

## **BIOMECHANICAL AND PSYCHOPHYSICAL ASPECTS OF HANDWHEEL TURNING**

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### **ABSTRACT**

An ergonomic study was conducted to assess the biomechanical and psychophysical affects of handwheel turning exercises on individuals who work in industries that require the use of handwheels in daily process operations. The objectives of this study were to 1) explore the affects of orientation and diameter of three different diameter handwheels, oriented both horizontally and vertically with respect to the subjects coronal plane, on the reacted elbow and shoulder moments as well as the total compressive force in the lower back and 2) determine subjects' preferences for handwheel diameter during the simulated handwheel turning tasks. The output generated by the biomechanical model developed by the University of Michigan, in terms of reacted elbow and shoulder moments and lower back compressive forces based on the forces and postural inputs emulating the specified handwheel turning configurations were compared to the subjects' preference of handwheel diameter in order to establish the degree of correlation associated with the smallest values for the reacted elbow and shoulder moments and compressive forces in the lower back. The results of the biomechanical analysis of the handwheel turning configurations modeled indicated that in every case with respect to elbow and shoulder moments, the moment supported by these joints decreased as the force applied using the hands decreased as a function of increasing handwheel diameter. A chi-square analysis was performed on the handwheel preference data. The results of this analysis indicated a 95% confidence that the data do not fit a naturally random distribution for the horizontal orientation when ranked by hand forces or handwheel speed, and a 99% confidence that the data do not fit a naturally random distribution for the vertical orientation when ranked by hand forces or handwheel speed. The results of this study indicated that, in general, subjects preferred larger diameter handwheels when both the force setting and the turning rate were increased together, or independently, from low to high. This preference was apparent for both the horizontal and vertical handwheel orientations.

## INTRODUCTION

### Background

Handwheel turning tasks are intrinsic to several industrial operations. Some of these applications include, but are certainly not limited to, petroleum refinement, chemical processing and wastewater treatment industries. The power generation and railroad industries also have multiple applications in which handwheels are employed in the operation of process controls. Handwheels have also been used in the past (see Figure 1), and are presently used in irrigation control applications.



Figure 1. Henry Cardwell Clegg opening Trial Lake valve, May 31, 1958

Presently, handwheels are used in applications where high torque levels are necessary in order to actuate process control devices such as valves or braking mechanisms. Handwheels are commonly found as control devices for valves, and it has been estimated that 50% of all valves currently in industrial use are operated manually (Shih et al., 1997). Handwheels are typically applied to process control devices and mechanisms that require low opening and closing rates and, as a result, low handwheel turning rates, and where turning tasks may be accomplished by one- or two-handed operation.

Job task requirements associated with handwheel turning often exceed the safe physical capacity of operators in terms of isometric strength and physical work capacity. The term “cracking” a valve refers to the isometric strength required to initiate opening or closing a valve. At times, emergency situations can arise that require operators to completely close valves in order to shutdown process operations. The muscular endurance and aerobic capacity of the operator are

both significant factors to be considered in evaluating these types of job requirements. In some cases, handwheel operators will improvise using various forms of “cheaters” or mechanical devices that change the effective length of the moment arm of the handwheel, thus creating a torque multiplier that assists in compensating for the excessive torque requirements associated with opening and closing these process control devices. These devices normally decrease biomechanical stresses; however, the use of these types of devices during process control operations or mechanism actuation can result in damage to equipment and injury to personnel. Delays in operations can result when cheaters are not available or equipment has been damaged.

In the past, plant or process design engineers have not always given ample consideration to the placement of handwheels used in the control of such devices, nor to the biomechanical and physiological requirements of operators that are required to perform these handwheel turning tasks (Parks, 1998; Schulze, 1997).

