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Research Study and Analysis of Ergonomic Design of Conventional Wrench Handle

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Abstract: One of the most common hand tool wrench used today does not come equipped with a handle facilitating a comfortable grip for its extended use. The purpose of this study was to create an ergonomic design for a hand tool (a wrench) that is commonly used in a wide range of industries all around the Globe. The overall goal of the project involved first designing ergonomic profiles for the wrench handles with grip diameter suitable for ninety-five percentile user population. These handle profiles were created using CAD to prototype subsequently using a 3D printing system. A conventional wrench was then assembled with each of the three handle profiles for ergonomic testing & evaluation. By choosing random male subjects, we compared a standard wrench (with regular handle) with (identical) wrench assembled with the three different profiles of the handle. The maximum amount of torque that the test subjects could apply on each handle was measured using a torque tester; we also measured the muscle activity with each of the handles for each subject with the help of EMG (Electromyography). The experimental data obtained from this process then were analyzed to infer about the performance of the three wrench handle with a standard handle in order to determine one most efficient ergonomic design for the wrench handle profile.

Keywords: Ergonomics, Handle design, Biomechanics

1. Introduction

In many industrial work situations, it is widespread that manual hand tools such as wrench are required for equipment assembly, maintenance and other tasks. US Bureau of Labor Statistics (2013) data showed that there were 186,830 nonfatal occupational injuries to hands and wrists involved days away from work. Wrist injuries led to 15 median days away from work and hand injuries led to 5 median days away from work. It was most likely that those injuries could be reduced if the tool handle was ergonomically designed to provide most comfortable grip while exerting maximum amount of torque. With such motivation, we redesigned the wrench handle with emphasis on user comfort, safety and improved torque performance.

Conventional adjustable wrench is made of a Chrome-Vanadium alloy steel, a wide-mouth extended tapered jaws and a compact handle. Its ubiquitous existence makes people hardly believe its design involving any flaws. During the subjective review phase, it was found that workers would prefer wrench with handle because the conventional handle caused pinching between fingers. In fact, during the study, some flaws of such wrench were observed. First, the wheel driving adjustable jaw aggregates dust and dirt and becomes difficult to be spun over time. As the jaw can’t hold screw precisely, the Hex angle of screw starts to wear out in turn makes screw less effective. Second, the wrench handle was not ergonomic designed. The thin and sharp contour made by metal causes extreme hand strains, pain and soreness even after a short duration. Third, the uncovered metal perhaps hurts human users in the case of an accidental drop. Hence, in order to reduce soreness and hand injuries, an ergonomic designed wrench handle become crucial.

In this project, with the goal of resolving the drawbacks of current wrench handles listed above, several wrench handles were designed with the combination of following factors: shapes (rectangular, sharp-edge curved, and round-edge curved), diameters (1.5 inch, 0.8 inch and 1.74 inch) and materials (metal, PLA plastic and HDPE plastic). A total of four different wrench handles were evaluated in a maximum torque task (screw fastening). The objectives of this study were: (1) to objectively and subjectively evaluate the effect of wrench handle shape, diameter, and material on torque output and muscle electromyography (EMG) activity; (2) to determine the wrench handle design characteristics so as to achieve the maximum torque output with minimum hand strains therefore reduce hand injuries.

2. Literature Review

A proper handle diameter maximizes performance and reduce hand strain with the forearm muscles and finger tendons. The general agreement among studies was that the optimum handle diameter differs from person to person as it was related to the hand size of individual. The torque output was proportional to handle diameter. Kong and Lowe (2005) showed that the maximum voluntary finger contraction force was diameter dependent, therefore handle diameter was one of the essential criteria in tool design. Grant, Habes and Steward (1992) suggested that a handle which allowed some overlap between the thumb and forefinger may be better for some applications than a larger handle. Handle 1cm smaller than the users inside grip diameter may reduce effort and the potential for injury. Even more precisely, Kong and Lowe (2005) reported that the optimal handle diameter was 19.7% of the user's hand length. Total finger force capability was inversely proportional with handle diameter. Lewis and Narayan (1993) also suggested multiple handle diameters which satisfied the populations of both male and females. The hand measurement of 50th percentile males approximate to those of 95th percentile female. Also, the hand measurement of 5th percentile males were close to those of 50th percentile females.

