Original

Investigating Glenohumeral Joint Contact Forces and Kinematics in Different Keyboard and Monitor Setups using Opensim

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Received: 19 January 2022
Accepted: 12 February 2022

ABSTRACT

Background: The musculoskeletal complaints of the shoulder are prevalent in people who work with computers for a long time.

Objective: This study aimed to investigate the glenohumeral joint contact forces and kinematics in different keyboards and monitor setups using OpenSim.

Material and Methods: Twelve randomly selected healthy males participated in an experimental study. A 3×3 factorial design was used in which three angles were considered for the monitor and three horizontal distances for the keyboard while performing standard tasks. The workstation was adjusted based on ANSI/HFES-100-2007 standard to maintain a comfortable ergonomic posture for controlling confounding variables. Qualisys motion capture system and OpenSim were used.

Results: The maximum mean range of motion (ROM) of both shoulders' flexion and adduction was observed when the keyboard was 15 cm from the edge of the desk, and the monitor angle was 30°. The maximum mean ROM of both shoulders' internal rotation was recorded for the keyboard at the edge of the desk. Peak forces for most right shoulder complex muscles were obtained in two setups. 3D shoulder joint moments were significantly different among nine setups (*P*-value<0.05). The peak anteroposterior and mediolateral joint contact forces were recorded for the keyboard at 15 cm and the monitor at zero angles (0.751 and 0.780 N/BW, respectively). The peak vertical joint contact force was observed for the keyboard at 15 cm and the monitor at 15° (0.310 N/BW).

Conclusion: The glenohumeral joint contact forces are minimum for the keyboard at 8 cm and the monitor at zero angles.

Citation: Gholami M, Choobineh A, Karimi MT, Dehghan A, Abdoli-Eramaki M. Investigating Glenohumeral Joint Contact Forces and Kinematics in Different Keyboard and Monitor Setups using Opensim. *J Biomed Phys Eng*. 2023;13(3):281-290. doi: 10.31661/jbpe.v0i0.2210-1450.

Keywords
Biomechanics; Shoulder; Musculoskeletal Disorders; Ergonomics

Introduction

Musculoskeletal disorders (MSDs) are among the major problems reported by computer users [1]. The musculoskeletal complaints of the arm, neck, and/or shoulders (CANS) are very common in people who work with computers for a long time and can lead to occupational diseases causing frequent absences from work, low productivity, poor quality of life, and increased medical costs [2]. Computer tasks are primarily characterized by a long time of monitor viewing and static postures with repetitive motion of arms [3]. Static

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postures of the neck and shoulder, repetitive motions, and workstation design are important factors that contribute to the risk of MSDs [4].

Marcus et al. reported that the workstation-related factors enhanc the risk of upper extremities disorders [5]. The locations of the keyboard and monitor determine the posture of the shoulder, arm, and wrist. Ignoring this issue in the design of a computer workstation increases the incidence of MSDs [6].

Few studies have been done on the effect of keyboard and monitor placement in computer workstations on shoulder kinematics and kinetics [7]. Since the shoulder kinematics can be a representative of potential reasons for shoulder disorders in computer work, it is critical to measure shoulder kinematics during computer use [8]. A prediction model for the risk of MSDs can help ergonomists to detect the MSDs risk in working postures and suitably adjust the postures to reduce the risk [9]. Musculoskeletal computer simulations have been widely used to assess the role of muscles during movement and survey the effects of motion on the musculoskeletal structure and neural control related to age, sex, injury, and disease [10]. The many degrees-of-freedom (DOF) of the shoulder girdle limit the usefulness of simple 2D models and require complex 3D models.