Studies have shown that handwheel placement and orientation, with respect to the operator, greatly affect the physical requirements necessary to perform handwheel-turning tasks (Parks, 1998; Schulze, 1997; Wood, 1999/2000). These studies have investigated the aspects of workplace design, environmental control, personnel selection, training and job aids as applied to handwheel turning tasks. The intent of these research efforts was to improve ergonomics and safety conditions associated with handwheel turning applications in these industries.

### **Motivation for Improvement**

Even though multiple studies have been conducted regarding handwheel operating task characteristics such as the high torque requirements to “crack” valves, handwheel rim diameter and shape, the effects of grip strength with and without gloves; handwheel location and position in terms height, angle and distance from the operator; posture, and environmental conditions such as temperature and humidity to which operators are exposed, very limited research has been conducted regarding the muscular endurance and aerobic capacity requirements associated with the task of fully opening or closing process control devices such as industrial valves. Knowledge of the physical work capacity requirements of handwheel turning in plant operations is necessary to facilitate improved plant designs and operations. The primary focus of this research will be on the biomechanical and psychophysical characteristics of operators that perform handwheel turning tasks in process control applications.

The development of guidelines based on the biomechanical and psychophysical factors associated with the performance of handwheel turning tasks would aid design engineers when industrial processes requiring the introduction of handwheels to control processes are considered.

## **STUDY DESIGN**

### **Intent of Research**

The intent of this research is to explore the effects of height, orientation, diameter, force required and the turning rate of handwheels, on the biomechanical and psychophysical aspects of

handwheel turning tasks that are performed by individuals required to use handwheels in the operation of process control devices in industrial applications.

The biomechanical interests that are the focus of this research are 1) the compressive forces in the lower back, and 2) the moment reacted by the elbows and the shoulders, as a result of performing handwheel turning tasks under various geometric and force configurations.

In terms of the psychophysical aspects of this research, the measure of the correlation between the subjective selection of the optimal handwheel diameter, and the results of the biomechanical analysis indicating quantitatively lower back compressive forces and elbow and shoulder moments will be examined. The basis for this correlation will be the dependent variables of handwheel height, orientation, diameter, force required and turning rate.

Psychophysical measurement methods typically require that subjects perform a level of submaximal work in the form of exerting a force or torque that will prevent the subject from becoming fatigued during the performance of the task. The work is performed at a specified frequency for a predetermined interval of time. The psychophysical approach to determining the workload capacity of a subject, under experimental conditions, typically requires the development of a test that emulates the task that is to be examined and evaluated. This method allows the subject being tested to adjust the workload or some other dependent variable, subsequent to the performance of the task for each test interval. During the test period, the subject is asked to continue making adjustments to the workload, or in the case of this research, the handwheel diameter, until he or she subjectively determines the handwheel diameter that represents the maximum acceptable workload that the subject is willing to perform.

## **Objectives**

The objective of this research was to determine subjects' preferences for handwheel diameter during simulated wheel turning tasks. Subjects were polled regarding their preference with respect to the handwheel diameter that they believed to be the most effective in terms of completing a series of handwheel turning tasks with each of three handwheels, located at a height determined by the subject in terms of comfort, in two orientations, namely vertical and horizontal with respect to the subjects coronal plane. Each subject was asked to perform a specific number of handwheel rotations at two turning rates for two force settings. Subjective information obtained as a result of the completion of a series of multiconfiguration, handwheel turning tasks by the subjects was then compared to the output generated by the biomechanical model, developed by the University of Michigan, in terms of lower back compressive forces and elbow and shoulder moments based on the forces and postural inputs emulating the specified handwheel turning configurations. This comparison was used to determine the correlation between the smallest values for the compressive forces in the lower back and for the reacted elbow and shoulder moments, and the dependent variables of handwheel orientation and diameter for the various handwheel-turning configurations coupled with the specified turning rate and force conditions.

## Design of Experiment

The physical arrangement of the apparatus used to conduct this experiment was such that handwheels with three diameters were located at a height that was specified by each individual subject's preference with respect to comfort, and oriented vertically and horizontally with respect to the subject's coronal plane (see Figure 2).

