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VALVE OPERATOR BIOMECHANICS WITH RESPECT TO HANDWHEEL DIAMETER AND ORIENTATION – AN ELECTROMYOGRAPHY ANALYSIS

by
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ABSTRACT
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Title: VALVE OPERATOR BIOMECHANICS WITH RESPECT to HANDWHEEL DIAMETER AND ORIENTATION – an ELECTROMYOGRAPHY ANALYSIS

Handwheel operated valve systems are prevalent in numerous industries, including the petroleum, chemical, power generation, water supply, and waste processing industries. The function of handwheels is primarily to regulate the flow of material within a valve. In many cases, the torque required to manually turn a handwheel far exceeds operators' strengths, reducing operators' efficiency and posing risk for musculoskeletal disorders. Furthermore, handwheels of various diameters and orientations are common in a typical plant as there is no standardized design for handwheels. Therefore, the objective of this research was to assess the effects of handwheel diameter size and orientation on user preference and biomechanics, in order to identify a design that reduces and/or distributes biomechanical loads across the body. An electromyography (EMG) device was utilized to assess biomechanical loadings acting on the upper extremities, shoulders, and back muscles. Twenty healthy male participants were recruited from the student population at the American University of Beirut. Four handwheel diameters were examined (35, 45, 60, and 70 cm), each at three different orientation angles (0, 45, and 90 degrees from the horizontal). For each diameter-orientation combination, participants were asked to gradually increase their force production up to a fixed torque level. The maximum EMG amplitude generated by each muscle of interest were recorded. Three repetitions were performed at each handwheel condition, and the average EMG recordings of the three repetitions were analyzed. In addition, at each handwheel orientation, participants were asked to rank the handwheel diameter sizes in terms of comfort and ease of generating the targeted torque. Then they were asked to rank the "winning" handwheel conditions to determine the overall most preferred handwheel diameter-orientation combination. Our results show no interaction between handwheel orientation and angles. However, biomechanics stress on studied muscles were lower at larger handwheel diameters. Vertically oriented (90°) handwheels were found to be associated with the lowest EMG activity. A tradeoff between user biomechanics and user perceived preference/comfort was noted as necessary for determining an optimal handwheel.

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CHAPTER 1

INTRODUCTION

Handwheel-valve systems are found in various industries, including the oil and gas, power generation, water supply, railway, chemical, and nuclear process industries (Al-Qaisi et al., 2019). The function of handwheels is primarily to regulate the flow of material, such as steam or oil, within a valve system or to regulate the movement of rail cars as done in the railway industry. The nuclear industry is one specific example on the prevalence of the handwheel usage; a nuclear power plant could have as many as 30 thousand valves (Xing et al., 2016), including both motor and manually operated valves. These non-powered hand tools are associated with many upper body injuries, affecting the hands, fingers, wrists, and shoulders (Kong & Lowe, 2005). Manual valve operation (MVO) tasks involve forceful, repetitive exertions most commonly on a handwheel actuator to regulate the flow of material within a valve (Stewart, 2016). They are often performed when starting up a process, in case of an emergency or a system malfunction, or sometimes to control a valve opening (Nesbitt, 2011). Also, many of the modern motor-operated valves come equipped with a handwheel actuator, which can override the automated control system if manual operation is necessary (Bahadori, 2016).

Manual labors – such as valve-operators – are among many other occupations affected by work-related musculoskeletal disorders (MSD). One of the most frequently reported causes of lost or restricted work time is work-related MSDs. The Bureau of Labor Statistics (BLS) documented in 2013 MSD cases to be 33% of all worker injury and illness cases. (Occupational Safety and Health Administration, 2014). The most affected part of the body was the back (51.8 percent of all MSD cases; Dressner, &

Kissinger, 2018). Parks and Schulze (1998) reviewed injury records of plant operators during a three-year period in five downstream facilities of the Phillips Petroleum Company. They investigated 336 valves and found that the cracking torque ranged between 100 and 225 Nm. They concluded that 57% of back injuries and 75% of head, neck, and face injuries were associated with manual valve operations. Through a questionnaire, Amell (2000) found that 88% of process operators at a large petroleum refinery attributed their musculoskeletal discomfort to their job. Also, they expressed that industrial valve handwheel actuation was the most physically demanding task they performed at work (Amell, 2000). A more recent study by Setiadi and Zuraida (2020) showed that 79% of plant operators in a chemical plant suffered from shoulder pain and 70% from low back pain. Also, poor work posture was identified as a high-risk factor in MVO using a Rapid Upper Limb Assessment (RULA). Most injuries result from a discrepancy between operators' strengths and the torque required to manually turn handwheels (Amell and Kumar, 2001). These high injury rates of the upper body have made valve-operations a field of interest in the ergonomics literature.

Jackson et al. (1992) used a torque wrench to measure the opening and closing torque of 188 valves at a chemical plant. They focused on the opening and closing of valves during emergencies, studying the maximal force needed to actuate valves. With the aid of a specially developed ergometer, they measured the valve turning endurance of the participants. They highlighted three main factors in producing the work to open and close the valve: the diameter of the valve, the number of handwheel rotations required, and the opening torque. They found out that 15 minutes with a power output of 1,413.5 foot-pounds/minute were enough to open or close 75% of the emergency valves.

Muscular endurance and the torque production capacity of workers are essential factors to consider in the design of handwheel-valve systems (West et al., 2003). Aghazadeh et al. (2012) indicated that there are possible cardiorespiratory risks associated with valve operations. High injury rates in valve-operations were due to the lack of consideration for human operator work capacity by the designers of the handwheels, which often exceed the safe work capability of the human operator (Amell and Kumar 2001). These are risk factors especially in emergency situations, where operators are required to close numerous valves to shut down process operations. This can place substantial biomechanical stresses on the worker increasing his/her risk of injury (West et al., 2003).