A complication arises since many interesting quantities, including neural control signals and joint loads, are difficult or impossible to measure by experiments [11]. Quantifying body kinematics and kinetics are extremely useful for evaluating the risks of MSDs for a variety of activities [12]. The capabilities of OpenSim software, such as inverse kinematics and static optimization, make it a practical tool for predicting joint contact forces, i.e., this software can be used in many applications. However, the joint contact force is an actual force applied to the articular surface to predict MSDs, it has been rarely reported for computer users. A three-dimensional muscle-actuated simulator with the ability to accurately reproduce the dynamic movement of individuals is beneficial to quantify the elements affecting MSDs and to prevent potential disorders [13]. OpenSim is widely used for modeling the musculoskeletal system while visualizing the motion and quantifying joint position, muscle forces, moments, and joint contact forces using inverse kinematics, inverse dynamics, and forward dynamics [11].

In many workstations, due to high workload or unawareness, the monitor(s) is rotated to some degree in front of the user, and the appropriate keyboard distance from the body is not considered, resulting in increasing the risk of disorders of the upper extremities.

The current study aimed to determine the effect of different horizontal keyboard distances and monitor angles on glenohumeral joint contact forces and kinematics. The findings of this study can be used to develop office ergonomics standards.

Material and Methods

Subjects

This experimental research was performed on twelve healthy males (25 to 30 years) without any MSDs. Right-handed individuals were randomly selected to decrease the confounding effect. Participants' mean (SD) typing speed was 45.37 (11.67), ranging from 25 to 87 words per minute to eliminate the impact of the skill.

Twelve right-handed adult males with 165-185 cm of height were included in the study, and those who had any MSDs history were excluded from the study.

Data gathering tools

Qualisys motion capture and OpenSim version 4.1 were used in this study.

1. Qualisys motion capture system

A Qualisys motion capture system with eight high-speed cameras with a frequency of 120 Hz was used to record the movement of the shoulders. Static and dynamic calibration of

Qualisys was done before recording the motion data. Qualisys system could determine the setup and direction of the visible space of each camera and reduce the lens error. The error magnitude in the motion analysis system was less than 1 millimeter for each camera. The data gathered were labeled by QTM software (version 2.17) and exported in C3D format. Mokka (version 0.6) was used to convert the data into TRC format, which OpenSim could read.

2. OpenSim

OpenSim was used for musculoskeletal modeling to measure kinematics as well as kinetics and estimate muscles and joint contact forces [13]. Both Shoulders' flexion-extension, abduction-adduction, and internal-external rotation were assessed using OpenSim. The inverse kinematics and dynamics were used to calculate read-only memory (ROM) and joint moments (as a three-dimensional). In this software, joint contact forces were calculated as a sum of joint reaction forces and muscle tension forces. Moreover, kinetic properties were calculated for the right shoulder complex. Rajagopal model was used to perform scaling [14]. The MoBL-ARMS dynamic upper limb model was used to calculate the muscle and joint contact forces [10]. In the present study, the anterior deltoid, medial deltoid, posterior deltoid, supraspinatus, infraspinatus, subscapularis, teres minor, teres major, pectoralis major clavicular, pectoralis major medial, pectoralis major inferior, latissimus dorsi superior, latissimus dorsi medial, latissimus dorsi inferior, and coracobrachialis muscles of the right shoulder were analyzed.

The simulation started in a static posture for all participants with the torso upright, arms vertical, and elbow angle in 90°. The static test was used to model scales; scaling the model was completed with an error of less than 2 cm.

Experimental conditions

This study used a 3×3 factorial design, including three lateral angles of a 17-inch monitor and three horizontal distances from a QWERTY keyboard (Table 1). The monitor positioned the length of the arm away at eye level in front of the participant under the following three conditions: at 0, 15, and 30 degrees relative to the direction perpendicular to the sagittal plane. The 1/3rd top section of the monitor screen was always adjusted to each participant's eye level. The keyboard was set up at three distances between the participant and the monitor, i.e., 0, 8, and 15 cm away from the edge of the desk. The keyboard was placed to the front of the subjects, and the mouse was placed on the right side of the keyboard. A standard ergonomic chair and an office desk were used to adjust the workstation based on the individuals' popliteal and elbow height. The environmental conditions of the room were controlled to avoid confounding errors.

