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Effect of Elbow Flexion, Forearm Rotation and Upper Arm Abduction on MVC Grip and Grip Endurance Time

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This experiment was designed to know the effect of upper limb postural deviations on grip strength and grip endurance time. A full factorial design of experiment, i.e., 3 (0°, 45°, 90° abduction angles of upper arm) × 3 (45°, 90°, 135° angles of elbow flexion) × 3 (0°, –60° prone, +60° supine angles of forearm rotation) was used to find the effect of 27 combinations of postures on maximum voluntary contraction (MVC) grip strength and grip endurance time. The results showed that none of the main factors were significant on MVC grip, although there was a change in MVC grip. Grip endurance time significantly decreased with an increase in upper arm abduction. Also, grip endurance significantly increased with the elbow flexion angle and decreased with forearm rotation from neutral. These data will help designers and engineers to improve the workplace and tools to reduce the risk of injuries.

elbow flexion   upper arm abduction   forearm rotation   MVC grip   grip endurance

1. INTRODUCTION

Work-related musculoskeletal disorders (WMSDs) are recognized as the most common occupational problems in industries [1]. WMSDs include a wide range of inflammatory and degenerative diseases and disorders, which can result in impairment. Such conditions of pain and functional impairment may also affect the neck, shoulders, elbows, forearms, wrists and hands [2]. Hagberg and Wegman found that materials handling, and force/torque exertion with the aid of human-powered hand tools, accounted for ~45% of all industrial overexertion injuries in the USA [3]. Kilbom and Persson demonstrated the relation of upper arm abduction with the onset of symptoms for WMSDs [4]. Similarly, Ritz recorded a prevalence rate of 14% for humeral epicondyilitis among gas and waterworks employees. It was found that the routine fitting of pipes was physically strenuous for the elbow [5]. Work-related upper limb disorders comprised 13% of the illness cases involving lost days from work and 69% of the total illness cases reported in 1994 [6]. According to Bernard, the Bureau of Labour Statistics reported a further cause, in that in 1994 there were ~705 800 (32%) cases of overexertion or repetitive motion injuries among all injuries reported in industry, of which 13% affected the shoulder [6]. Moreover, 92 576 injuries or illnesses occurred as a result of repetitive motions including the use of objects other than tools. A number of studies showed that most cases of forearm and elbow injuries in industry included various forms of lateral epicondylitis.

Grieco, Molteni, De Vito, et al. reported that along with other postural problems, pronation and supination of the forearm were related to upper limb disorders [7]. Industrial tasks involving forceful exertions, repetition and bad postures had been related to WMSDs but there were no quantitative data on the relationship between these factors and injuries [8]. Yun, Lee, Eoh, et al. reported 51.4%

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cases of shoulder musculoskeletal problems among video display terminal (VDT) workers in banks of Korea [9]. Smith, Sato, Miyajima, et al. performed an epidemiological investigation of WMSDs among nursing students in Japan; they found that the shoulder was the most affected part in ~14.9% of cases [10]. Other studies also reported a similar level of WMSD problems among rural Australian nursing students; Smith and Leggat observed a prevalence rate of 23.8% for shoulder-related disorders [11], also 58% of hotel restaurant workers in Taiwan reported WMSDs [12].

Because of workplace layout, product design, hand tool design, forceful exertions and repetitive postures, workers are bound to adopt awkward postures for long periods, a causative factor for WMSDs [13]. A number of studies documented cases of forearm/elbow injuries in industries, most of which included forms of lateral epicondylitis, which is associated with forceful laborious tasks, e.g., wallboard installation, roofing, masonry, foundries, building construction, furniture making, paper products manufacturing and meat dealers, all occupations that involve repetitive, forceful work involving the hands and arms and requiring pronation and supination [14].

Hagberg and Wegman found that awkward postures, such as upper arm abduction combined with repetitive movements of the forearm, contributed to WMSDs among assembly line workers, shop assistants, slaughter house workers, scissors makers, data entry workers and computer operators [3]. Coury, Kumar, Rodgher, et al. observed that upper arm flexion in the range of 0° to 90° in pencil packaging industry was responsible for WMSDs [15]. Moreover, as reported in Brazilian industry, movements such as inward rotation of the humerus and humeral forward flexion were responsible for WMSDs. In a handmade brick manufacturing plant, Trevelyan and Haslam observed that 45° medial rotation of the humerus accompanied by 45° abduction and 45° forward flexion of the upper arm was responsible for WMSDs [16]. Spray painters painting workpieces on a horizontal worktable may risk shoulder tendinitis due to the large upper arm abduction required [17]. A few studies also reported that increased abduction of the upper arm in the glenohumeral joint was an important risk indicator for musculoskeletal disorders in the neck and shoulders [18, 19].