The material of tool handle was also an important factor that affects torque output, muscle strain, and injuries. Magill and Konz (1986) compared seven screwdrivers of similar design and size with different handle materials, four plastic, two wooden and one rubber-coated. They reported, based on torque output and subjective preference, the rubber handles were most preferred, followed by plastic and wooden handles. Results showed rubber and plastic handles provided greater torque output and manipulative capability than wooden handle. Kong and Lowe (2007) compared 24 screwdriver handles with different surface materials (plastic and rubber-coated). They reported the plastic surface handles were associated with 15% less torque output than the rubber coated handles. Although, there was no study investigating the material effect on torque and force required to operate a wrench. The previous researches suggested that the plastic and rubber handles should be a preferred choice for tool handle.

The handle shape as another important factor should be designed to maximize the area of contact between the tool and the palm of hand. The reduced unit pressure can be achieved with larger contact area providing better pressure distribution on hand. Lewis and Narayan (1993) reported that if a tool had a short handle which did not span the hand breadth. High forces were created at the center of the palm causing extreme hand pain. Thus the tool handle should be designed to extend beyond the hand breadth when gripped. Lewis and Narayan (1993) also suggested that cavities such as finger grooves should be avoided because of the wide variations of finger anthropometry in the population. Sharp edges and corners can hurt finger and palm. Hence rounded edges and corners were always preferred to prevent from hazard such as hand cuts, bruises, or abrasions.

3. Method and Procedure

A. Subjects

For this experiment 3 university students were selected as the subjects. The subjects did not have any history of damage to their dominant hands. The experiment were done with the consent of the subjects and the experimental procedure was explained to them before starting with the trials.

B. Apparatus

In the experiment, several equipment were associated with designs and measuring systems. SolidWorks software was used for 3D handle design. The designed handle was printed by 3D Printer (Flash Forge Creator Pro). Torque tester was attached on the table wise for measuring torque exertion by wrench. Electromyography (EMG) system was measuring muscle activities with associated muscles during task. Dynamometer was pressed to achieve maximum voluntary contraction (MVC) of the muscles.

C. Handle Design

We conducted the experiment with 4 types of wrench handles of which 1 was with a conventional handle which was just metal with no grip. The designs of the other 3 handles were done using SolidWorks software. The designs were modelled in three dimensional views. Refer appendix for the 2D layout of the handles. All the handles were designed to accommodate 95% of the US population. Design 1a & 1b from the appendix notifies that, it has two curvatures which were equally spaced from the centerline of the handle. A smooth surface in the handle does not cause any pinching effect on the hand which will scale down carpal tunnel syndrome and the smooth surfaces were modelled by using fillet tool. As we can see in design 2a & 2b there was more curving at the rear end of the handle which motivates more discomfort when holding it, but this design was more compatible than the conventional wrench. Design 3 replicated same as the design 2, but the only difference was that, there was a significant possibility of pinching in the hands due to the nature of the profile, which eventually can lead to injuries. All the three designs were modelled using lofted extrude because of the nature of the core. Core was nothing but the conventional wrench. Each of the handle were sectioned into two, so that it was easy to assemble the core inside the handle. The width of one handle was about 38mm (1.5inches) which was derived from the hand anthropometric data of the 50th percentile of US population. The curvature was designed keeping human hand anatomy and ergonomics into considerations, thus expected to provide necessary comfort for a good grip while using one of these handles in the workplace.

