriver handle for no longer than 6 seconds. The maximum torque you apply and the maximum force you apply will be recorded by a computer. You will be tested while using 3 different screwdriver bit configurations and 2 different torque directions. Each tests configuration will be tested twice. All the tasks will be performed consecutively, with a break of no less than 2 minutes between each. After completing the tasks, anthropometric dimensions of your body will be measured. The total time of the experiment will be no more than 2 hours, which includes 45 minutes for filling out forms, describing the experiment, and setting up equipment.

DURATION: Your participation will consist of one laboratory session of approximately 2 hours.

RISKS: The risks associated with participation in this study include are no more than you would encounter in everyday life.

BENEFITS: There are no direct benefits to you associated with participation in this study. However, the correct application of the results of this study will assist product designers in making proper fastener choices when designing products that require manual screw driving operations. Generalizations of the results may also be made for the general population and hand tool designers.

Initials: __________
Date: __________

Protocol Number : **HR-2538**

CONFIDENTIALITY: All information you reveal in this study will be kept confidential. All your data will be assigned an arbitrary code number rather than using your name or other information that could identify you as an individual. When the results of the study are published, you will not be identified by name. The data will be destroyed by shredding paper documents and deleting electronic files 5 years after the completion of the study. All documents will be stored in a locked cabinet in the principle investigator's locked office. Electronic data will be stored on a password protected computer which is also stored in the principle investigator's locked office. 5 years after the study is complete all paper documents will be shredded and all electronic data will be permanently deleted. Your name will not be used in any reports and will only be recorded on this sheet. All other sheets will only have a subject code number. Your research records may be inspected by the Marquette University Institutional Review Board or its designees and (as allowable by law) state and federal agencies.

VOLUNTARY NATURE OF PARTICIPATION: Participating in this study is completely voluntary and you may withdraw from the study and stop participating at any time without penalty or loss of benefits to which you are otherwise entitled. If you choose to withdraw during your participation, please notify the researcher and your data will be destroyed. It is not possible to withdraw your data after participation because the data are collected confidentially and the researcher will not be able to determine which data are yours.

CONTACT INFORMATION: If you have any questions about this research project and/or what to expect as a participant in a testing session, please feel free contact Mark Hickok, the principle investigator, at (262) 783-8656 (office) or (262) 347-1440 (cell). If you have questions or concerns about your rights as a research participant, you can contact Marquette University's Office of Research Compliance at (414) 288-7570.

I HAVE HAD THE OPPORTUNITY TO READ THIS CONSENT FORM, ASK QUESTIONS ABOUT THE RESEARCH PROJECT AND AM PREPARED TO PARTICIPATE IN THIS PROJECT.

______________________________ ________________

Participant's Signature Date

____

Participant's Name

______________________________ ________________

Researcher's Signature Date

Form 2

10.2: Occupational and Health Background Information Form

MARQUETTE UNIVERSITY

Be The Difference.®

Laboratory Study of Maximum Torque and Axial Force Application Using a Manual Screwdriver

Occupational and Health Background Information Form

Date: ______/_____/______

Name:_________________________________

Age: ______________ Gender: ____________

Occupation: ____

How long have you been in this occupation? ____

Have you ever had an injury or illness of a musculoskeletal nature? *YES* *NO*.

If *YES*, please describe____

____

____

Do you have any current injury or illness or pain of a musculoskeletal nature? *YES* *NO*.

Please describe and when it occurred ____

____

If *YES*, would using a screwdriver while participating in this experiment make your injury or illness or pain worse? *YES* *NO*.

If *YES*, Please describe____

10.3: Subjective Assessment Form

MARQUETTE UNIVERSITY

Be The Difference.