Plant operators have described MVO and specifically the cracking torque as the most physically demanding task in their jobs (Amell and Kumar, 2001); this torque is required to unlock the fixed position of the valve and start the initial movement of the handwheel. To overcome the high force demands, many mechanical devices, known in industry as “cheaters”, are utilized to increase the moment arms of handwheels. However, cheaters can lead to delays in valve operations when they are not readily available or are damaged (West et al., 2003); furthermore, the use of a damaged cheater may further increase the risk of injuries.

Many handwheel design features influence the torque production capabilities of workers, such as handwheel height, orientation, rim diameter, rim design, and distance from the operator (Al-Qaisi et al., 2019). A handwheel design that aids workers in generating larger torques is generally preferred. However, limited research has been conducted regarding the effects of the handwheel diameter and orientation on the operator. Schulze et al. (1997) examined the effect of four handwheel diameters (17.8, 20.3, 22.9, and 40.6 cm) at three height levels and two orientations on maximum torque production. They showed that only the diameter and height main effects were statistically significant. However, post hoc tests did not reveal any significant differences between heights. Regarding the diameter effect, the largest diameter was associated with the highest mean torque, followed by the smaller diameters. Torque production capabilities were not significantly different between the two smallest diameters. Al-Qaisi et al. (2019) investigated even larger diameter handwheels (35, 45, 60, and 70 cm) in three orientations (horizontal, slanted 45o, and vertical) on user torque production capabilities. Unlike Schulze et al. (1997), they detected a significant height and orientation interaction effect, which could be a result of having a larger sample of participants (60 vs 12) and/or investigating larger diameter handwheels. They found a direct relationship between diameter and torque production capabilities; as diameter increased, torque production also increased. The 0o orientation for all handwheel diameters was associated with the greatest torques. On the other hand, the 45o orientation was associated with relatively low torque exertions, especially with larger handwheel diameters. They suggested that future research could consider the effects of handwheel diameter on other outcomes relevant to usability and injury risks among operators. Additional investigations considering other variables such as user biomechanics is needed to determine the optimal handwheel diameter size at different orientations. A major concern with existing designs in industry is that handwheels can be found in many different sizes and orientations. There are no standards regarding the handwheel’s diameter size and orientation. It may be assumed that larger handwheel diameters should facilitate the generation of higher torques; however, the impact of large diameters on operator biomechanics and comfort has not yet been investigated.

Only three studies were found considering operator biomechanics in handwheel valve operations, but their investigations were limited to factors other than the diameter effect. Wieszczyk et al. (2008) used an electromyography (EMG) device to determine the biomechanical loading during torque exertions on handwheels of different heights. Al-Qaisi et al. (2017) utilized EMG measurements in evaluating an ergonomically designed valve wrench relative to conventional valve-opening methods. Another study by Al-Qaisi et al. (2018) used EMG to analyze the effects of different handwheel heights and angles on shoulder and back muscle loadings. Studies examining the diameter effects of handwheels on biomechanics were not found.

The handwheel orientation may also have an impact on biomechanical loading – especially on the upper extremities – since it can affect the wrist posture and grip. Finneran and O'Sullivan (2013) devised an experiment to test three hypotheses pertaining to the biomechanics of grip types and wrist posture on forearm muscle activation (including flexor carpi radialis (FCR), flexor carpi ulnaris (FCU), extensor carpi radialis (ECR), and extensor carpi ulnaris (ECU)), grip endurance, and task performance. EMG was used in the three parts of the experiment. The researchers found out that grip type has a significant effect on the muscle activity of the selected forearm extensors and flexors. Moreover, the posture effects on the EMG activity of the ECR and ECU muscles were significant. Also, a significant interaction effect was detected between posture and grip type on the FCU muscle. The second hypothesis regarding the effects of posture and the interaction of grip type and posture on endurance was also proven to be significant. However, for the third part of the experiment – which tested the effects of grip type, wrist posture, and grip exertion level on task performance – only grip type was found to have a significant effect on task performance. Mogk and

Keir (2003) investigated the effects of wrist and forearm posture and grip force combinations on the forearm musculature activation. They examined five handgrip efforts with three wrist postures and three forearm postures. They found that the baseline extensor muscle activity was greatest in the case of wrist extension and the flexor muscle activity was greatest during wrist flexion. A flexed wrist was found to reduce maximum grip force by 40 – 50%, but EMG amplitude remained elevated during the exertions (Mogk & Keir, 2003). Extensor muscles were active at higher levels (5-15% of maximum voluntary electrical (MVE) activation) than the flexors in most postures for low to mid-range force gripping tasks (Mogk and Keir, 2003). They concluded that the levels of forearm loading during the execution of the gripping tasks depend on the grip strength. However, there is yet no research that has investigated the effects of handwheel orientation on upper extremity muscle activation.

Given the existing gaps in the literature, this study has two objectives: 1) to assess the effects of the handwheel diameter size and orientation on user biomechanics and preference/comfort; and 2) to identify the handwheel diameter-orientation combination that reduces and/or distributes biomechanical loads across the body. An EMG device was utilized to assess biomechanical loadings specifically on upper extremity, shoulder, and back muscles. We hypothesized that the biomechanical loads (i.e., EMG muscle activations) will decrease as the handwheel diameter size increases. Also, we hypothesize that handwheel orientation will have a significant effect on biomechanical loadings.

CHAPTER 2

METHODOLOGY

Participants

Twenty healthy male participants were recruited from the student population at the American University of Beirut. The experimental procedures were clarified to participants before data collection, and their consents were obtained by signing forms approved by the institutional review board (IRB) at the American University of Beirut. The participants were screened for cardiac and other health problems, such as dizziness, chest pain, or heart trouble using the Physical Activity Readiness Questionnaire (PAR-Q, British Columbia Ministry of Health; Hafen and Hoeger, 1994). Answer “yes” to any of the questions on the PAR-Q led to the exclusion of the participant from the study. Participant demographics were recorded, including age, height, and weight.