Subjects were then required to complete a specified number of handwheel rotations during a specified interval of time at two force settings. Subjects were asked to complete handwheel turning tasks under four combinations of turning rate and force conditions, namely; 1) a low number of handwheel rotations at a low force setting, 2) a high number of handwheel rotations at a low force setting, 3) a high number of handwheel rotations at a low force setting, and 4) a high number of handwheel rotations at a high force setting. Each of the four experimental conditions described above were completed for the three handwheels and two orientations in both the clockwise and counterclockwise rotation directions.

## Subject Population and Anthropometric Data

The subject population consisted of 20 English speaking male adult subjects over 18 and less than 55 years of age with no known physical or mental disabilities. Female subjects were excluded from participation in this study. This research was limited to males because the vast majority of workers who rotate handwheels as a regular part of their job are males. Participation in the study was strictly voluntary. With respect to anthropometrics and the subject population, 90% of the subjects fell within the 5<sup>th</sup> to 95<sup>th</sup> percentile range according to stature and 80% of the subjects fell within the 5<sup>th</sup> to 95<sup>th</sup> percentile range according to weight.



a) 16 inch wheel-horizontal



b) 16 inch wheel-vertical

Figure 2. Handwheel diameters and orientations

## ANALYSIS

### Force Measurement

Resistive forces that opposed handwheel rotation were measured by attaching a chain to the outermost edge of the rim of the 12-inch handwheel and using a Chatillon PH 200D hand-held force gauge to measure the force required to rotate the handwheel in both the clockwise and counterclockwise directions. These forces were measured for both the high and low force settings for each individual subject. The moment about the axis of rotation of the handwheel was constant, independent of handwheel diameter, for both the high and low force settings. The average of the forces measured for the sum total of the 20 subjects was used to extrapolate to force values for both the 8 inch and 16 inch handwheels. Table 2 lists the average forces used as inputs to the University of Michigan biomechanical model for both the high and low force settings.

### Turning Rates

The high and low turning rates for this experiment were governed by requiring that the subject turn each of the three handwheels, under any given force and orientation condition, approximately on third of a full rotation ( $120^\circ$ ) per beat of an electronic metronome. The frequency of the metronome was 52 b.p.m. (beats per minute) for the low turning rate and 63 b.p.m. for the high turning rate. These frequencies resulted in a low turning rate of 17.3 rpm (revolutions per minute) and the high turning rate of 21 rpm.

Table 2. Force Settings and Hand Forces

Force setting	Force - 8 inch handwheel [lbf]	Force - 12 inch handwheel [lbf]	Force - 16 inch handwheel [lbf]
Low	39	26	20
High	77	51	38

For each force setting and turning rate, subjects were required to rotate each of the three handwheels in either a clockwise or counterclockwise direction, depending upon which each individual subject preferred, for a period of 30 seconds. Subjects were then allowed to rest for a period of 15 seconds, and then were required to rotate each of the three handwheels for an additional 30-second period of time, in the opposite direction of that chosen for the first 30-second time period. Subjects were allowed to rest approximately 1 minute between different diameter handwheels.

## Reverse Kinematics

Reverse kinematics were used to determine each individual subject's posture by positioning the subject's hands at the height and width of each handwheel diameter and orientation combination. The vertical position of the subject's hands was a function of each individual subject's preference with respect to handwheel height in both the horizontal and vertical orientation. The lateral position of each subject's hands was a function of handwheel diameter. The horizontal position of the each individual subject's hands was dependent upon the vertical and lateral location of the subject's hands as well as the subject's individual anthropometric characteristics.