(Forms varied based on Condition being performed)
SUBJECTIVE ASSESSMENT SURVEY
Laboratory Study of Maximum Torque and Axial Force Application Using a Manual Screwdriver
Subject ID: ____________________ Date: ____________________

Condition: PH Bit
Please rate the ease of applying torque in a counterclockwise direction:

1	2	3	4	5	6	7
Very Difficult	Difficult	Somewhat Difficult	Neutral	Somewhat Easy	Easy	Very Easy

Please rate the ease of applying torque in a clockwise direction:

1	2	3	4	5	6	7
Very Difficult	Difficult	Somewhat Difficult	Neutral	Somewhat Easy	Easy	Very Easy

Condition: ECX Bit
Please rate the ease of applying torque in a counterclockwise direction:

1	2	3	4	5	6	7
Very Difficult	Difficult	Somewhat Difficult	Neutral	Somewhat Easy	Easy	Very Easy

Please rate the ease of applying torque in a clockwise direction:

1	2	3	4	5	6	7
Very Difficult	Difficult	Somewhat Difficult	Neutral	Somewhat Easy	Easy	Very Easy

Condition: Straight Bit

Please rate the ease of applying torque in a counterclockwise direction:

1	2	3	4	5	6	7
Very Difficult	Difficult	Somewhat Difficult	Neutral	Somewhat Easy	Easy	Very Easy

Please rate the ease of applying torque in a clockwise direction:

1	2	3	4	5	6	7
Very Difficult	Difficult	Somewhat Difficult	Neutral	Somewhat Easy	Easy	Very Easy

Please rank order the bits with respect to which you feel best allowed you to apply torque:

1)__________________(Best)
2)__________________
3)__________________

Comments:____

____

____

Form 3

10.4: Blank Anthropometry Data Sheet

MARQUETTE
UNIVERSITY
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Subject #	Gender	Dominant Side (R or L)	Stature (cm)	Acromial Height (cm)	Acromium to Dactylion Length (cm)	Hand Length (cm)	Hand Breadth (cm)	Wrist Circum-ference (cm)	Forearm Circum-ference (cm)	Arm Circum-ference (cm)	Weight (kg)
1											
2											
3											
4											
5											
6											
7											
8											
9											
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Form 4

11.0 APPENDIX C: PARTICIPANT BACKGROUND

Table 11.1: Participant Background Information

Subject	Date	Age	Gen.	Occupation	Yrs.	Injury	Comment	Current
S03	9-13-13	29	M	Engineer	1	N	N/A	N/A
S04	9-13-13	24	M	Technician	3	N	N/A	N/A
S05	9-13-13	39	M	Engineer	13	N	N/A	N/A
S06	9-13-13	21	M	Intern	.5	N	N/A	N/A
S07	9-13-13	45	M	Engineer	21	N	N/A	N/A
S08	9-13-13	43	M	Database prgmr.	19	Y	Back injury from sports	N
S09	9-13-13	24	M	Office Asst.	3	N	N/A	N/A
S10	9-13-13	40	F	Tech Writer	15	N	N/A	N/A
S11	9-13-13	34	F	Engineer	15	N	N/A	N/A
S12	9-13-13	46	F	Office Asst.	4	N	N/A	N/A
S13	9-13-13	40	F	Paralegal	5	N	N/A	N/A
S14	9-13-13	37	F	Accounting	3	N	N/A	N/A
S15	9-13-13	44	F	Accounting	8	N	N/A	N/A
S16	9-13-13	35	F	Analyst	14	N	N/A	N/A
S17	9-13-13	44	F	Accounting	3	N	N/A	N/A
S18	9-13-13	43	M	Technician	15	Y	Lower Back, car accident	N