The anthropometric and demographic variables, such as age, weight, body mass index, elbow, hip, knee, popliteal, eye level, and arm length were recorded. The workstation dimensions were adjusted to control confounding factors for each participant based on the ANSI/HFES-100-2007 standard and maintain a comfortable ergonomic posture [15].

Table 1: Experimental setup; trials (T) 1 to 9 show the combinations of keyboard and monitor setups

Variable		Monitor position from sagittal		
		Zero°	15°	30°
Keyboard distances from the edge of the desk	0 cm	T1	T2	T3
	8 cm	T4	T5	T6
	15 cm	T7	T8	T9

According to Table 1, a combination of nine keyboards and monitor setups was evaluated for each participant.

The participants randomly performed standard computer tasks for 10 min in the nine setups to prevent the order and carry-over effects. In the experimental setup (shown in Figure 1), subjects had to complete two tasks, including reading comprehension and writing, for 10 min in two five-minute intervals.

A pre-defined text was provided to the subjects to type; the font size was set 14 pt, and the Microsoft word zoom was set to 120%. The participant rested for 5 min after completing each trial. The participants were given two computer tasks that included 10 min of writing and reading comprehension.

Reflective markers were placed on the 7th vertebrae of the cervical, acromion, arm, forearm, anterior-superior iliac spine, sternum, one, two, and five of the base of the metacarpals, handle, mediolateral elbow, and mediolateral styloid of the wrist on both the sides according to the standard protocol [16].

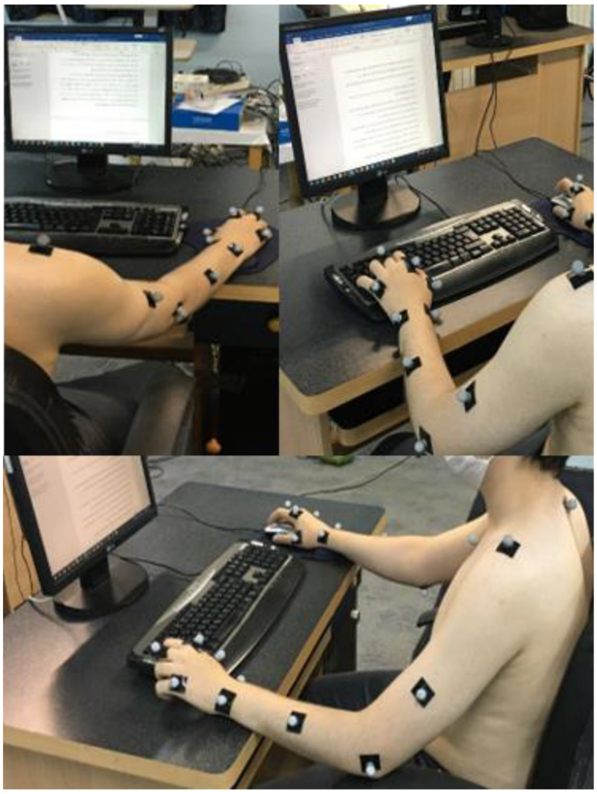


Figure 1: Study setups in the motion analysis laboratory

Data analysis

The Kolmogorov–Smirnov test was used to determine the normal distribution of the variables. The Friedman test was used to compare differences between the ROM and mean values of the moments and joint contact forces at different setups. Wilcoxon test was used for comparisons in different setups. SPSS software (version 16, IBM, USA) was used for statistical analysis, and the significance level was considered at 0.05.

Results

The participants' mean (SD) age, weight, and height were 27 (2.8) years, 73 (5.6) kg, and 178 (3.9) cm, respectively. Table 2 shows the mean ROM of flexion-extension, adduction-abduction, and internal-external rotation of both sides of shoulders in the nine setups.

The statistical analysis revealed that the flexion-extension ROM, adduction-abduction, and internal-external rotation of the right and left shoulders differed significantly in the nine setups (P-value<0.05).

The peak value of muscle forces at the right shoulder muscle complex shows in Table 3, including 16 muscles with the primary role in shoulder motions. The calculated muscle forces were normalized to the participant's weight. Table 3 indicates the maximum muscle forces for the shoulder muscle complex in nine trials representing the nine setups. Most peak muscle forces were recorded in setups T7 and T3, whereas the lowest muscle forces were observed in setup T4.