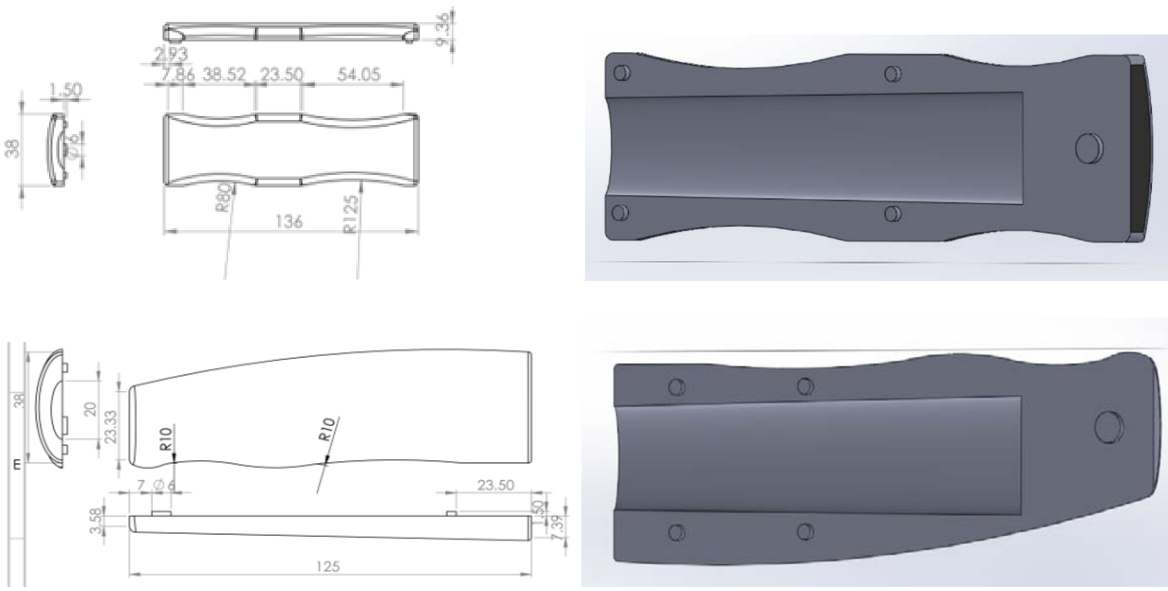

Figure 1. Different handles designed in Solid works.

D. 3D Printing

The wrenches were manufactured using various methods, the wrench 2 & 3 (From Figure 3) were manufactured using 3D printing technology with PLA plastic. A 3D printer adds successive layers of material one over the other under a computer control to create an object. We used .stl files from solid works and uploaded them to the 3D printer to get the designs manufactured.

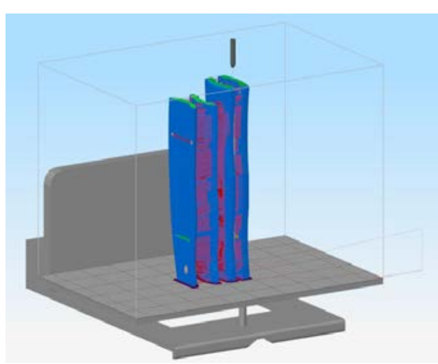

Figure 2. 3D Printing of Designed Handles.

The wrench 4 was manufactured using cutting, grinding and milling the High-density polyethylene (HDPE) the thickness varying from the other two designs. The finished designs of all the wrenches can be seen in Figure 3

Figure 3. 3D-Printed Handles in Experiment

Wrench 1 was conventional wrench. Wrench 2 was rectangular handle with PLA plastic. Wrench 3 was curve handle with PLA plastic. Wrench 4 was larger sized curve handle with HDPE plastic

E. EMG Measurement

In the experimentation process we used Electromyography (EMG) which was used for recording and evaluating the electrical activity produced by skeletal muscles by measuring the electrical pulses produced by the muscle cells, we had selected few muscle groups which had a direct impact while working on the wrench. The muscles were flexor digitorum, extensor digitorum, and flexor carpi ulnaris which were connected to channel 1, 2 and 3 in the EMG. Because a consensus of opinion that EMG and force were “linear” under isometric condition, maximum voluntary contraction (MVC) was obtained for each of the three muscles under isometric contraction. Thus, the subjects were asked to turn the torque tester which was secured to a table wise using the various wrenches. The maximum possible torque was obtained from the torque tester for each of the wrench.

3. Experimental Procedure

First the locations of the muscles were found for each of the subjects using muscle sensor. Three Electrodes were placed on the selected locations of the forearm and were connected to the channel 1 through 3 in EMG and one electrode was placed on the elbow as the ground in EMG. The subjects were asked to apply maximum force in standing position with no actual body movement (isometric contraction) to find the maximum voluntary contraction (MVC) for all three muscles. Following which the subjects were asked to twist the torque tester which was placed in the table wise using the wrenches which were numbered from 1 to 4. The maximum possible torque that can be applied to the wrench was measured using a torque tester.

A. Anthropometry

Table 1. Anthropometry of Subjects.