12.0 APPENDIX D: ANTHROPOMETRY

Table 12.1: Summary of Anthropometry Data

Subject #	Gender	Dominate Side	Stature (cm)	Acromion Height (cm)	Acromion to Dactylion Length (cm)	Hand Length (cm)	Hand Breadth (cm)	Wrist Circ. (cm)	Fore-arm Circ. (cm)	Arm Circ. (cm)	Hand Dyno. (kg)	Weight (kg)
S03	M	R	177.2	148.3	78.6	19.0	9.3	18.1	31.2	40.0	54.0	104.5
S04	M	R	185.8	153.3	83.6	20.5	9.7	18.0	31.2	36.8	88.5	82.1
S05	M	R	177.5	148.2	78.6	19.2	9.0	17.2	26.4	29.0	41.5	53.4
S06	M	R	183.2	152.8	82.7	19.6	9.1	17.8	31.0	37.3	61.5	89.6
S07	M	R	178.8	151.0	79.0	20.0	8.9	17.2	29.5	31.4	60.5	69.0
S08	M	L	179.5	151.6	79.2	19.8	8.9	17.8	30.7	32.5	59.0	91.4
S09	M	R	161.4	134.4	71.5	19.0	7.9	16.2	25.6	28.5	39.0	54.9
S10	F	R	169.7	143.0	72.8	18.0	8.3	17.0	29.0	37.0	38.5	84.0
S11	F	R	162.4	135.5	70.5	17.2	7.5	13.9	21.5	24.2	31.0	42.9
S12	F	R	157.7	129.3	70.9	18.3	8.0	16.3	26.3	32.7	31.5	52.3
S13	F	R	159.7	131.7	69.9	17.2	7.9	16.1	24.3	26.0	19.5	57.9
S14	F	R	158.4	137.0	69.1	19.0	7.4	15.9	26.2	29.7	24.5	53.0
S15	F	R	159.9	133.5	68.6	17.2	8.0	16.2	26.0	29.0	27.5	54.5
S16	F	R	158.6	133.0	69.9	18.2	8.5	14.8	22.5	25.0	34.5	43.7
S17	F	R	155.6	131.0	68.8	17.5	7.9	17.0	23.8	26.5	28.5	54.5
S18	M	R	183.2	153.0	81.4	20.1	9.7	17.9	30.8	32.0	58.5	93.3
Mean:	--	--	169.3	141.7	74.7	18.7	8.5	16.7	27.3	31.1	43.6	67.6
SD:	--	--	11.0	9.2	5.5	1.1	0.7	1.2	3.3	4.8	18.4	20.0
Max:	--	--	185.8	153.3	83.6	20.5	9.7	18.1	31.2	40.0	88.5	104.5
Min:	--	--	155.6	129.3	68.6	17.2	7.4	13.9	21.5	24.2	19.5	42.9

12.2: Anthropometric Measurement Locations

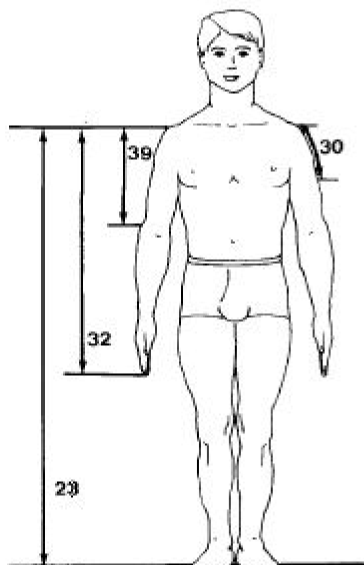
Heights, Breadths, Depths, Circumferences, and Arcs

Heights, breadths, and depths are straight line measurements made with an anthropometer, calipers, or a similar instrument. Lengths are measured similarly unless the word tape is specified. Circumferences and arcs are tape measurements.

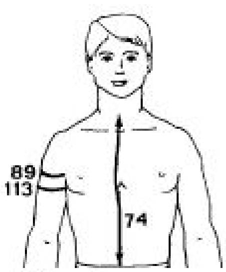
(1) A standing height is the vertical distance from a specified point on the body to the floor.

23. Acromial Height. The height of the acromion.

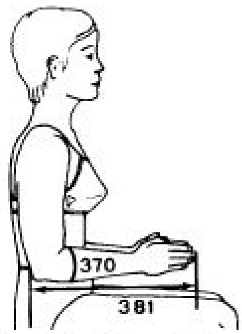
32. Acromion to Dactylion Length. The vertical distance from acromion to the tip of the middle finger.



113. Biceps Circumference, Relaxed. The maximum circumference of the arm at the level of the biceps measured with the arm hanging relaxed.