Equipment

The experimental setup consisted of handwheels of various diameter sizes (35, 45, 60, and 70 cm). These diameter sizes fall within the range of diameters commonly found in the field (Parks and Schulze, 1998). Each handwheel diameter was set at three orientation angles (0, 45, and 90 degrees relative to the horizontal). An isometric strength testing fixture was used to adjust the angle of the handwheel. The fixture consisted of a horizontal handle and a vertical column. The arm can be moved along the vertical column and clamped at a certain height. The handwheel is fastened to the end of the lever arm. The lever arm has five holes in a semicircular fashion for adjusting the angle of the handwheel. By placing a pin through one of the holes, the handwheel angle can be manipulated. The orientation of the handwheel can be adjusted to five different planes.

The Trigno wireless surface EMG system (Figure 1) was adopted to record muscle activations (Delsys Inc., Boston, MA, USA). Trigno sensors with a single differential configuration was used as the surface EMG electrodes. Each sensor consists of four silver bars, which were positioned parallel to muscle fibers. The sensors were set at a band-pass filter of 20–450 Hz and a common mode rejection ratio of 80 db. Data was collected at a sampling rate of 2000 Hz and processed using the root mean square (RMS) method with a time window of 0.125 s and an overlap of 0.0625 s (De Luca, 1997; Konrad, 2005). The EMGworks software (Delsys Inc., Boston, MA, USA) was used to process and analyze the collected data.

Figure 1: Trigno Wireless EMG System

Experimental Task

Participants were required to stand erect at a comfortable distance from the handwheel with their feet flat on the ground and approximately shoulder length apart. Participants should always ‘open’ the valve; thus, torque was exerted in a counterclockwise direction, with the left hand placed at the 10-11 o’clock position and the right hand placed at the 4-5 o'clock position (Al-Qaisi et al., 2015), as shown in Figure 2. Participants were instructed to gradually achieve a certain fixed torque exertion in 3–5 s (without jerking), maintain this effort for 3 s, and finally gradually decrease their exertions in 3 s (Konrad, 2005). The fixed torque was 25 Nm, which is based on a recommended torque limit (RTL) that accommodates the population strength (Al-Qaisi et al., 2019). Specifically, Al-Qaisi et al. (2019) presented RTLs for different handwheel diameters and orientations. The RTLs ranged between 26.4 Nm and 57.6 Nm, depending on the handwheel condition. We used the lowest RTL (26.4 Nm, rounded down to 25 Nm) in order to ensure that all participants were able to generate the fixed torque at all handwheel conditions. Participants practiced generating torque before starting the experiment. To avoid muscular fatigue, repetitions were separated with 30–60 s of rest, and the different diameter-orientation combinations were separated with two minutes of rest (Konrad, 2005). Additional rest was provided, if requested.

Figure 2: The posture adopted in gradually generating the (counterclockwise) fixed torque.

Experimental Design

A two factor, split-plot experimental design followed, with participants serving as blocks within which experimental conditions were randomized. The independent variables of this study are handwheel diameter (35, 45, 60, and 70 cm: Figure 3) and angle (0, 45, and 90°). Thus, a total of 12 handwheel conditions/experimental tasks were considered (4 diameters x 3 angles). The 12 experimental tasks were divided into three sets of four tasks, and angles were randomized to the three sets. Within each angle/set, diameter was randomized to the four tasks. Angles serve as the whole-plot treatment and diameter as the sub-plot treatment. The presentation orders of both independent variables were counterbalanced across the participants. Furthermore, at each handwheel condition, three repetitions were performed. Therefore, in total, each participant completed 36 trials.

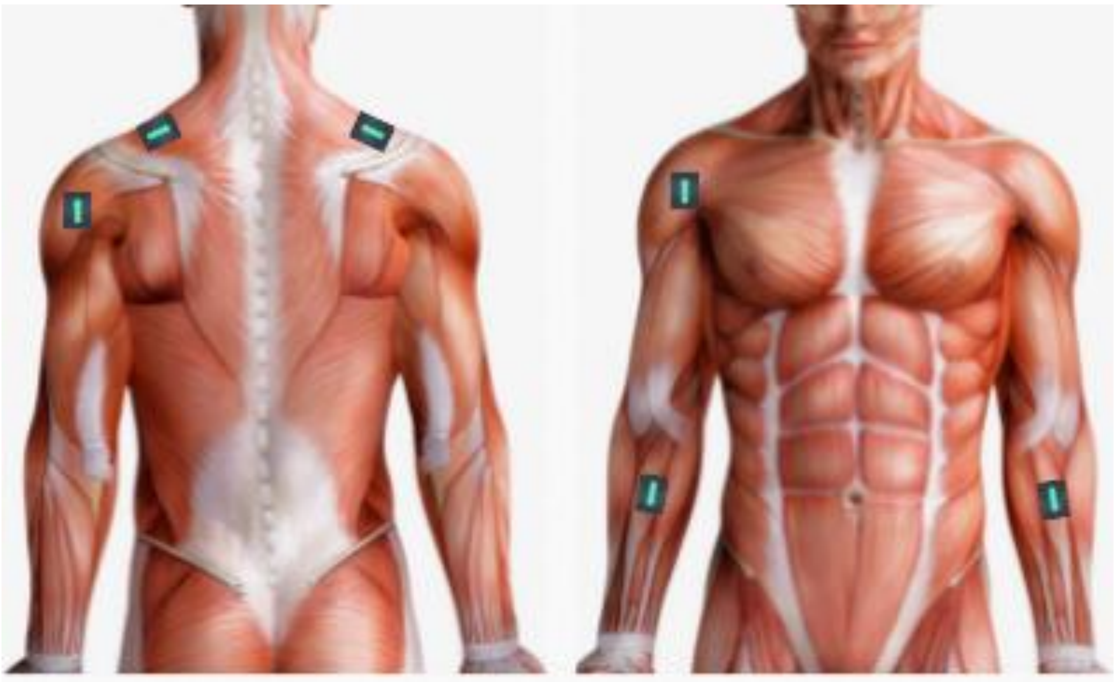
Figure 3: The four handwheels used in the study, with respective diameters of 35, 45, 60, and 70 cm.