Anthropometry		Subject 1	Subject 2	Subject 3
Age		20	26	22
Hand Dimension	Length (inch)	8	7	7.2
	Breadth (inch)	3.8	3.125	3.4
	Depth (inch)	1.125	1	1.1

Anthropometric data was collected (Table 1) for the subjects using a measuring scale. The subjects were also asked if they had any prior injuries on the dominant hand. This data also confirmed that the subjects were healthy as well as they belong to 95th percentile male population.

B. Data processing

RAW EMG signals cannot be quantitatively compared between subjects. Muscle information was extracted after proper signal processing. Basmajian and DeLuca recommended Root Mean Square (RMS) method to process RAW EMG signal. In our experiment, RAW EMG data was first truncated to discard garbage signal portion, followed by a Root Mean Square (RMS) transform. RMS converted all negative signals into positive value and smoothed entire signal. The formula (1) of Root Mean Square (RMS) is shown below:

$$RMS = \left(\frac{1}{S}\sum_{1}^{S} f^2(S)\right)^{\frac{1}{2}}$$

$RMS - Root\ Mean\ Squar$

$S - Window\ Length\ (Points)$

$f(s) - Data\ witnin\ the\ Window$ (1)

Once all RAW EMG signals were transformed by RMS, the method of EMG normalization was adopted so that all subjects can be compared to each other quantitatively. It was a preferred method suggested by Mathiassen and Winkel (1995). To normalize the EMG signal, formula (2) was used.

$$Normalized\ EMG = \frac{EMG_{Activity} - EMG_{rest}}{EMG_{max} - EMG_{rest}} \quad (2)$$

To simplify the problem, EMGrest was assumed to be zero. EMGmax was equivalent to maximum voluntary contraction (MVC). And EMGactivity represented each of the muscle activity signals. The calculated normalized EMG data became a percentage value between 0 and 1. This fractional value can be further evaluated for the level of muscle activities between subjects.

4. Results and Discussion

A. Torque Output

A torque tester was used to measure the maximum torque the subject could exert with the regular wrench without handle and with various design of handles. The results were as follows in Figure 5.

From the Figure 5 graphical data, it can be observed that the wrench with no handle would provide the least torque, which was 16.9 N-m. The next least Torque obtained was Wrench 3 at 17.0 N-m. One of the possible reasons might be due to lack of thickness of the handle and leading to pinch between the figures. The maximum torque was obtained for wrench 2 and wrench 4 at 21.7 N-m and 22 N-m. This also proved our theory that handled with lesser pinch between figures provided maximum torque.

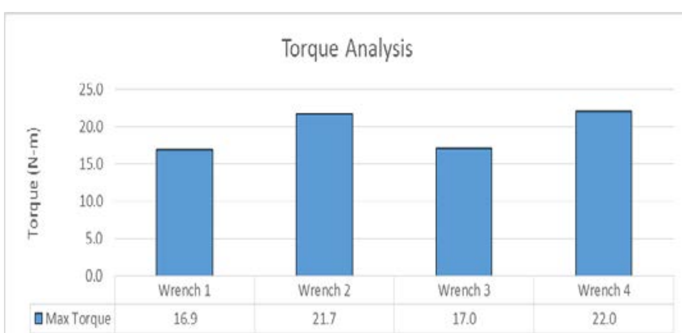

Figure 5. Torque Outputs.

B. Muscle Activity

In our experiment, we considered muscle activity as one of the key aspects to understand the fatigue rate while using the wrenches. EMG was used to collect the data of our 3 primary muscles in this experiment. The method of Root Mean Square (RMS) was performed for initial analysis. The obtained data for each individual muscle was as follows.

B.1 Flexor Digitorum

From the activity analysis Figure 6 we can observe that wrench 2 had the least activity for Flexor digitorum at 0.00018V and wrench 4 had the maximum muscle activity at 0.0004V. We were also able to determine the maximum muscle activity for our subjects at 0.00053V. Although the muscle activity for all the muscles was well under the maximum muscle activity, the least muscle activity would be the one which would lead to lesser fatigue rate for that muscle.