## RESULTS

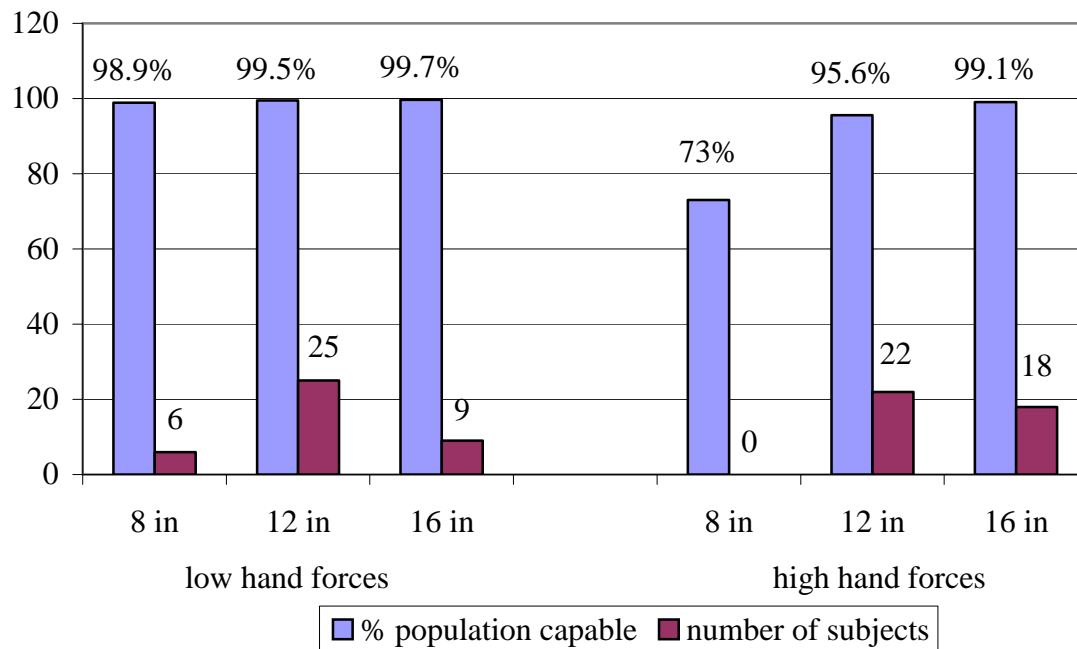


Figure 3. Handwheel preference/percent capable-elbow moment-horizonal orientation