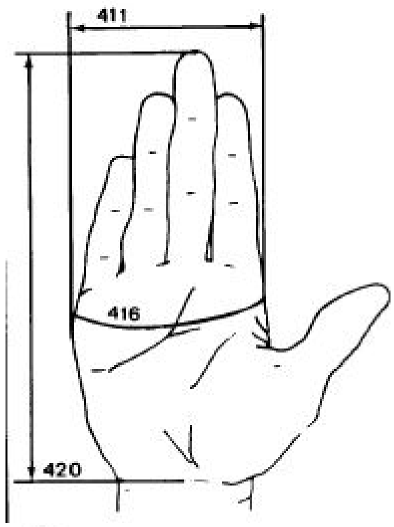


370. Forearm Circumference, Relaxed. The maximum circumference of the lower arm.



411. Hand Breadth. The breadth of the hand as measured across the distal ends of the metacarpal bones.

420. Hand Length. The distance from the base of the hand to the top of the middle finger measured along the long axis of the hand.



967. Wrist Circumference. The circumference of the wrist at the level of the tip of the styloid process of the radius.

13.0 APPENDIX E: DATA ANALYSIS

Table 13.1: Summary of mean torque data (Nm)

	Gender	Str. Sup	Str. Pro	PH Sup	PH Pro	ECX Sup	ECX Pro
S03	M	3.392	3.789	4.732	5.051	3.446	2.877
S04	M	4.837	4.931	4.284	5.828	4.555	5.715
S05	M	4.463	4.924	3.930	4.133	5.049	5.121
S06	M	2.256	1.977	2.172	2.416	2.043	2.616
S07	M	2.595	3.349	3.440	3.649	2.863	2.730
S08	M	3.006	2.806	2.774	2.964	2.641	2.855
S09	M	1.924	2.509	1.422	1.874	2.191	2.379
S10	F	3.609	3.732	2.760	3.385	3.375	3.612
S11	F	2.124	2.441	2.408	2.455	2.285	2.346
S12	F	1.490	2.736	1.235	2.876	1.406	2.309
S13	F	1.225	1.904	1.163	1.301	0.938	1.907
S14	F	1.998	2.025	1.625	2.052	1.480	1.950
S15	F	2.044	1.640	1.953	1.570	1.860	1.742
S16	F	2.404	2.712	2.876	2.808	3.228	2.813
S17	F	1.106	0.887	1.359	1.158	1.585	1.256
S18	M	3.706	3.612	4.119	4.049	2.920	3.366
Mean	N/A	2.636	2.873	2.641	2.973	2.617	2.850
SD	N/A	1.106	1.128	1.175	1.325	1.134	1.170
Max	N/A	4.837	4.931	4.732	5.828	5.049	5.715
Min	N/A	1.106	0.887	1.163	1.158	0.938	1.256

Table 13.2: Analysis of Variance for torque data

		SS	d.f.	MS	F	P
Total SS		126.165	95			
Subjects		1.861	15	0.124	0.075	1.000
	Bit	0.092	2	0.046	0.028	0.973
	Dir.	1.719	1	1.719	1.037	0.312
	DxB	0.050	2	0.025	0.015	0.985
Error		124.304	75	1.657		