Data collection and Processing

After introducing the participant to the equipment, a warm-up session preceded EMG data acquisition. The IRB-approved consent form was signed by each of the participants. Demographic information (age, height, and weight) of the participants was recorded. Then the participants underwent a 5-minute warm-up session with basic stretches. Following to the warm-up session, EMG data acquisition preparations can start. Hair was shaved from the skin over six muscle sites, which included the: right anterior deltoid; left poster deltoid; right and left flexor carpum radialis; and right and left trapezii. After cleaning the skin with alcohol to get rid of dead cells and sweat, electrodes were attached over the muscles' sites (*Figure 4*). For optimal EMG signal detection, electrodes were positioned on the muscle belly parallel to the muscle fibers at the following locations:

- Right and left flexor carpum radialis: The arm was supported with the fingers while palpating the anterior side of the forearm near the elbow on the medial (little finger) side of the arm. The participant was asked to flex the wrist. The electrode was placed over the muscle belly so that it runs parrallel to the muscle fibers (Criswell, 2010).
- Right anterior deltoid: With arms resting at the sides of the body, the electrode was placed three fingerbreadths below the anterior margin of the acromion (Al-Qaisi et al., 2015).
- Left posterior deltoid: Electrode was placed 2 cm below the lateral border of the scapular spine in an oblique angle towards the arm (i.e., parallel to the muscle fibers; MacLean and Dickerson, 2019; Criswell, 2010).
- Right and left upper trapezii: With arms resting at the sides of the body, electrodes were placed along the line joining the acromion and the spinous process of the seventh cervical vertebra (C7) at one-third the distance from the lateral edge of the acromion (Al-Qaisi et al., 2015).

Figure 4: Electrode location and positioning for right and left flexor carpum radialis, right anterior deltoid, left posterior deltoid, right and left upper trapezii.



The EMG data of each muscle was normalized with respect to a maximum voluntary contraction (MVC) and, as such, was reported as a percent of the MVC (%MVC). Normalization of raw EMG signals is crucial for interpretation, which can be achieved by dividing the EMG data by the maximum EMG amplitude from the MVC of the same muscle (Al-Qaisi et al., 2020). The participants performed the following MVC exercises for each muscle:

- Right and left flexor carpum radialis: The participant was seated with the forearms placed in a supine position on a stable support. Wrist flexion was performed against manual resistance (Criswell, 2010).
- Right anterior deltoid: While seated, the shoulders were flexed 90° and the elbows also flexed 90°. Participants then performed further shoulder flexion against manual resistance at the distal end of the humerus (Al-Qaisi et al., 2015).

- Left posterior deltoid: the shoulder was abducted 90^o and externally rotated, and the elbow was flexed 90^o (fingers point to ceiling). Participants then performed shoulder extension against manual resistance (MacLean and Dickerson, 2019; Criswell, 2010).
- Right and left upper trapezii: While seated, the shoulder was abducted 100^o, and the elbow was flexed 90^o with the hands prone. Participants then performed further shoulder abduction against manual resistance at the elbow (Al-Qaisi et al., 2015).

The maximum EMG amplitude generated by each muscle of interest was recorded during the different experimental tasks. Three repetitions were performed at each handwheel condition, and the average EMG recordings of the three repetitions were analyzed.

User Preference Ranking

For further exploring the effects of handwheel design, user data was collected in terms of the subjects' preferred handwheel diameter and orientation. At each handwheel orientation, subjects were asked to rank the handwheel diameters in terms of comfort and ease of generating the targeted torque. If a tie is believed to exist, participants were asked to place the tied diameters in the same ranking. For example, a ranking as follows: "(1) 70 and 60; (2) 45; (3) 35" would suggest that the 70 and 60 cm diameters are equally the most comfortable followed by the 45 cm diameter and finally by the 35 cm diameter. The "winning" handwheel diameter(s) at each handwheel orientation was identified. After testing all handwheel conditions, participants were asked to repeat the trials of the winning handwheel conditions, in order to determine the overall most preferred handwheel diameter-orientation combination(s). The order presentation of the winning handwheel conditions was also be randomized. Appendix A contains the data collection sheet to be completed by participants in ranking the different handwheel conditions.

Statistical Analyses

A two-factor split-plot analysis of variance (ANOVA) was used to evaluate the effects of handwheel diameter and orientation on the normalized EMG activities. Post hoc analyses, in the form of Tukey tests, was performed to determine the source(s) of the significant effect(s). The significance level (α) was set at 5%. Statistical significance was based on calculated p-values.

CHAPTER 3

RESULTS

This research measured the maximum EMG activities of the right and left flexors, right and left trapezii, right anterior deltoid, and left posterior deltoid muscles during isometric torque exertions at different handwheel diameters and angles. The aim was to identify the handwheel diameter-orientation combination that reduces and/or distributes biomechanical loads across the body, preventing heavy concentrated loads on any one muscle. The effects of diameter on the EMG activities for all the studied muscles were not dependent on the angle of the handwheel, and vice versa. This finding suggests that angle and diameter are independent of each other and can be interpreted separately. This conclusion is based on the ANOVA results of the interaction effect (diameter*angle) shown in *Table 1;* a statistically significant effect of angle ($p < 0.05$) was only detected for specific muscles (right flexor, right deltoid, left deltoid, left trapezius). Since the interaction effect was not statistically significant, diameters and angles were considered separately in determining the effects on muscle loading.