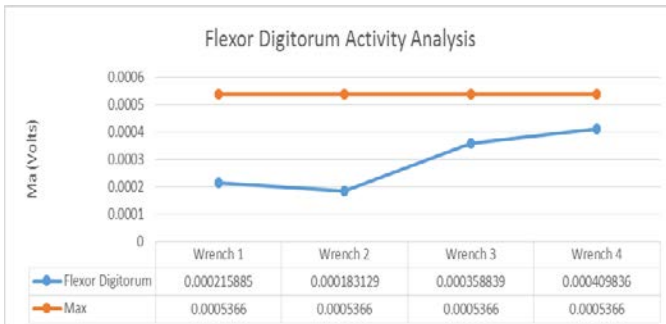

Figure 6. Flexor Digitorum Acitivity.

B.2 Extensor Digitorum

From the activity analysis Figure 7 we can observe that wrench 1 had the least activity for Extensor digitorum at 0.00023V and wrench 4 had the maximum muscle activity at 0.00031V. We were also able to determine the maximum muscle activity for our subjects at 0.0016V. Although the muscle activity for all the muscles was well under the maximum muscle activity, the least muscle activity would be the one which would lead to lesser fatigue rate for that muscle

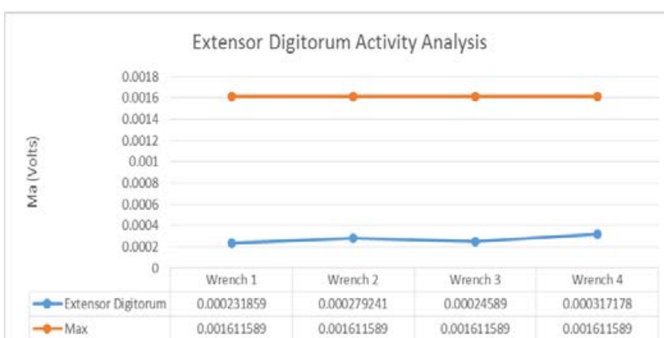

Figure 7. Extensor Digitorum Activity.

B.3 Flexor Carpi Ulnaris

From the activity analysis Figure 8 we can observe that wrench 2 had the least activity for Flexor Carpi Ulnaris at 0.00214V and wrench 3 had the maximum muscle activity at 0.000237V. We were also able to determine the maximum muscle activity for our subjects at 0.0016V. Although the muscle activity for all the muscles were well under the maximum muscle activity and the activities from each wrench were not much of a difference, the least muscle activity would be the one which would lead to lesser fatigue rate for that muscle

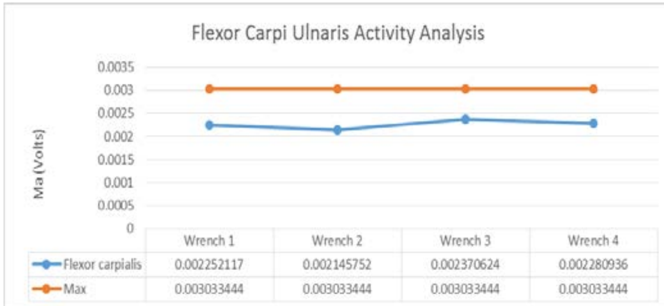

Figure 8. Flexor Carpi Ulnaris Activity Analysis.

B.4. Normalization

The EMG data was normalized to understand and analyze the muscle activity between all subjects. To verify the data, RMS transform was performed. The data was normalized using the formula (2).

The obtained data (Table2) and graphical analysis (Figure 9) is as follows.

B.5. Elements of Subjectivity

Subject 1 felt wrench with covered handle was more comfortable that the wrench without covered handle. Among 3 handles wrench 4 was the most comfortable handle followed by wrench 2 handle and finally wrench 3 handle

Subject 2 felt covered handle was more comfortable than the wrench without handle. Among 3 handles, Wrench 2 handle was the most comfortable one followed by wrench 4 handle and wrench 3 handle.

Subject 3 too felt that covered handle was more comfortable than the wrench without handle. Among 3 handles, Wrench 2 handle was the most comfortable one followed by wrench 4 handle and wrench 3 handle.