Grip strength is an important parameter of an individual's performance; hence measurement of grip strength is frequently included in the assessment of individuals who have an impairment performing both occupational and nonoccupational tasks. Maximum voluntary contraction (MVC) of grip strength is also used as a subjective measure of the worthiness of the upper limbs. Therefore, grip strength may be considered as a criterion in task design. Johansson and Sojka showed that greater grip must also be considered so that it may represent a safety margin against unanticipated perturbing forces or slips of the tool from grip [20]. Coury et al. studied shoulder abduction strength in various body postures and observed that discomfort, pain and decrease in grip strength at different postures of the elbow and shoulder flexion, a combination of shoulder at abduction 0°, elbow at 135° and wrist at neutral (i.e., no radial/ulnar deviation and also no flexion/extension) produced the greatest amount of forces among all combinations of postures [15]. Kattel, Fredericks, Fernandez, et al. found that shoulder abduction, elbow flexion, wrist flexion and ulnar deviation significantly affected output grip force [1]. Researchers consistently indicated that significant deviations of the wrist from neutral decreased grip strength [1, 21, 22]. The other strength parameter, i.e., torque, was also found affected by change in upper limb postures. According to Salter and Darcus, the effect of hand position on the maximum torque developed in attempted pronation and supination showed there was a linear relationship between the position of the hand and the developed torque and, as the position of the hand changed in supine, the isometric pronation torque increased and the supination torque decreased [23].

Laboratory-based experiments examined the relationship between these task factors and subjective feelings of discomfort [24, 25, 26]. It is desirable to predict the comparative discomfort level for a combination of postures to eliminate potentials problems before they arise. This knowledge of different discomfort levels will enable designing workplaces that reduce discomfort and the risk of injury. In the manufacturing environment, where hand tools with power grip have to be used, postures where discomfort is minimum are beneficial for both the employer and the workers. Workers should be made aware of the fact that at deviated postures, they should be working at a lower percentage of their MVC [1].

Few studies investigated the combined effect of shoulder abduction, elbow flexion and forearm rotation on MVC grip and grip endurance time [27, 28]. In the first study, Roman-Liu developed a relationship for maximum grip force for upper limb postures. The predictive equation expressed maximum handgrip force as a function of seven angles defining upper limb postures [27]. In another study, Roman-Liu and Tokarski reported different upper limb strengths (in pushing, pulling and lifting) by taking handgrip and torque as a function of upper limb posture [28]. To know the relation of endurance time for handgrip, with respect to the angular deviation in upper limb posture (i.e., combination of forearm rotation, elbow flexion and upper arm abduction), the present study was designed to further investigate the effect of upper limb posture angles on MVC handgrip and grip endurance time. Therefore, the present experiment was designed to know the effect of these postures on grip strength and grip endurance for specific postural angles of upper arm abduction and elbow flexion combined with forearm rotation. The study was to investigate further the interaction effects of the aforementioned postures which previous studies did not look at. Manual and semimanual tasks, such as punching, press work, die casting, etc., mainly involve a bad postural combination of the upper arm, elbows and forearms. It could be noticed that those workplaces involved a combined postural deviation of the upper limbs. Therefore, it was kept in mind that these data would help designers and engineers to improve the workplaces and tools to reduce the risk of injuries related to tasks requiring power grip.

2. METHOD

2.1. Participants

The age group of 20–40 years was preferred because most workers in this age group were involved in repetitive gripping tasks in small-scale hardware industry. For the experimental investigations, 20 right-handed male participants of mean (*SD*) age 26.5 (6.42) years, height 171.1 (7.46) cm and mass 63.3 (7.51) kg were selected through departmental notices and e-mails.

2.2. Postures

There have been different studies on the combined postures of upper limbs; however, there have been none on the effect of upper arm abduction and elbow flexion combined with forearm rotation on MVC grip and grip endurance time. Mukhopadhyay, O'Sullivan and Gallwey investigated the effect of upper arm abduction (0° and 90°) combined with elbow flexion (45°, 90° and 135°) and forearm rotation (0 and 60% of ROM [range of movement] in prone and supine) on repetitive task performance in terms of discomfort [29]. They did not consider any angle of upper arm abduction between 0° and 90°. Moreover, they did not investigate the effect on endurance time, which is most important in tool and work design. Therefore, for the present study, three levels of upper arm abduction (0°, 45° and 90°) in combination with three levels of elbow flexion (45°, 90° and 135°) (in line with Mukhopadhyay et al.) and three levels of forearm rotation (0° and 60° in prone and supine) (in line with Kattel et al. [1] and O'Sullivan and Gallwey [30]) were chosen. In this study, 0° forearm rotation was the position of the forearm, while the wrist was in the plan formed by the axis of the forearm and upper arm. Figure 1 shows the postures used in this study.