Table 1: The p-values of each effect under each dependent variable. Values with asterisks (*) represent significant p-values.

Effects	Right Flexor	Left Flexor	Right deltoid	Left deltoid	Right trapezius	Left trapezius
Angle	0.038*	0.742	0.010*	0.026*	0.316	0.001*
Diameter	0.286	0.302	0.864	0.229	0.532	0.790
Angle*Diameter	0.502	0.300	0.488	0.359	0.987	0.551

Least and Most activated muscles

Error! Reference source not found. and *Table 3* summarize the maximum EMG activities at the different handwheel angles and diameters respectively for all six muscles. Values highlighted with yellow represent the numerically lowest EMG activity detected in a column or muscle, whereas those highlighted with red represent the numerically highest EMG activity in that muscle. This table shows that all of the handwheel angle positions required at least one muscle to have a maximum EMG activity. Some handwheel orientation even required maximal muscle activations from more than four of the muscles. Identifying handwheel positions that are associated with high muscle activities indicate which handwheel positions require heavy muscle loadings and, in turn, should be avoided. In general, the higher the muscle loading is correlated to higher risk of developing MSDs. The average EMG activity per muscle was computed for each handwheel angle and diameter position to analyze the concentration of load on the whole body at that handwheel position.

Angle

Error! Reference source not found. shows that all the handwheel orientations required at least one muscle to sustain a maximum load (max. EMG activity). At angle 0 ° the loadings on the left trapezius and right deltoid muscles were the lowest. However, the low loading of these muscles was counterbalanced by higher activation of the right flexor muscle and by near maximum EMG values for the other three muscles. This is illustrated in ***Error! Reference source not found.***, where the comparison of angles 0° and 90° shows two more muscles with minimum EMG for the 90°. At angle 45° most of the studied muscles were heavily loaded, receiving among the highest EMG activities relative to the other handwheel.

Figure 5 presents the graphs of the average maximum EMG activities of the six muscles under study with the different handwheel angles. For the left flexor and right trapezius, the difference across the different angle between the average maximum EMG levels was not large enough to be detected by ANOVA as a significant difference. Their p-values were 0.742 and 0.316 respectively (*Table 1*).

Angle	Right Flexor	Left Flexor	Right Deltoid	Left Deltoid	Right Trapezius	Left Trapezius	Average EMG	Highest EMG activity
0	17.00	17.101	17.72	15.48	19.540	16.202	17.17	19.5% Right Trapezius
45	15.19	17.62	23.16	17.42	20.473	17.893	18.63	23.16% Right Deltoid
90	12.58	16.480	18.63	13.21	19.023	19.767	14.24	19.76% Left Trapezius

Table 2: Summary of the maximum and minimum average maximum EMG (%MVC) at the different handwheel angles.

In regard to the EMG activity of the right flexor, right and left deltoids, and left trapezius, *Figure 5* illustrates their corresponding average maximum EMG in bar graphs with the standard error associated with each handwheel angle. The significance difference between angles is denoted by grouping handwheel angles into different letter groups. Handwheel angles in the same letter group indicate that no significant difference exists between them in the average maximum torque exertion; while handwheel positions in

🟧 Maximum EMG detected in muscle (column)

🟨 Minimum EMG detected in muscle (column) different letter groups indicate that significant differences exist between them in the average maximum torque exertions. The handwheel angle associated with the highest maximum torque exertion for both the right and left deltoids was the 45° orientation. The other two angles were significantly different from angle 45° in the case of the right deltoid, and angle 0° was not significantly different from 45° in the case of the left deltoid. Angle 90° was found to be significantly lower than orientation 45° in the case of the two deltoids and non-significantly different for the other muscles.