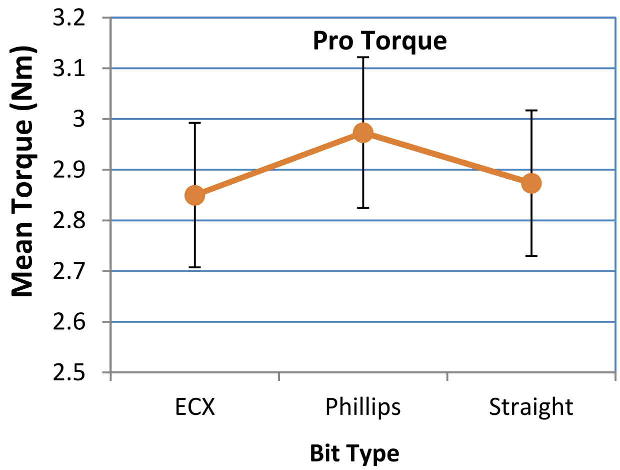


Fig. 13.1: Graph of Torque in Pronation

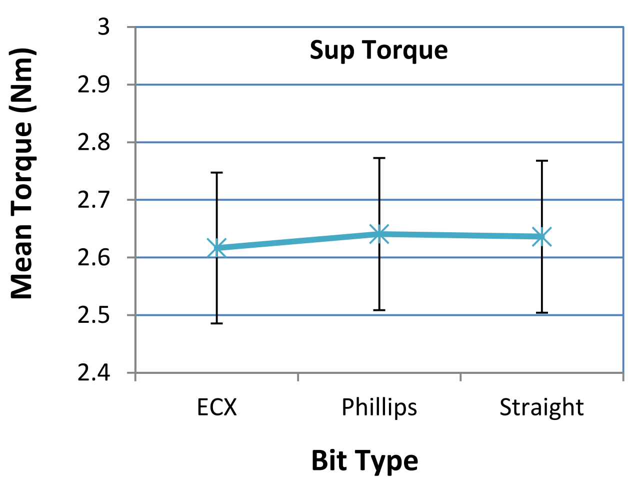


Fig. 13.2: Graph of Torque in Supination

Table 13.3: Summary of axial force data (N)

Subject	Gender	Str. Sup	Str. Pro	PH Sup	PH Pro	ECX Sup	ECX Pro
S03	M	131.454	204.843	128.207	154.785	224.502	196.355
S04	M	187.463	176.528	181.939	191.277	161.484	187.510
S05	M	141.265	134.729	106.113	80.131	150.610	140.071
S06	M	88.992	89.644	86.402	86.174	96.530	91.658
S07	M	119.497	102.666	121.250	106.760	92.388	99.770
S08	M	108.491	78.742	108.523	75.494	120.539	79.428
S09	M	53.970	64.736	39.850	69.704	68.912	63.393
S10	F	28.301	37.952	34.141	24.552	22.219	42.273
S11	F	41.174	47.614	29.240	48.532	34.066	52.736
S12	F	24.331	28.632	22.274	21.376	18.344	44.994
S13	F	18.472	26.418	12.065	12.921	17.480	20.895
S14	F	43.044	24.215	27.731	23.555	31.969	22.483
S15	F	23.565	38.278	34.673	48.531	44.755	45.868
S16	F	27.591	30.148	22.297	23.844	33.021	30.116
S17	F	74.510	85.961	74.254	89.274	110.708	107.174
S18	M	54.629	56.452	23.809	22.801	51.547	71.289
Mean	N/A	72.922	76.722	65.798	67.482	79.942	81.001
SD	N/A	51.195	54.664	50.512	51.015	60.755	54.255
Max	N/A	187.463	204.843	181.939	191.277	224.502	196.355
Min	N/A	18.472	24.215	12.065	12.921	17.480	20.895

Table 13.4: Analysis of Variance for axial force data

		SS	d.f.	MS	F	P
Total SS		317131.335	95			
Subjects		151363.744	15	10090.916	4.566	<0.005
	Bit	151248.450	2	75624.225	34.215	<0.005
	Dir.	49.148	1	49.148	0.022	0.882
	DxB	66.147	2	33.073	0.015	0.965
Error		165767.591	75	2210.235		