2.3. Experimental Design

A 3 (upper arm abduction angles) × 3 (elbow flexion angles) × 3 (forearm rotation angles) full factorial design was used. There were 27 combinations available for each participant. There were

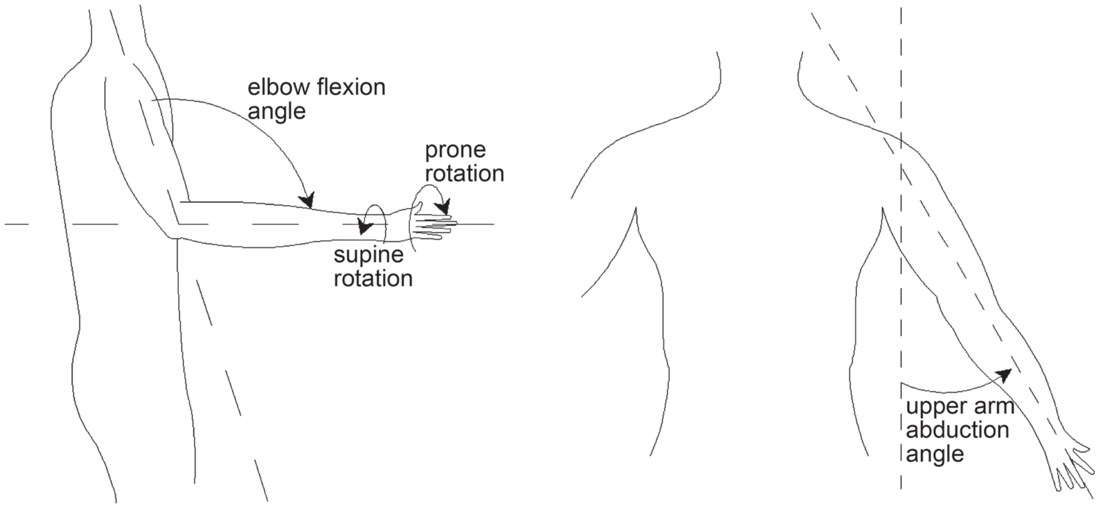

Figure 1. Postures considered in the experiment.

20 participants and to balance the effect of order, the order of the experimental combinations was random. There were two dependent variables, grip strength and grip endurance time (at 50% of an individual's grip strength).

Analysis of variance (ANOVA) was applied on the data obtained from the experiment. In the repeated measures ANOVA, to eliminate the effect of inter-subject variability, maximum grip strength (in neutral posture)/wrist circumference was used as a covariate.

2.4. Apparatus

The experimental rig was attached to a chair (Figure 2). This rig was designed according to the requirements of the study; it comprised three main components:

- for arm abduction, the support could move from 0° to 90°, so that the arm could be set at 0°, 45° and 90°;
- for elbow flexion, the support could move from 0° to 180°, so that the arm could be set at 45°, 90° and 135°;
- for forearm rotation, a circular attachment could measure angles from 0° to 360°, so that the forearm could be set at the required postures.

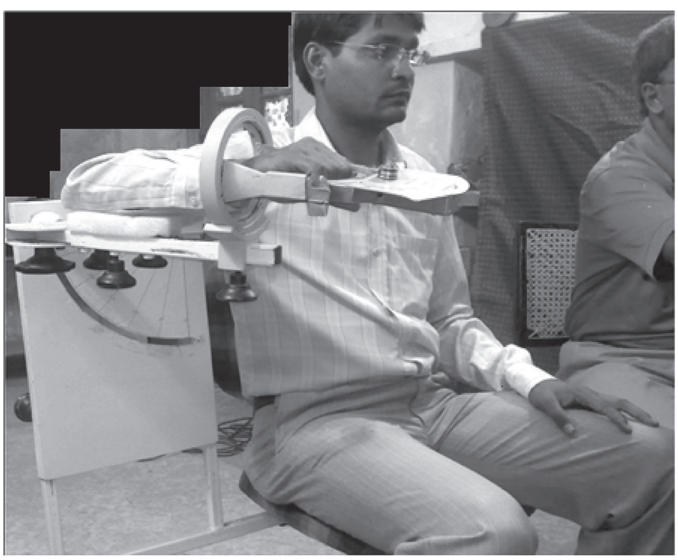

Figure 2. Experimental setup.