SUBJECT	WRENCH	M1	M2	M3	TORQUE	MATERIAL	DIAMETER	Length	thickness
1	1	0.60566	0.254597	8.809259	18.1	1	23	112	0.5
1	2	0.528	0.232201	7.251986	22.3	2	38	138	19
1	3	0.501	0.239582	6.753603	18.2	2	38	130	18
1	4	0.6138	0.306713	9.361258	23.5	3	38	127	20.5
2	1	0.037888	0.73328	0.485063	16.6	1	23	112	0.5
2	2	0.04117	0.104691	0.471711	18.9	2	38	138	19
2	3	0.06714	0.079386	0.622349	14.7	2	38	130	18
2	4	0.062281	0.102496	0.624465	17.4	3	38	127	20.5
3	1	0.208824	0.219826	0.641204	16.1	1	23	112	0.5
3	2	0.148552	0.145636	0.433526	24	2	38	138	19
3	3	0.161375	0.175861	0.449394	18.2	2	38	130	18
3	4	0.157436	0.166258	0.358785	25.2	3	38	127	20.5

Table 2. Normalized EMG Data.

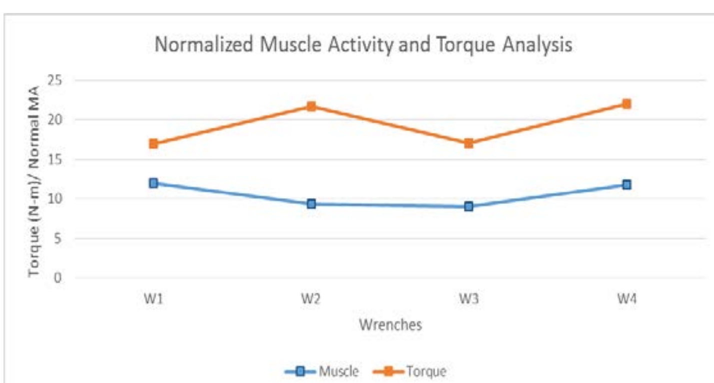

Figure 9. Normalized EMG and Torque Outputs.

From the normalized data (Figure) 9 we can conclude that the total muscle activity was lowest for wrench 2 with maximum torque obtained.

B.6. Statistical Analysis

A statistical based analysis was used in our experiment to identify if there was any relationship between the muscle activity and torque for our different design handles based on 50 percentile anthropometric data for 50 percentile US male population. The statistical data analysis was attached in Figure 10 and Figure 11.

From the Residual Plots (Figure 10) and ANOVA Table (Figure 11) it was found that the R-square of torque output was 85.56 % which means this model explains 85.56% variability of the torque output around its mean, therefore the model we chose was reliable. The p-value of wrenches obtained was less than 0.05 which interpreted that different wrench handles had significant effects on the torque output. But for the muscle activity the p-value was greater than 0.05 which interpreted that there was no significant effect between muscle activity, subject, material and wrenches.

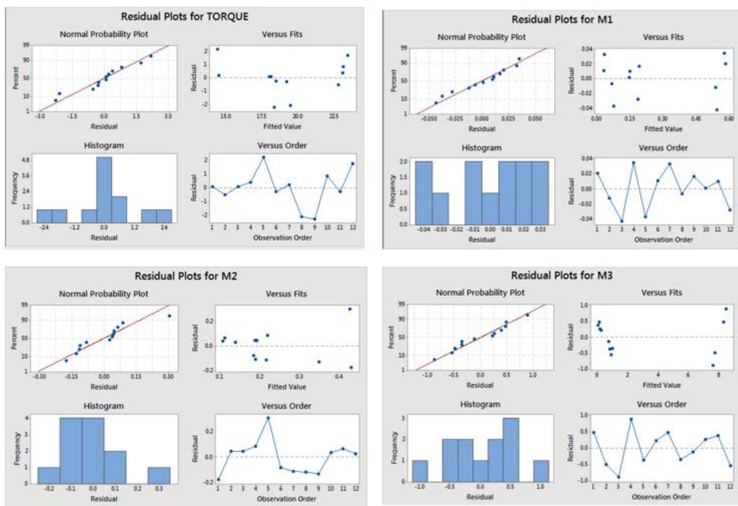

Figure 10. ANOVA Residual Plots.

B.7. Discussion

Based on the statistical data analysis it can be concluded that there was no significant effect between muscle activity and wrenches but, there was a significant effect between torque and wrenches and from our theoretical observation we found that there was a relationship between muscle activity (flexor digitorum, extensor digitorum and flexor carpi ulnaris) and maximum torque that can be obtained for 50 percentile US male population anthropometric data. Due to lack of subjects it might be one of the reasons causing the insignificant results between muscle activities and wrench handles in our experiment.