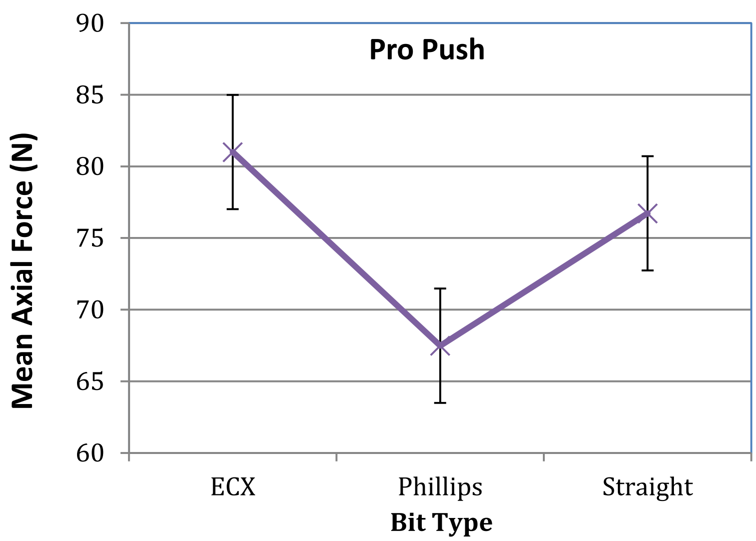


Fig. 13.3: Graph of Axial Force in Pronation

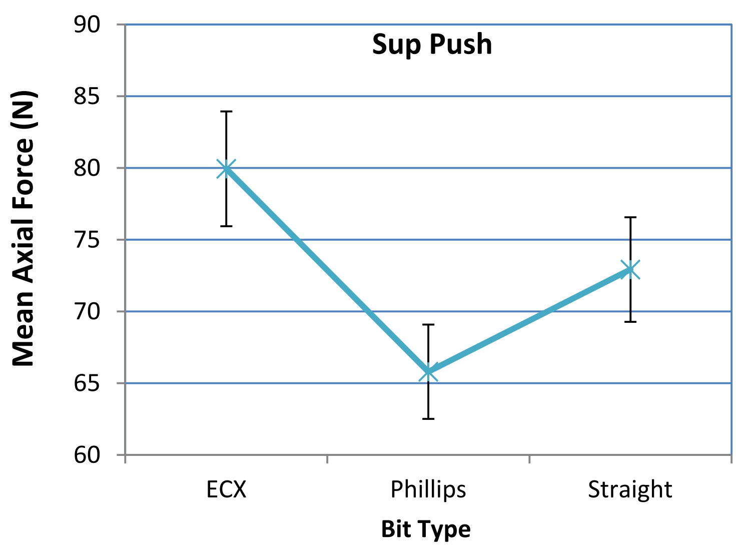


Fig. 13.4: Graph of Axial Force in Supination

Table 13.3: Summary of ratio data (N/N)

Subject	Gender	Str. Sup	Str. Pro	PH Sup	PH Pro	ECX Sup	ECX Pro
S03	M	1.672	1.199	2.392	2.115	0.995	0.950
S04	M	1.672	1.810	1.526	1.975	1.828	1.975
S05	M	2.048	2.369	2.400	3.342	2.173	2.369
S06	M	1.643	1.429	1.629	1.817	1.371	1.850
S07	M	1.407	2.114	1.839	2.215	2.008	1.774
S08	M	1.796	2.309	1.657	2.545	1.420	2.330
S09	M	2.310	2.512	2.312	1.742	2.061	2.433
S10	F	4.865	4.169	4.571	6.481	6.666	3.597
S11	F	2.345	3.724	2.737	3.841	2.674	2.838
S12	F	3.263	4.309	3.384	3.944	3.312	2.747
S13	F	7.010	4.968	8.731	10.295	5.488	6.048
S14	F	3.077	4.388	4.565	4.321	3.771	5.021
S15	F	6.612	4.593	5.376	3.750	4.675	3.975
S16	F	2.598	1.907	3.949	3.148	3.111	2.702
S17	F	3.223	2.723	3.595	2.940	1.709	2.035
S18	M	4.282	4.285	7.512	9.622	4.244	3.284
Mean	N/A	3.114	3.051	3.636	4.006	2.969	2.870
SD	N/A	1.741	1.261	2.116	2.616	1.623	1.287
Max	N/A	7.010	4.968	8.731	10.295	6.666	6.048
Min	N/A	1.407	1.199	1.526	1.742	0.995	0.950

Table 13.5: Analysis of Variance for ratio data

		SS	d.f.	MS	F	P
Total SS		319.544	95			
Among Cells		15.965	15	1.064	0.263	0.997
	Bit	14.761	2	7.380	1.823	0.169
	Dir.	0.115	1	0.115	0.028	0.867
	DxB	1.089	2	0.544	0.135	0.874
Within cells		303.579	75	4.048		