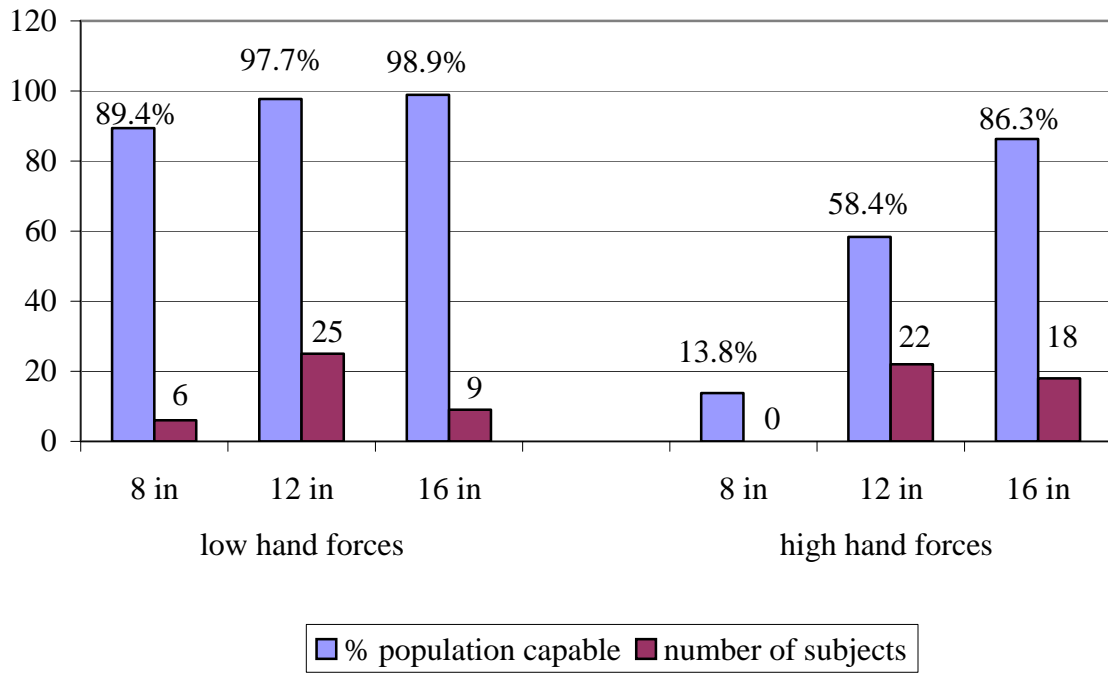


Figure 4. Handwheel preference/percent capable-shoulder moment–horizontal orientation