2.5. Preliminary Data Collection

The participants read a briefing sheet and signed an informed consent form after their questions had been answered. Then, preliminary data were collected.

2.6. Procedure

The participant sat on a fully adjustable chair, which had a fixed position on the floor (Figure 2). The hand was placed in the proper position with an arm support so that the treatment condition of the upper limbs was fixed for each combination. After setting the upper arm, elbow and forearm in the required posture, the participant was asked to press the grip meter up to full strength. A reading was collected. Then, the participant was asked again to press up to maximum grip after a minimum recovery time of 2 min or until he felt no discomfort. The recovery time was set according to O'Sullivan and Gallwey [30] and Mukhopadhyay et al. [29]. The greater of the two was recorded as the MVC grip for that particular treatment condition for the participant.

To record grip endurance time, 50% values of MVC grip were calculated. Then, the participants were asked to hold the grip meter in the same posture until the maximum discomfort level. To record endurance time, a LABVIEW code was written. It was displayed to the participant as well as to the experimenter. A 5-point scale was used to record endurance time [26]. The participant informed the experimenter about the stages set on the scale for recording endurance time.

The experiment was continued for all the treatments set in a random order with a gap of at least 5 min between each treatment. In this way, MVC grip was recorded for every combination of three postures.

3. RESULTS

3.1. MVC Grip Strength

The data of MVC grip strength was checked for normality with a histogram and normal score plots that satisfied for normality. The data were analysed with ANOVA. Table 1 presents the results. No main factors or their interactions were significant.

Figures 3–5 show profile plots of MVC grip versus upper arm abduction, elbow flexion and forearm rotation angles. The curve between grip strength and upper arm abduction angle shows that strength increased from 0° to 45°, and after attaining the maximum value at 45°, it decreased as the angle changed from 45° to 90° for further abduction of the upper arm (Figure 3). The main thing observed was that the increase and decrease were not very fast: they were slow and steady. The curve between MVC grip strength and elbow flexion angle showed strength increased continuously at all angles, i.e., 45°, 90° and 135° (Figure 4). The curve between MVC grip strength and forearm rotation revealed that the decrease in strength was from 60° prone to neutral, i.e., 0°. The decrease continued when the position changed from neutral to 60° supine (Figure 5).

TABLE 1. The Results of Analysis of Variance (ANOVA) for MVC Grip Strength as Dependent Variable

Source	Type III SS	*df*	*MS*	*F*	*p*
Participant	21507.559	9	2389.729	0.924	.505
UA	1254.985	2	627.493	0.243	.785
EF	91.230	2	45.615	0.018	.983
FAR	4027.785	2	2013.893	0.778	.460
UA × EF	4556.015	4	1139.004	0.440	.779
UA × FAR	2389.926	4	597.481	0.231	.921
EF × FAR	11599.015	4	2899.754	1.121	.347
UA × EF × FAR	25482.741	8	3185.343	1.231	.282
Error	605495.341	234	2587.587		
Corrected total	676404.596	269			

Notes. MVC = maximum voluntary contraction, UA = upper arm abduction, EF = elbow flexion, FAR = forearm rotation.