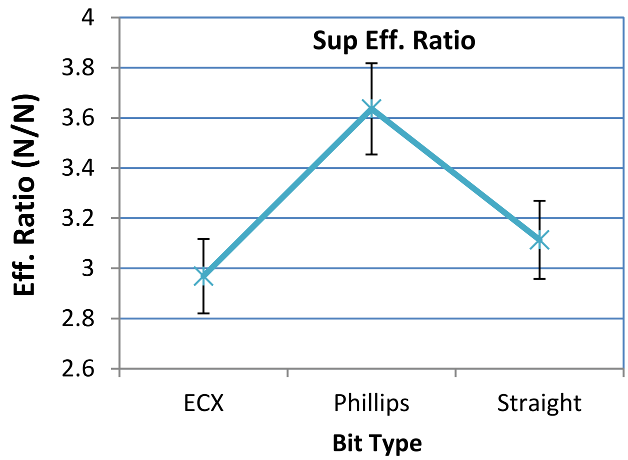


Fig. 13.5: Graph of Ratio in Pronation

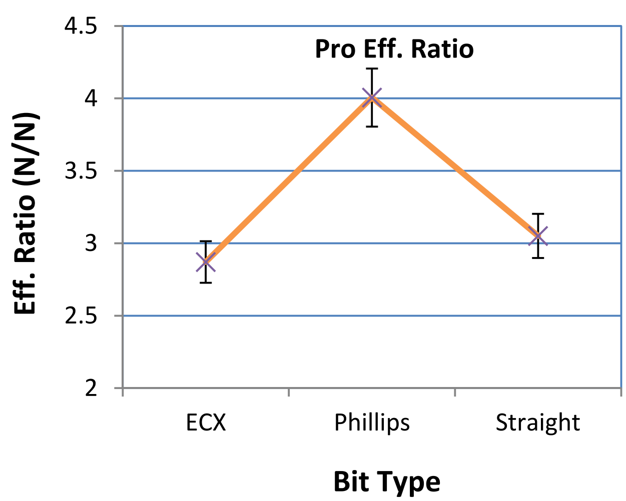


Fig. 13.6: Graph of Ratio in Supination

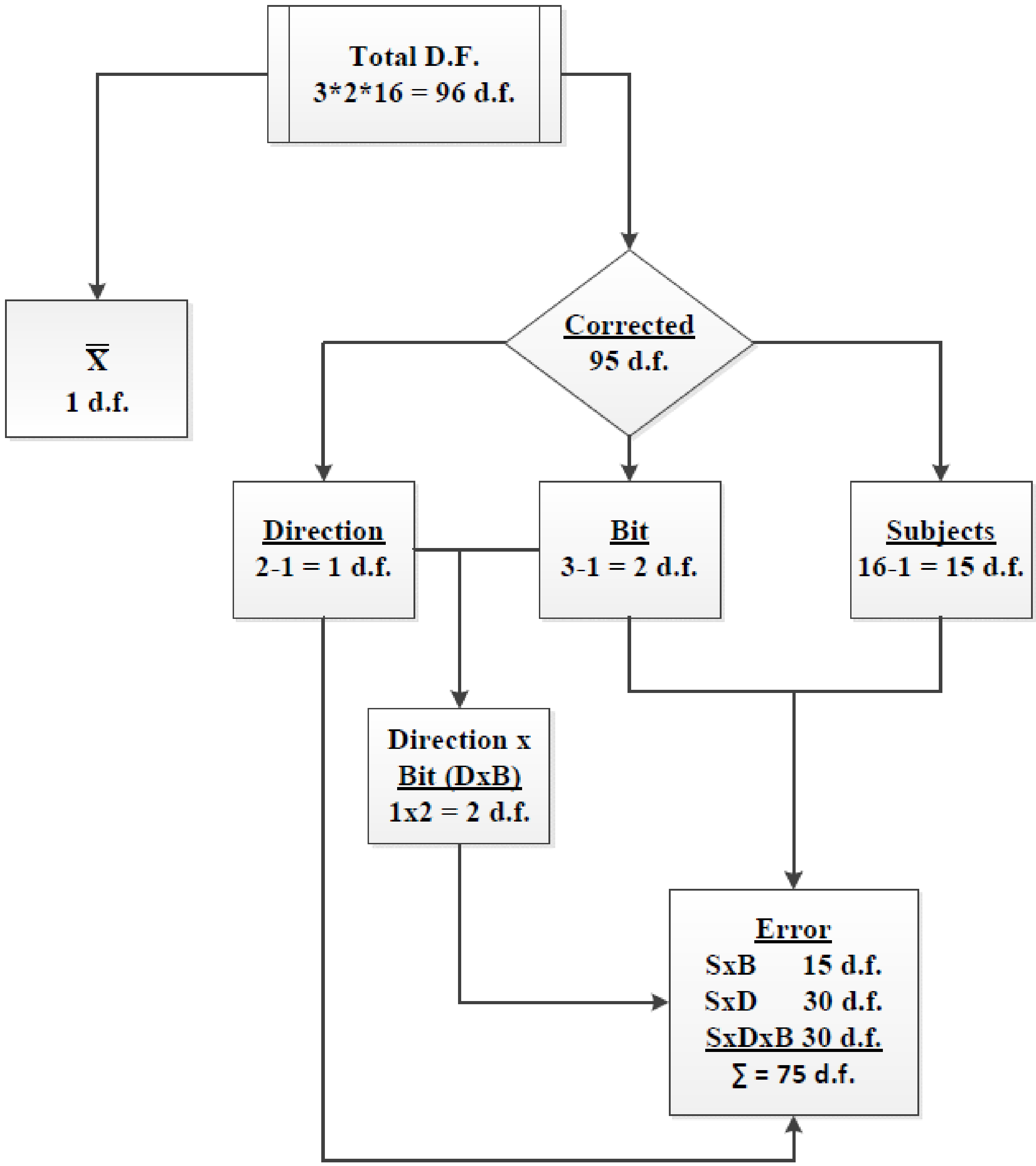


Fig. 13.7 – Degrees of Freedom Analysis

14.0 APPENDIX F: NON-PARAMETRIC FRIEDMAN'S TEST

Table 14.1: Descriptive Statistics for Subjective Assessment

	Phillips		ECX		Straight	
	Pro	Sup	Pro	Sup	Pro	Sup
Average	5.56	5.44	5.13	5	5.31	5.38
Sum	89	87	82	80	85	86
Median	6	6	5.5	5.5	6	6