The shoulders moments (flexion-extension) mean values were different in the 9 setups (P-value<0.05). Figure 2 shows that the maximum flexion moments of the right and left shoulders corresponded to set up T8. The minimum flexion-extension moments of the right and left shoulders occurred in setup T2.

The comparisons of mean shoulders flex-

Table 2: Mean range of motion (ROM) (SD) values of flexion-extension, adduction-abduction, and internal-external rotation of the shoulders in nine trials (T1 to T9) representing nine setups (°)

Variable		Experimental setup T1	T2	T3	T4	T5	T6	T7	T8	T9	**P*-value
Right	Flexion-Extension (°)	^{a}0.50 (0.06)	^{a}1.00 (0.08)	^{b}5.21 (1.87)	^{c}9.41 (4.35)	^{c}10.28 (4.27)	^{c}12.61 (4.33)	^{d}18.30 (6.64)	^{d}19.13 (6.89)	^{d}22.62 (9.31)	0.001
	Adduction-Abduction (°)	^{a}0.29 (0.01)	^{b}2.00 (0.12)	^{c}8.71 (4.39)	^{c}11.39 (4.96)	^{c}12.62 (4.42)	^{d}15.33 (5.27)	^{e}19.16 (5.12)	^{e}22.67 (8.42)	^{e}23.31 (9.47)	0.001
	Internal-External Rotation (°)	^{e}54.27 (26.41)	^{e}52.41 (23.03)	^{d}35.62 (15.49)	^{c}19.31 (6.58)	^{b}9.96 (4.89)	^{b}8.00 (3.01)	^{b}6.32 (2.36)	^{a}2.73 (0.34)	^{a}1.69 (0.21)	0.001
Left	Flexion-Extension (°)	^{a}0.50 (0.04)	^{a}1.25 (0.72)	^{c}5.42 (1.21)	^{b}2.78 (0.98)	^{b}3.36 (1.01)	^{b}3.51 (1.05)	^{c}8.50 (3.94)	^{d}11.23 (4.72)	^{d}14.40 (5.03)	0.001
	Adduction-Abduction (°)	^{a}0.40 (0.03)	^{a}0.71 (0.09)	^{b}2.93 (0.89)	^{b}2.11 (0.81)	^{b}3.68 (1.09)	^{c}8.76 (3.16)	^{c}11.34 (4.21)	^{c}12.49 (4.78)	^{d}17.74 (5.18)	0.001
	Internal-External Rotation (°)	^{d}17.82 (8.41)	^{c}10.94 (5.47)	^{b}4.97 (1.13)	^{b}6.61 (2.03)	^{b}7.78 (3.09)	^{c}12.32 (4.94)	^{b}3.75 (1.07)	^{b}3.42 (1.74)	^{a}1.15 (0.06)	0.001

* Friedman test. Bolded values indicate statistically significant results. Values with a similar letter indicate groups without significant differences. Values with different letters are rated as: a<b<c<d<e. T: Trial, setup number 1-9

Table 3: Peak muscle forces at the right shoulder in nine setups (N/BW)