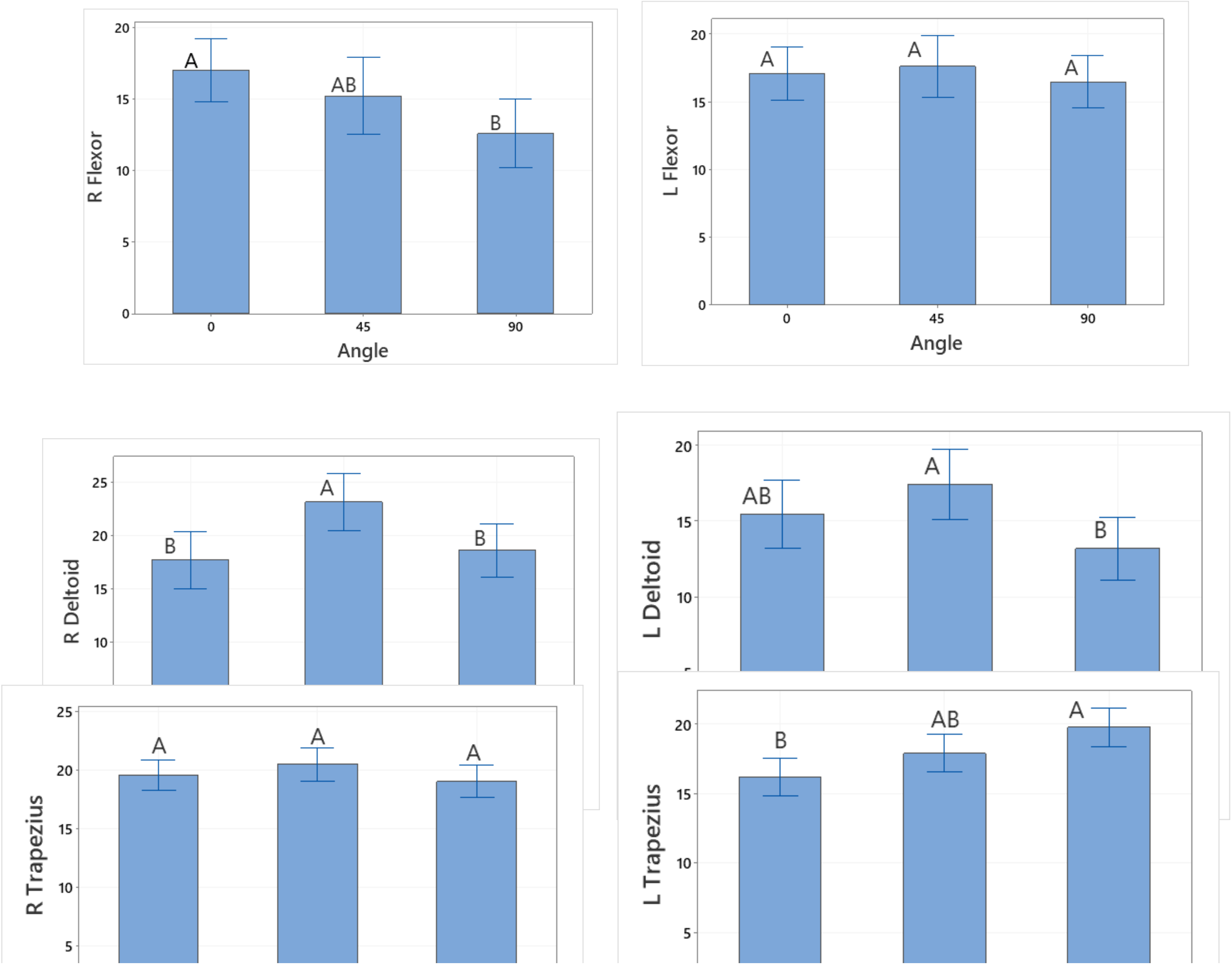


Figure 5: Mean average Maximum EMG with SE bars for each muscle associated with the different handwheel angles. Letter groupings are presented over the bars to identify the specific means with statistically significant differences.

The 45° handwheel position was found to require maximum muscle activations from more than one muscle (17.62% MVC of L-Flexor, 23.16% MVC of R-Del, 17.42% MVC of L-Del, 20.473% MVC of R-Trapezius). For example, a comparison of angle 45° and angle 0° at the right deltoid shows that the former position's EMG exceeded the 0° orientation EMG by over 31%. Overall, 45° appears to be the most undesirable handwheel angle, in that it was associated with high muscle loadings at the shoulder, neck, and hands. This concentration of maximum loads rather than distributing it across different muscles is also reflected in the average of EMG activity per muscle for each handwheel condition, where angle 45° have the highest value of 18.63 % MVC of the muscles under study (highest EMG activity of 23.16% on the right deltoid). Hence, the 45° handwheel positions would not be a recommended design for valve operations.

Diameter

Similar to ***Error! Reference source not found.***, *Table 3* summarizes the EMG results at each handwheel diameter. 35 cm and 45 cm put the most strain on the studied muscles, having the two highest EMG average per muscle of 18.04 % MVC and 17.69 % MVC respectively. None of the 45 cm diameter handwheel EMG values was minimal on the studied muscle, whereas diameter 35cm had only one minimum (17.418 % MVC of L-Trapezius). The other two diameters required less muscle activity (less max. EMG activity). The results at diameter 60 cm and 70 cm were quite similar to each other in EMG activities. At both handwheel diameters, at least one side of the hands, shoulders, and neck had high EMG activities. However, diameter 60 cm had the least number of muscles at maximum load and the greatest number of muscles with minimal load (13.19 % MVC of R-Flexor, 15.09 % MVC of L-Flexor, 19.07 % MVC of R-Del) whereas diameter 70 cm exerted maximum load on two of the muscles (20.89 % MVC of R-Del and 18.404 % MVC of L-Trapezius) and required minimal muscle activations from two muscles (13.29 % MVC L-Del and 18,949 % R-Trapezius). Both diameters required one of the two trapezius muscles to work at levels that were highest EMG (20.57 % R. Trapezius for the 60 cm and 18.404 % L. Trapezius for the 70 cm). The diameter 60 cm position's distribution of loads across different muscles is reflected on the average EMG activity per muscle being the lowest value (16.97 % MVC) among the muscles under study with only one highest EMG activity of 20.57 % on the right trapezius.

In summary, torque exertions at diameters 35 cm and 45 required relatively heavy loadings of at least one side of the hands, shoulders, and neck, muscles. They would not be a recommended design for valve operations. In contrast, at diameter 60 cm, all the muscles, except for the right trapezius, were working at minimal or near minimal EMG. Of the four handwheel diameters investigated, this handwheel diameter appears to have the best distribution of the loading across all muscles. This distribution is shown in *Table 3*, as its row has the lowest number of red and the greatest number of yellow cells suggesting that most of the muscles were working at minimal levels.

Diameter	Right Flexor	Left Flexor	Right Deltoid	Left Deltoid	Right Trapezius	Left Trapezius	Average of EMG	Highest EMG activity
35	16.70	17.55	19.87	16.96	19.737	17.418	18.04	19.87 % R. Del. and 19.74% R. Trapezius
45	15.77	18.19	19.45	15.54	19.462	17.714	17.69	19.45 % R. Del. and 19.46% R. Trapezius
60	13.19	15.09	19.07	15.65	20.569	18.286	16.98	20.57 % R. Trapezius
70	14.00	17.39	20.89	13.29	18.949	18.404	17.15	20.89 % R. Del.

🟧 Maximum EMG detected in muscle (column)

🟨 Minimum EMG detected in muscle (column)

Table 3: Summary of the maximum and minimum average maximum EMG (%MVC) at the different handwheel diameters.