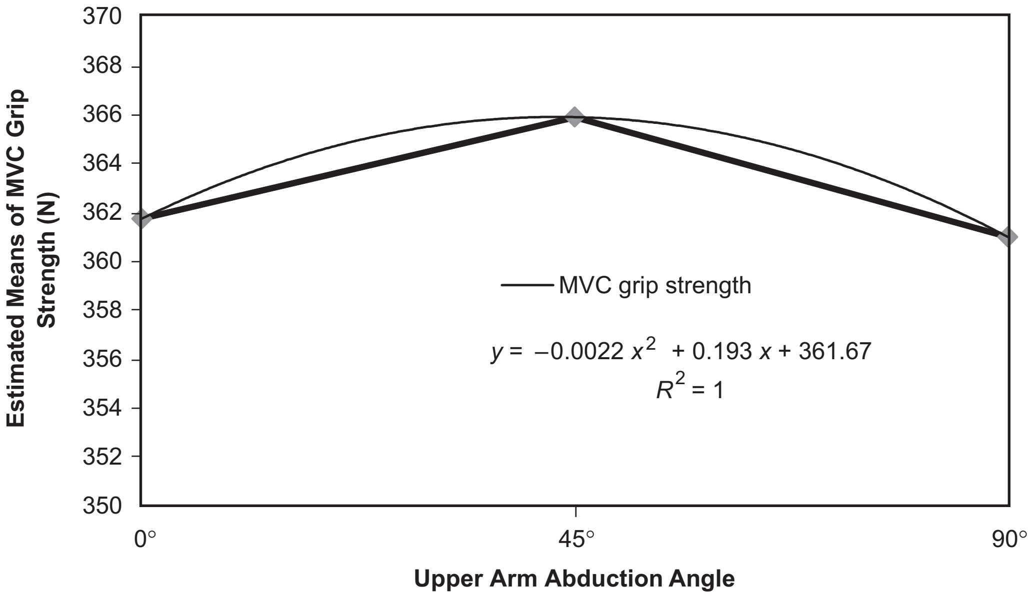

Figure 3. A profile of MVC grip strength (Newtons) versus upper arm abduction angle (degrees).
Notes. MVC = maximum voluntary contraction.

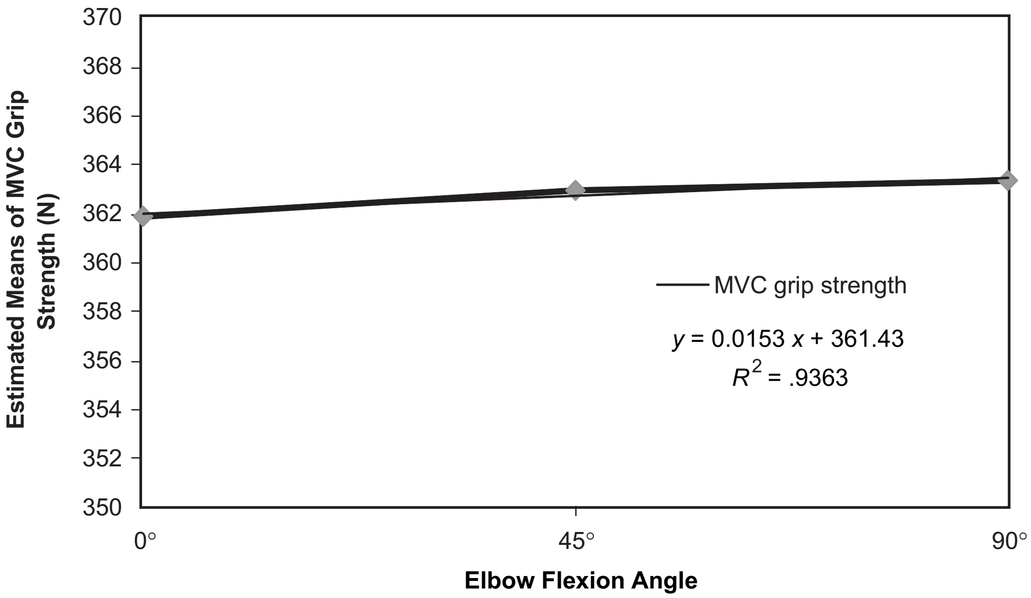

Figure 4. A profile of MVC grip strength (Newtons) versus elbow flexion angle (degrees).
Notes. MVC = maximum voluntary contraction.

The decrease was faster between prone to neutral than neutral to supine.

3.2. Grip Endurance Time

Table 2 presents the results of the ANOVA performed on the data of grip endurance time. The results showed that there were highly significant effects of upper arm abduction, elbow flexion and forearm rotation on grip endurance time (at $p < .001$, $p < .001$ and $p = .003$, respectively). All two- and three-way interactions of independent variables were also found significant on grip endurance time.

A further post hoc Students-Newman-Keuls test was performed on the data on endurance time. These tests showed that there were significantly different effects of each level of the abduction angle and of the elbow flexion angle on endurance time. Although the effect of no rota-