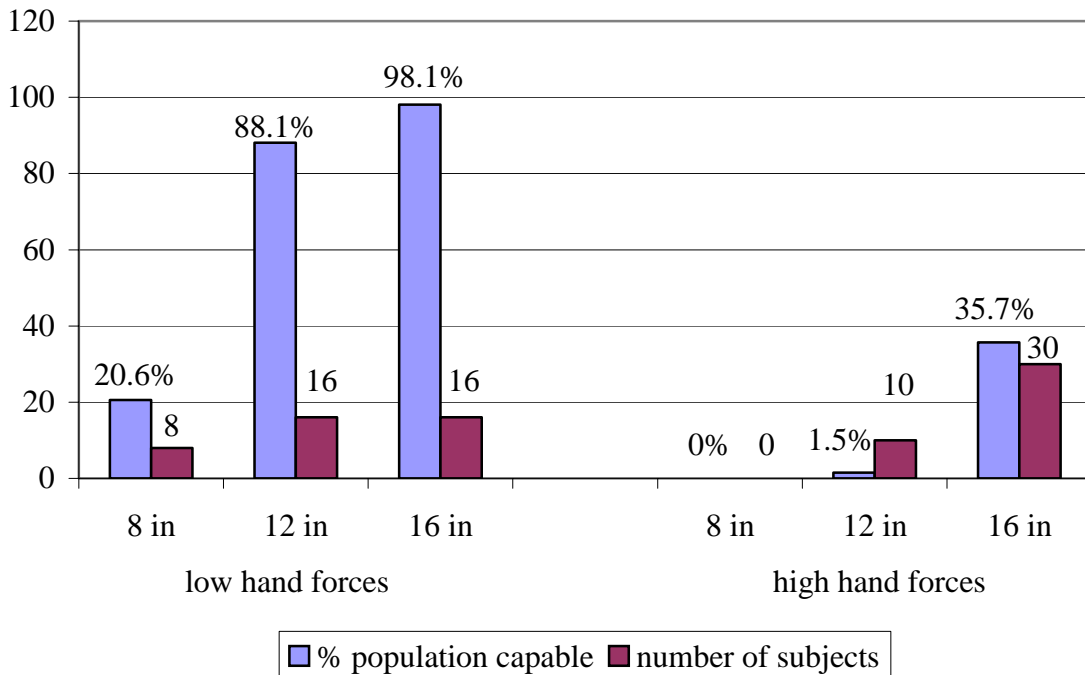


Figure 5. Handwheel preference/percent capable-elbow moment–vertical orientation

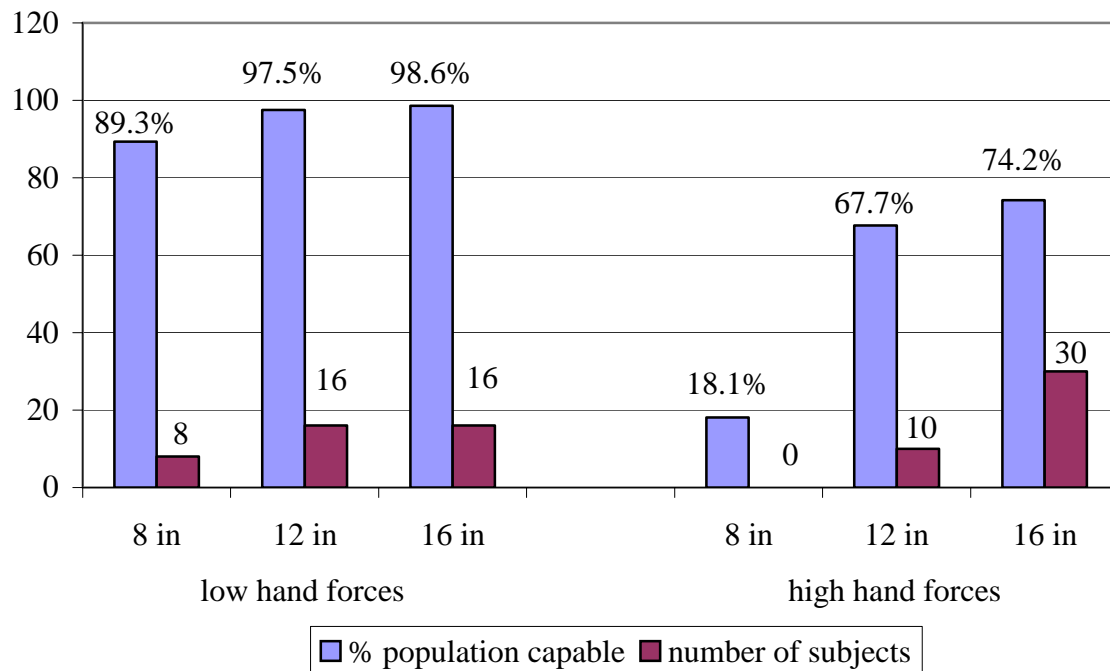


Figure 6. Handwheel preference/percent capable-shoulder moment-vertical orientation

### Sources of Error

Possible sources of error associated with this research are 1) inconsistency in the production and measurement of the resistive forces intrinsic to the handwheel turning apparatus that impeded rotational motion of the handwheels during the handwheel turning tasks, 2) inconsistency in turning rates from subject to subject as a function of each individual subject's ability to rotate the handwheel through the same number of degrees of rotation per beat of the metronome which was used to pace the handwheel turning exercises in terms low and high turning rates, 3) indecision on the part of individual subjects when polled for handwheel diameter preference following each series of handwheel turning exercises, and 4) keyboarding errors during the input process in transferring the data from the individual subject preference sheets, and the reports generated by the University of Michigan biomechanical modeling software, to tables used in reducing and analyzing the data.

## DISCUSSION

### Summary

The design of the experiment was such that the order in which the subjects were exposed to the three handwheels, two hand force requirements and the two handwheel speeds were completely random. With respect to handwheel orientation, an alternating pattern from horizontal to vertical was employed from subject to subject (i.e., subject number one started and completed the first

half of the series of handwheel turning exercises with the handwheel in the horizontal orientation and finished the second half of the series of handwheel turning exercise with the handwheel in the vertical orientation; subject number two began the series of handwheel turning exercises with the handwheel in the vertical orientation and finished the series with the handwheel in the horizontal orientation, etc.).

The number of subjects that preferred the 8-inch diameter handwheel decreased as the force increased from low to high. The number of subjects who preferred the 12-inch diameter handwheel also decreased as the force increased from low to high. The number of subjects who preferred the 16-inch diameter handwheel increased as the force increased from low to high. These trends were present in both the horizontal and vertical handwheel orientations.

The number of subjects that preferred the 8-inch diameter handwheel decreased as the speed increased from low to high. The number of subjects who preferred the 12-inch diameter handwheel also decreased as the speed increased from low to high. The number of subjects who preferred the 16-inch diameter handwheel increased as the speed increased from low to high. These trends were present in both the horizontal and vertical handwheel orientations.