User Preference Ranking

For further exploring the effects of handwheel design, user data was collected in terms of the subjects' preferred handwheel diameter and orientation. At each handwheel orientation, subjects were asked to rank the handwheel diameters in terms of comfort and ease of generating the targeted torque. If a tie is believed to exist, participants were asked to place the tied diameters in the same ranking. By ranking the different handwheel conditions, the participants chose the winning combination. *Figure 6* presents the winning angle-diameter combinations along with their frequency. The 90° and 70 cm was the most preferred combination chosen by 5 out of 20 (25%) of the participants, followed by a tie between the combinations 45° 60 cm (4 out of 20 participants) and 45° 70 cm.

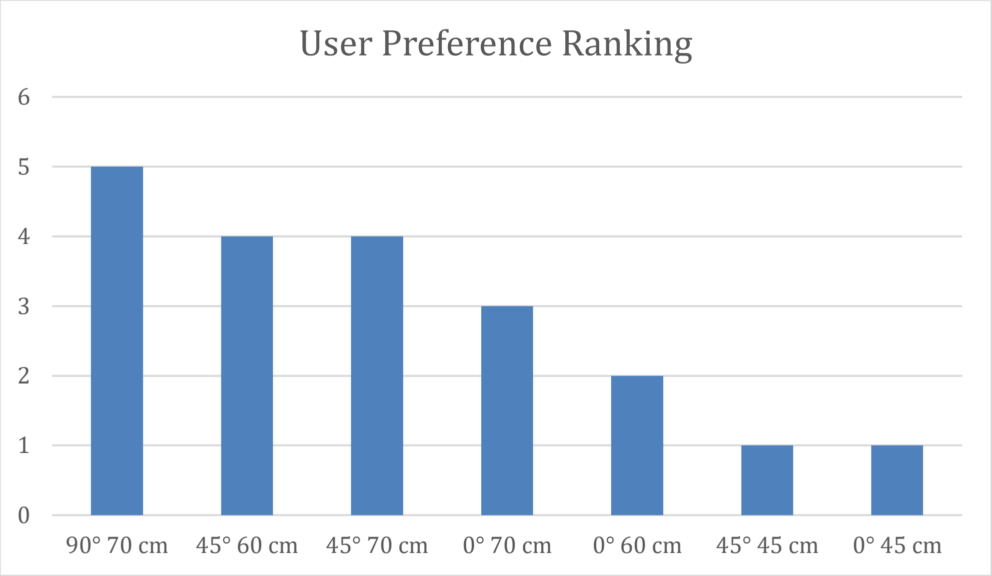


Figure 6: A bar graph of the frequency-ratings of the preferred handwheel angle-diameter combinations by users.

Figure 6 and *Figure 7* represent the frequency distribution for user ranked preference for angle and diameter respectively. 45% of participants chose the 45° orientation as the easiest and described it as being the most comfortable angle while 60% chose the 70 cm diameter as being the most comfortable handwheel diameter. None of the participants ranked the 35 cm diameter as one of the easy-to-handle dimensions. This conclusion goes partially in line with the biomechanics results for the 35 cm handwheel being the least optimal in terms of EMG activity and muscle load distribution.

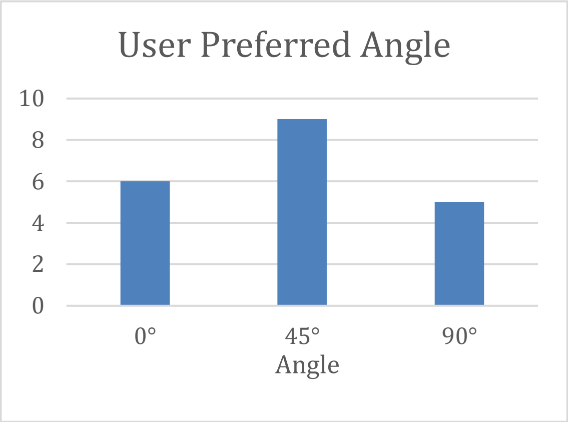


Figure 7: A bar graph of the frequency-ratings of the preferred handwheel angles by users.

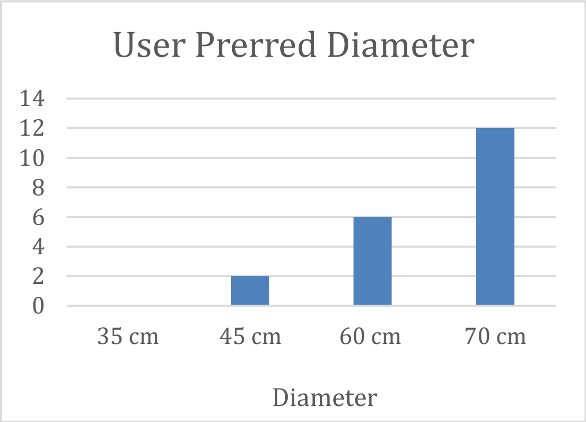


Figure 8: A bar graph of the frequency-ratings of the preferred handwheel diameters by users.

Handwheel-valve systems are found in various industries, including the oil and gas, power generation, water supply, railway, chemical, and nuclear process industries (Al-Qaisi et al., 2019). The function of handwheels is primarily to regulate the flow of material, such as steam or oil, within a valve system or to regulate the movement of rail cars as done in the railway industry. The nuclear industry is one specific

CHAPTER 4

DISCUSSION

We investigated the effects of handwheel diameter and handwheel orientation on user biomechanics and preference/comfort. All two-way interactions among these three factors were statistically insignificant, thus each factor was studied separately. Muscle activation decreased as diameter increased, implicating a better distribution of loads across the muscles of the body. This finding is explained and supported by the earlier work of Schulze et al. (1997), who hit upon torque production increase with increasing diameter; thus, for a fixed 25 Nm torque, higher diameters lower the physical activity needed to execute the task. However, Schulze study was limited to small handwheels (17.8, 20.3, 22.9, and 40.6 cm) whereas we included larger diameters (60 and 70 cm) that turned to be more favorable in terms of torque production, user comfort, and the reduction of the risk of injuries since operators will work at lower levels of their maximum capabilities at a given torque (Keyserling et al., 1980).