Variable	Friedman ANOVA and Kendall Coeff. of Concordance (Spreadsheet1) ANOVA Chi Sqr. (N = 16, df = 5) = 6.362126 p = .27256 Coeff. of Concordance = .07953 Aver. rank r = .01816 Average Rank	Sum of Ranks	Mean	Std.Dev.
Phillips P	4.000000	64.00000	5.562500	1.093542
Phillips S	3.718750	59.50000	5.437500	1.093542
ECX P	3.093750	49.50000	5.125000	1.087811
ECX S	3.000000	48.00000	5.000000	1.211060
Straight P	3.500000	56.00000	5.312500	1.138347
Straight S	3.687500	59.00000	5.375000	1.204159

Fig. 14.1: Results of Friedman's ANOVA

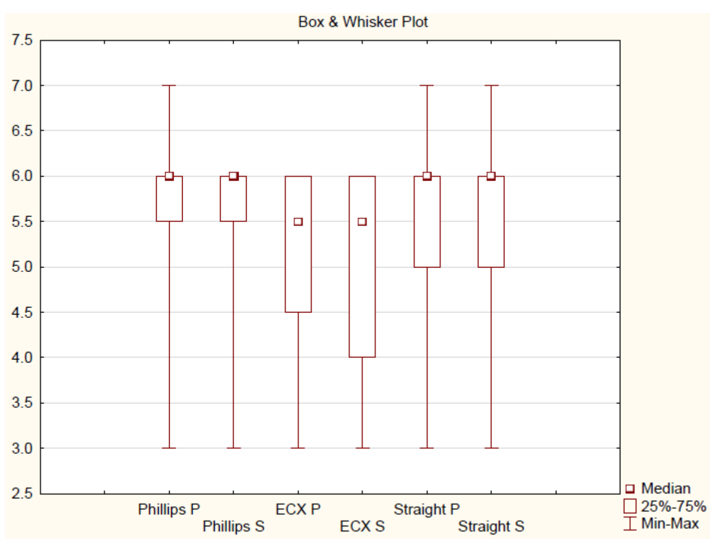


Fig. 14.2: Box Plot of Friedman's ANOVA Results