General Linear Model: TORQUE versus SUBJECT, WRENCH, MATERIAL

```
The following terms cannot be estimated and were removed:
   MATERIAL

Method

Factor coding  (-1, 0, +1)

Factor Information

Factor   Type   Levels  Values
SUBJECT  Fixed       3  1, 2, 3
WRENCH   Fixed       4  1, 2, 3, 4

Analysis of Variance

Source     DF  Adj SS  Adj MS  F-Value  P-Value
  SUBJECT   2   38.75  19.376     6.21    0.035
  WRENCH    3   72.18  24.060     7.71    0.018
Error       6   18.72   3.119
Total      11  129.65

Model Summary

      S    R-sq  R-sq(adj)  R-sq(pred)
1.76612  85.56%     73.54%      42.26%
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General Linear Model: M1 versus SUBJECT, WRENCH, MATERIAL

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The following terms cannot be estimated and were removed:
   MATERIAL

Method

Factor coding  (-1, 0, +1)

Factor Information

Factor   Type   Levels  Values
SUBJECT  Fixed       3  1, 2, 3
WRENCH   Fixed       4  1, 2, 3, 4

Analysis of Variance

Source     DF    Adj SS    Adj MS  F-Value  P-Value
  SUBJECT   2  0.571026  0.285513   228.87    0.000
  WRENCH    3  0.004829  0.001610     1.29    0.360
Error       6  0.007485  0.001247
Total      11  0.583340

Model Summary

        S    R-sq  R-sq(adj)  R-sq(pred)
0.0353190  98.72%     97.65%      94.87%
```

General Linear Model: M2 versus SUBJECT, WRENCH, MATERIAL

```
The following terms cannot be estimated and were removed:
   MATERIAL

Method

Factor coding  (-1, 0, +1)

Factor Information

Factor   Type   Levels  Values
SUBJECT  Fixed       3  1, 2, 3
WRENCH   Fixed       4  1, 2, 3, 4

Analysis of Variance

Source     DF   Adj SS    Adj MS  F-Value  P-Value
  SUBJECT   2  0.01697  0.008485     0.27    0.775
  WRENCH    3  0.12076  0.040252     1.26    0.368
Error       6  0.19101  0.031835
Total      11  0.32874

Model Summary

       S    R-sq  R-sq(adj)  R-sq(pred)
0.178423  41.90%      0.00%       0.00%
```

General Linear Model: M3 versus SUBJECT, WRENCH, MATERIAL

```
The following terms cannot be estimated and were removed:
   MATERIAL

Method

Factor coding  (-1, 0, +1)

Factor Information

Factor   Type   Levels  Values
SUBJECT  Fixed       3  1, 2, 3
WRENCH   Fixed       4  1, 2, 3, 4

Analysis of Variance

Source     DF   Adj SS   Adj MS  F-Value  P-Value
  SUBJECT   2  151.344  75.6722   146.82    0.000
  WRENCH    3    1.585   0.5284     1.03    0.445
Error       6    3.093   0.5154
Total      11  156.022

Model Summary

       S    R-sq  R-sq(adj)  R-sq(pred)
0.717926  98.02%     96.37%      92.07%
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Figure 11. ANOVA Table.

5. Conclusion

This study investigates the effects of adjustable wrenches with and without handle while the user was operating the tool, by comparing the effects of torque and muscle activity in a task environment where the maximum tightening of the torque tester with these wrenches was carried out.

The torque output showed that wrenches 2 and 4 produced the maximum torque, while the wrenches 1 and 3 showed the least torque output. If we look at the output of the muscle activity for all the four wrenches, wrenches 2 and 3 showed the least muscles activity, whereas wrenches 1 and 4 were ranked after 2 and 3.

In order to satisfy the objective of finding the best possible design for the wrench it should satisfy the following condition - the wrench must produce maximum torque with low muscle activity. By comparing both the torque output and muscle activity of all the wrenches we came to a conclusion that wrench 2 satisfied the above condition by producing output with maximum torque and low muscle activity.

Furthermore, our study can be expanded by increasing the number of subjects and designing a much better work environment, so that we could get even better results.

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