Right Shoulder Muscles	Experimental Setup T1	T2	T3	T4	T5	T6	T7	T8	T9
DELT1	****0.428**	0.356	0.342	***0.190**	0.215	0.377	0.319	0.250	0.402
DELT2	0.321	0.320	0.570	0.290	***0.287**	0.393	****0.627**	0.317	0.328
DELT3	0.031	0.032	****0.052**	***0.006**	0.006	0.006	0.017	0.006	0.006
SUPSP	0.047	0.046	0.065	***0.043**	0.044	0.054	****0.115**	0.045	0.044
INFSP	0.240	0.223	****0.526**	***0.166**	0.171	0.167	0.437	0.236	0.199
SUBSC	0.284	0.323	****0.627**	0.036	0.037	0.218	0.374	***0.033**	0.154
TMIN	0.013	0.014	0.022	***0.007**	0.008	0.008	****0.071**	0.009	0.008
TMAJ	0.019	0.019	****0.021**	0.017	0.016	0.018	***0.014**	0.017	0.020
PECM1	0.036	0.031	****0.060**	***0.011**	0.012	0.039	0.024	0.011	0.014
PECM2	0.041	0.032	****0.165**	0.015	0.014	0.051	0.145	0.015	***0.014**
PECM3	0.007	0.007	0.084	0.007	0.007	0.010	****0.091**	0.008	***0.006**
LAT1	0.023	0.022	****0.046**	***0.006**	0.006	0.006	0.022	0.006	0.006
LAT2	0.040	0.038	****0.078**	***0.005**	0.006	0.006	00.29	0.006	0.006
LAT3	0.014	0.012	****0.037**	***0.004**	0.004	0.004	0.017	0.004	0.004
CORB	0.006	0.005	0.010	0.005	0.005	0.006	****0.021**	0.005	***0.005**

DELT1: Anterior deltoid, DELT2: Medial deltoid, DELT3: Posterior deltoid, SUPSP: Supraspinatus, INFSP: Infraspinatus, SUBSC: Subscapularis, TMIN: Teres minor, TMAJ: Teres major, PECM1: Pectoralis major clavicular, PECM2: Pectoralis major medial, PECM3: Pectoralis major inferior, LAT1: latissimus dorsi superior, LAT2: latissimus dorsi medial, LAT3: latissimus dorsi inferior, and CORB: coracobrachialis.

**highest, and *lowest value in each row. T: Trial, setup number 1-9 ion-extension moments in the nine setups are shown in Figure 2. The reported moments were normalized to the participant's weight. Two by two differences of independent parameters ROM, muscle forces, moment, and joint contact forces among the nine setups were assessed using the Wilcoxon test.

Figure 3 compares mean values of shoulders adduction-abduction moment in nine setups. The mean values of shoulder adduction-abduction moments differed in the nine setups (P-value<0.05). The maximum adduction moments of the right and left shoulders were observed in setups T3 and T7. Moreover, the minimum abduction moments of the right and left shoulders were recorded in setups T4 and T6, respectively.

The comparison of mean values of shoulders internal-external rotation moment in nine setups is shown in Figure 4. The mean values of shoulder internal-external rotation moments were different in the nine setups (P-value<0.05). According to the findings, the maximum moments (internal rotation) of the shoulders on both sides were observed in setup T3 and the minimum values of the right and left sides were recorded in T4 and T6 setups, respectively.

The comparison of peak joint contact forces (anteroposterior) at the right shoulder is shown in Figure 5 (Fx). The reported joint contact forces were normalized to the participant's weight. Based on Figure 5 (Fx), the peak joint contact forces at the right shoulder were different in the nine setups (P-value<0.05). The highest and lowest anteroposterior joint contact forces were observed in setups T7 and T4, respectively.

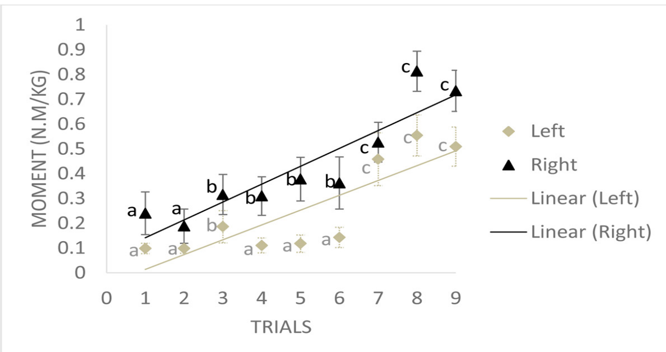


Figure 2: Mean value of shoulder flexion-extension moment in nine setups (N.m/kg). Values with a similar letter indicate groups without significant differences. Values with different letters are rated as: a<b<c.