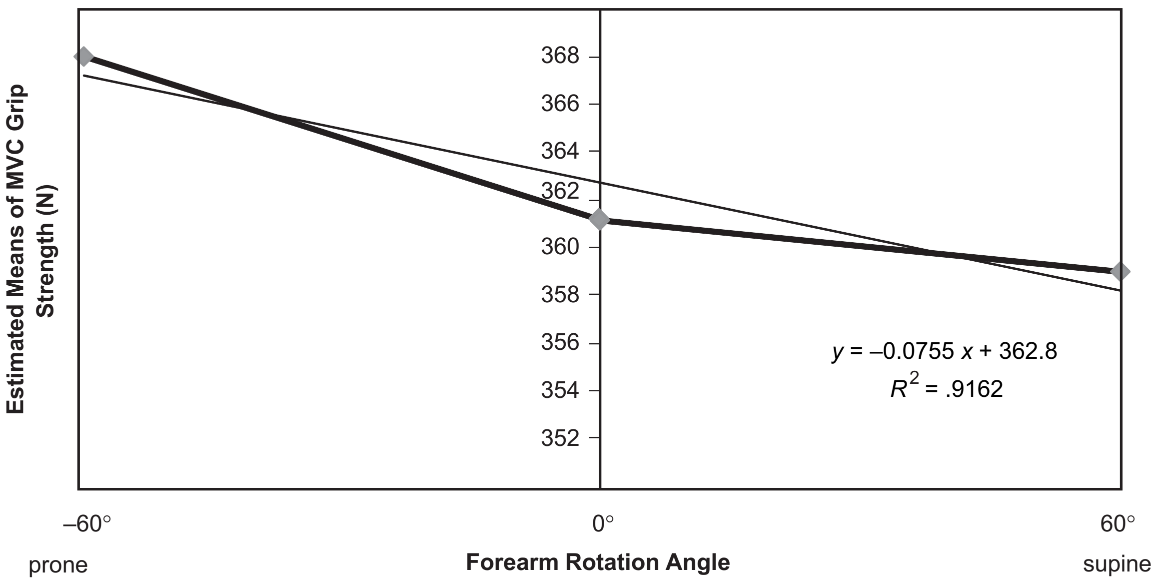

Figure 5. A profile of MVC grip strength (Newtons) versus forearm rotation angle (degrees).
Notes. MVC = maximum voluntary contraction.

TABLE 2. The Results of Analysis of Variance (ANOVA) for Grip Endurance Time as Dependent Variable

Source	Type III SS	*df*	*MS*	*F*	*p*
Participant	1151.485	9	127.943	2.988	.002
UA	4786.941	2	2393.470	55.889	<.001
EF	11004.941	2	v5502.470	128.485	<.001
FAR	518.896	2	259.448	6.058	.003
UA × EF	16229.837	4	4057.459	94.744	<.001
UA × FAR	12319.081	4	3079.770	71.914	<.001
EF × FAR	51348.881	4	12837.220	299.755	<.001
UA × EF × FAR	28054.874	8	3506.859	81.887	<.001
Error	10021.215	234	42.826		
Corrected total	135436.152	269			

Notes. UA = upper arm abduction, EF = elbow flexion, FAR = forearm rotation.

tion of forearm was significantly different from 60° prone and 60° supine, neither prone or supine had a significantly different effect on endurance time.

Figures 7–9 show changes in grip endurance time. The curve in Figure 6 shows that grip endurance time decreased as the position of the upper arm changed from 0° to 45° and from 45° to 90°. At 0°, the time was maximum, while at 90°, it was minimum. The curve in Figure 7 shows that endurance time increased rapidly from 45° to 90° and, after attaining the maximum value at 90°, the curve decreased at 135°. The comparison showed that the increase was quite faster than the decrease. The curve between forearm rotation and grip endurance time in Figure 8 showed that endurance time increased towards neutral, i.e., 0°, and then again it decreased from neutral towards 60° supine.

4. DISCUSSION

4.1. Elbow Flexion Angle

In this study, MVC grip for the postural combinations of the upper limb was not found significant, but it increased or decreased with a change in the postural angles of the upper arm, forearm rotation and elbow flexion. MVC grip force has been discussed: Kattel et al. reported that grip strength at