The average percent of the subject population that is capable in terms of isometric strength, of performing the prescribed handwheel turning task under the low and high force settings, in the horizontal and vertical orientations, for each of the three different handwheel diameters.

### **Chi-Square Analysis**

A chi-square analysis was performed on the handwheel preference data. The results of this analysis indicates a 95% confidence that the data does not fit the expected random distribution shown for the horizontal orientation when ranked by hand forces or handwheel speed and a 99% confidence that the data does not fit the expected random distribution for the vertical orientation when ranked by hand forces or handwheel speed. These results are not unexpected, due to the fact that a preference for larger handwheels under higher hand force requirements, as well as under certain high handwheel speed conditions, was expected.

### **Analysis of Variance**

An analysis of variance (ANOVA) was conducted in order to determine the statistical significance of the following handwheel combinations with respect to the left and right elbow moments, left and right shoulder moments and lower back compressive forces for low and high hand forces in both the horizontal and vertical orientations. The three different combinations that were analyzed were the 8-inch diameter handwheel versus the 12-inch diameter handwheel, 8-inch diameter handwheel versus the 16-inch diameter handwheel and the 12-inch diameter handwheel versus the 16-inch diameter handwheel. The general trend of the data for the elbow and shoulder moments indicates that there is a statistically significant difference between the three different diameter handwheels. The ANOVA also indicates that there is no statistically significant difference with respect to the lower back compressive forces as a result of the three handwheels.

## RECOMMENDATIONS AND CONCLUSIONS

### Future Work

Regarding future work with respect to handwheel turning tasks, work in the area of aerobic requirements for handwheel turning tasks should be investigated in order to gain a better understanding of the physical work capacity requirements of operators working in industries in which handwheels are used. According to studies conducted by Seseek (1996, 1998) at the Rangely Weber Sand Unit and Carter Creek Gas Plant, handwheels are utilized in many valve operation applications that often require several hundred full rotations in order to control petroleum refining processes. For this reason alone, it would be worthwhile to look at these types of tasks in terms operator age, physical fitness index, physical work capacity, work rest cycles and metabolic factors such as oxygen consumption and maximum heart rate trends.

The effects of increased forces at the hands, as a result of increased handwheel resistance in terms of the moment sustained by devices operated using handwheels should also be investigated in order to obtain additional information regarding elbow and shoulder moments as well as lower back compressive forces. The studies conducted by Seseek (1996, 1998) at the Rangely Weber Sand Unit and Carter Creek Gas Plant indicate that the forces required in order to turn handwheels in these applications were on the same order of magnitude as those investigated during this research project.

### Concluding Remarks

As one might expect, as the hand forces required to turn the handwheel were increased; the preference for larger diameter handwheels increased. An increased mechanical advantage is gained when larger handwheels are employed to overcome the resistance to motion that is a function of devices in which processes or operations are controlled or regulated using handwheels.

Larger diameter handwheels were also preferred when handwheel turning rates increased, however, some subjects seem to prefer smaller diameter handwheels when turning rates were higher.

The biomechanical analysis indicates that the horizontal orientation is more favorable than the vertical orientation in terms of the elbow and shoulder moments supported by the subjects body when performing handwheel turning tasks such as those configured in this study.

Subjects' handwheel preference indicates that the horizontal orientation is preferred over the vertical orientation due to the fact that the subject population selected the 12-inch diameter handwheel 47 times versus selecting the 16-inch diameter handwheel 27 times for the horizontal orientation, as opposed to the selection of the 12-inch diameter handwheel 26 times versus selecting the 16-inch diameter handwheel 46 times for the vertical orientation.

The results obtained using the biomechanical modeling tool, developed by the University of Michigan, strongly supports the psychophysical findings of this research in terms of the subject population's handwheel diameter preference.

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