On the other hand, smaller diameter put significant strain on user’s biomechanics and distribute the load unevenly. These small size handwheel were ranked lowest in terms of the comfort by the users and thus should be avoided.

We found the best load distribution at angle 90° whereas the 45° angle was the least optimal. This can be explained with the previous findings of Al-Qaisi et al. (2015), who investigated the same three orientations using a handwheel diameter of 37.4 cm where 45° orientation was found to be the lowest in terms of torque production. Conversely, our findings from the EMG muscle activation data were contradicted with the participants reported preference of handwheel orientation; 45° orientation was the number one choice angle for the majority of tested participants. Nevertheless, Al-Qaisi recommends that the 45° orientation should be avoided because it was associated here with relatively low torque exertions, especially at the larger diameters (60 and 70 cm).

Moreover, our results on the 0 ° diameter don’t reflect the findings of Al-Qaisi, where he reported that torque production capacities at the 0° handwheel orientation were the highest between the three angles. This discrepancy between the two studies might be due to the level of torque that the participants were required to achieve (25 Nm vs 50 Nm). Another study by Attwood et al. (2002) similarly reported a greater mean torque with a 0° orientation than with 90°. Consequently, horizontally oriented handwheels were postulated to be more effective for increasing operator torque production capacities. Regardless of the discrepancy between our study and the previous ones regarding the 0° orientation, the results are limited to handwheels at elbow level since other handwheel heights were note explored.

Recommended handwheel position

In summary, the recommended handwheel angle and diameter from those investigated would be 90° and 60 cm respectively. At each of these diameter and angle, the load was distributed on several muscles and the user reported relative comfort while applying his force.

Limitations and future research

This study had several limitations that should be stated suggesting the need for future research. The participants recruited were college students recruited from the American University of Beirut and not professional valve operators. Consequently, generalizing the results to the working population should be used carefully especially that the student has lower torque production capabilities (Wieszczyk et al., 2009). Therefore, our participants' torque strength and physiological state can be representative of capabilities of young, novice valve operators. Repeating the study with valve-operators with different levels of experience (e.g., no experience versus experienced valve-operators) is thus recommended to increase the external validity of the recommended torque values.

Second, participants were sampled from a Lebanese population, and therefore the findings may be difficult to generalize to other populations.

Third, only one relative handwheel height was studied: at elbow level. However other body landmarks (e.g., knee, elbow, and shoulder body landmarks) are found in the workplace that were not considered in this study.

Fourth, participants were required to use a specific hand and foot positioning during torque production, thus having an effect on muscle recruitment patterns when generating a torque. Future work can study the effects of various hand and foot postures.

Fifth, we examined only the EMG in determining the effects of wheel diameter and orientation angles. Future studies may consider other physiological outcomes, such as maximum heart rate, maximum oxygen consumption, subjective ratings of exertion and discomfort, and performance measures of time to fully open valves in determining an optimal handwheel diameter and orientation.

CHAPTER 5

CONCLUSION

We explored the effects of two factors- handwheel diameter, and handwheel orientation- on user biomechanics and preference/comfort. No interaction was found between handwheel orientation and angles. However, biomechanics stress on studied muscles were lower at larger handwheel diameters. This goes in line with reported user preference since the majority rated diameter 70 cm as the most comfortable position. Future research should consider the effects of handwheel diameter on additional outcomes that may cause injury risks among operators. Regarding the orientation of the handwheel, vertically oriented (90°) handwheels were consistently associated with the lowest EMG activity. However, a tradeoff between user biomechanics and user perceived preference/comfort may be required for determining an optimal handwheel angle since users rated the 0° angle instead of the experimentally optimal 90° angle as their most comfortable orientation. Further, we suggest that 45° orientation should be avoided, because it was associated with relatively the highest EMG activity.

CHAPTER 6

ACKNOWLEDGEMENTS

Handwheel-valve systems are found in various industries, including the oil and gas, power generation, water supply, railway, chemical, and nuclear process industries (Al-Qaisi et al., 2019). The function of handwheels is primarily to regulate the flow of material, such as steam or oil, within a valve system or to regulate the movement of rail cars as done in the railway industry. The nuclear industry is one specific.

CHAPTER 7

CONFLICT OF INTEREST

The authors declare no conflict of interest.

CHAPTER 8

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APPENDIX

Data Collection Sheet

Name: ___________________

Age: ____ Weight (kg): ____ Height (cm): ____

1. For the **___** handwheel orientation, rank the handwheel diameters in terms of comfort and ease of generating the targeted torque (from most to least comfortable and easy).

   Note: If you believe a tie exists between diameters, place tied diameters in the same ranking. For example, a ranking as follows: “(1) 70 and 60; (2) 45; (3) 35” would suggest that the 70 and 60 cm diameters are equally the most comfortable followed by the 45 cm diameter and finally by the 35 cm diameter. Rank ties in the following questions in the same manner.

2. For the **___** handwheel orientation, rank the handwheel diameters in terms of comfort and ease of generating the targeted torque (from most to least comfortable and easy).

3. For the **___** handwheel orientation, rank the handwheel diameters in terms of comfort and ease of generating the targeted torque (from most to least comfortable and easy).

4. Rank the “winning” handwheel conditions from above in terms of comfort and ease of generating the targeted torque (from most to least comfortable and easy) to determine your overall most preferred handwheel design(s).

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