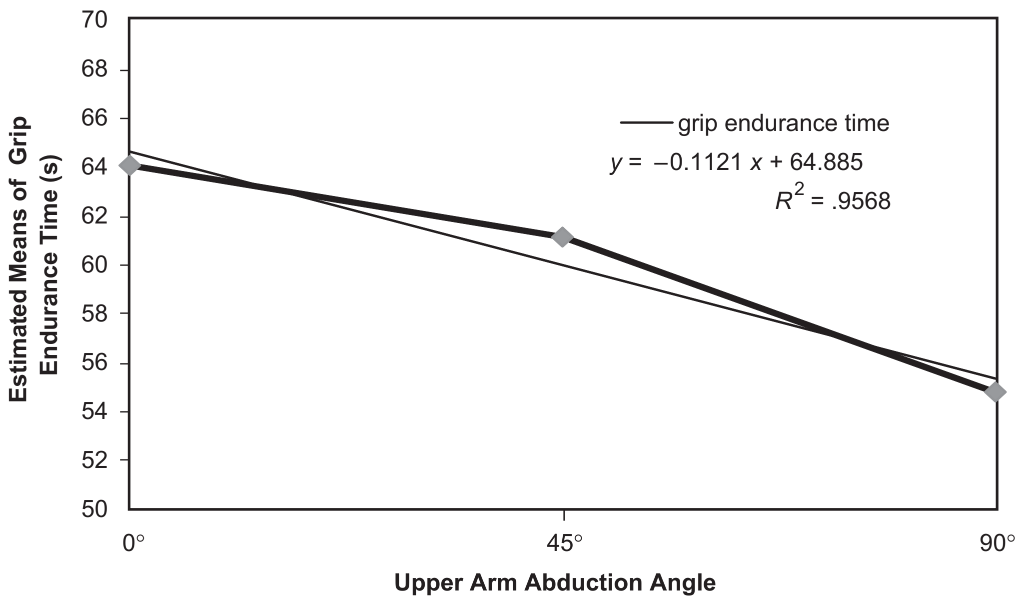

Figure 6. Profile plots of grip endurance time (seconds) versus upper arm abduction angle (degrees).

Figure 7. Profile plots of grip endurance time (seconds) versus elbow flexion angle (degrees).

elbow flexion at 135° was significantly different from that with the elbow at 90° and 180° [1]. Mukhopadhyay et al. also reported there was no difference in discomfort between 90° and 135°, but at 45° it was significantly different from the other two angles [29]. For forearm rotation, all three angles were significantly different from each other. It was also noticed that MVC grip strength was maximum for the posture combination of elbow flexion at 135° with the forearm at 60° prone for no abduction. Contrary to the present results, Kattel et al. reported that the maximum grip strength was exerted in the neutral position of the body (i.e., no abduction of the shoulder, elbow flexion at 90° and wrist at neutral). The result of the present study showed that

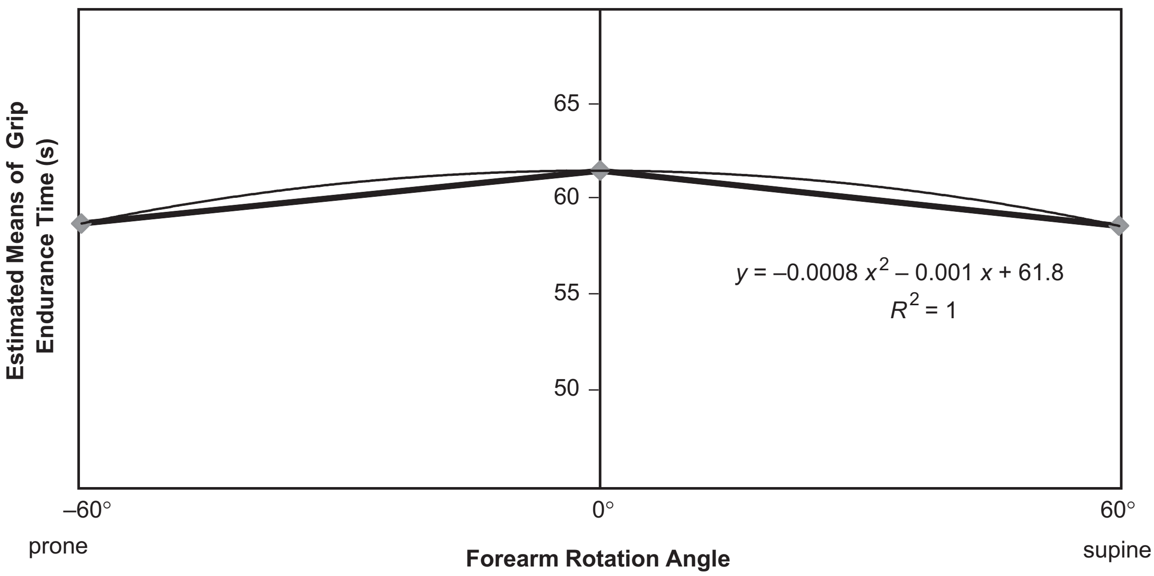

Figure 8. Profile plots of grip endurance time (seconds) versus forearm rotation angle (degrees).

this occurred at the elbow flexed at 135° with the shoulder at neutral and forearm at 60° prone.

4.2. Upper Arm Abduction

The results of this study showed that there was no significant change in MVC grip strength for upper arm abduction from the no abduction to 90°. However, there was a significant decrease in endurance time from no abduction to 90°. It seems that while grip strength remained unchanged, endurance changed with the abduction angle. That is why there might be some other causes of the change in grip strength and the change in endurance time with an increase in the abduction angle of the upper arm. The recruitment of motor units might be a factor as it changes with posture. Finsen and Christensen found that muscle activity in the right trapezius muscle was 21 and 15% of maximal EMG during high and moderate upper arm abduction, respectively [31]. Gupta and van der Helm's findings could be a reason for the decreased endurance time with 90° abduction [32]. They reported that at higher abduction angles, the moment arm becomes negative and the muscle is inactive. A number of EMG studies also showed that muscle activation varied with the abduction angle [33, 34, 35].

4.3. Forearm Rotation

The results did not show any significant difference in MVC grip strength for forearm rotation angles, but there was a decreasing trend from prone to supine rotation of the forearm. The present findings are in line with O'Sullivan and Gallwey's results for supination torque strength [25]; they found that it decreased from 75% of ROM prone to neutral and further down to 75% of ROM supine. An, Hui, Morrey, et al. reported the moment arms of biceps muscles were similar for neutral and prone posture of the forearm but considerably lower for the supine posture [36]. In the present study, the supine posture, too, had lower MVC grip compared to neutral and prone. It is known that biceps muscles also contribute directly to a gripping task. There is a slight contradiction compared to Mogk and Keir's findings, who reported a decrease in MVC grip for prone and supine, both compared to neutral forearm [37]. However, in the present study, for prone rotation, MVC grip increased compared to neutral forearm. Moreover, endurance time was found to significantly decrease with the rotation of the forearm from neutral in prone or supine directions. O'Sullivan and Gallwey showed a similar trend for discomfort; they reported an increase in discomfort with the deviation in forearm rotation from neutral in either prone or supine directions. Endurance time recorded in the present study was based on perceived discomfort scored on a 5-point scale. O'Sullivan and Gallwey, too, reported perceived discomfort on a 10-point scale. Hence, the aforementioned studies support the present findings.

4.4. Validation

The data of the present study was further compared with Roman-Liu's [27]. Roman-Liu's formula was used to estimate the handgrip; Table 3 presents the results. The results compared with the experimental findings showed that the range of the handgrip was nearly the same as in the present study (216–510 N), while the values reported by Roman-Liu ranged approximately from 180 to 600 N as seen in the correlation curve of male and female handgrip strength of that study. Table 3 compares the mean values of MVC grip for every posture combination selected in the present study with Roman-Liu's calculated values. The results show data for this and Roman-Liu's studies are in a similar range.

TABLE 3. A Comparison of Values From This Study With Roman-Liu's [28] for Estimated Mean Values of MVC Handgrip

			Estimated Means of MVC Hand Grip (N)	
UA	EF	FAR	This Study	Roman-Liu [28]
0°	45°	–60°	382.7	293.75
		0°	358.0	316.77
		60°	322.7	311.37
	90°	–60°	343.5	289.38
		0°	376.7	314.45
		60°	365.9	309.80
	135°	–60°	378.6	285.63
		0°	357.0	310.51
		60°	369.9	305.82
45°	45°	–60°	361.0	292.26
		0°	366.9	317.54
		60°	371.9	312.85
	90°	–60°	380.8	286.75
		0°	359.1	311.70
		60°	353.1	307.25
	135°	–60°	376.5	283.91
		0°	359.1	308.43
		60°	364.0	303.91
90°	45°	–60°	372.8	298.72
		0°	375.8	327.74
		60°	346.3	319.78
	90°	–60°	357.1	296.53
		0°	351.2	327.56
		60°	379.7	317.44
	135°	–60°	360.1	293.39
		0°	347.2	318.76
		60°	358.1	314.08

Notes. MVC = maximum voluntary contraction, UA = upper arm abduction, EF = elbow flexion, FAR = forearm rotation.

5. CONCLUSIONS

- Posture was not found significant for MVC grip. A change in MVC grip was noticed, however.
- Grip endurance time significantly decreased with an increase in upper arm abduction.
- Grip endurance time significantly increased with elbow flexion angles and decreased with forearm rotation with respect to neutral forearm.
- The more important finding was the significant interaction effects of the main factors on grip endurance time. This indicates that combined deviations of upper limb postures have critical importance for task design.

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