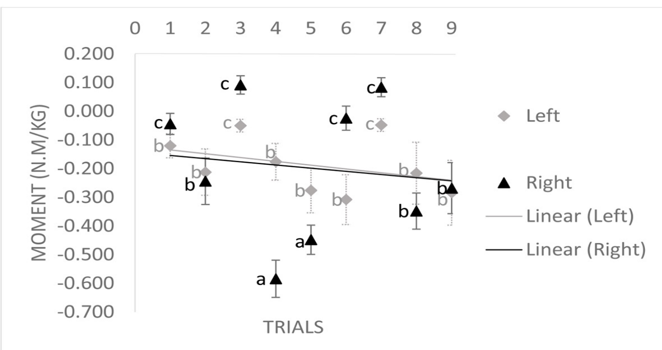
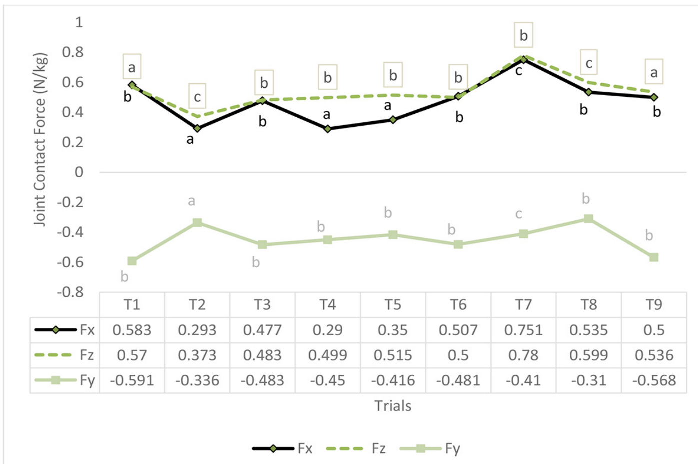


Figure 3: Mean value of shoulder adduction-abduction moment in nine setups (N.m/kg). Values with a similar letter indicate groups without significant differences. Values with different letters are rated as: a<b<c.

Figure 4: Mean value of shoulder internal-external rotation moment in nine setups (N.m/kg). Values with a similar letter indicate groups without significant differences. Values with different letters are rated as: a<b<c.



	T1	T2	T3	T4	T5	T6	T7	T8	T9
Fx	0.583	0.293	0.477	0.29	0.35	0.507	0.751	0.535	0.5
Fz	0.57	0.373	0.483	0.499	0.515	0.5	0.78	0.599	0.536
Fy	-0.591	-0.336	-0.483	-0.45	-0.416	-0.481	-0.41	-0.31	-0.568

Figure 5: Mean value of shoulder flexion-extension moment in nine setups (N.m/kg). Values with a similar letter indicate groups without significant differences. Values with different letters are rated as: a<b<c.

Figure 5 (Fz) compares the peak mediolateral joint contact forces for the right shoulder, and these values were different (P-value<0.05) in the nine setups.

The peak joint contact forces (vertical) at the right shoulder were compared in the nine setups, as shown in Figure 5 (Fy). The highest force corresponds to setup T7, whereas the lowest force corresponds to T2. The vertical joint contact forces have little difference in setups T3, T4, T5, and T6.

Discussion

The current study investigates the glenohumeral joint contact forces and kinematics in different monitor and keyboard setups. The findings showed that the monitor and keyboard setups significantly affected the glenohumeral joint contact forces. According to Table 2, the peak flexion and adduction moments of the right and left shoulders were observed in setup T9, and the lowest values were recorded in setup T1. For the internal rotation of the right and left shoulders, the highest and lowest values were observed in setups T1 and T9, respectively.

A significant increase in the values of both the right and left shoulder adduction was observed in setups T3 and T9 due to the changes in the monitor angle.

By increasing the distance of the keyboard from the edge of the desk to more than 8 cm and changing the monitor angle to 15 and 30 degrees, the shoulder flexion increased on both sides. This is consistent with the results obtained by Marcus et al. [5], who showed that the head adduction increased when the keyboard was moved away from the participants, and the monitor angle changed. Kotani et al. showed that shoulder abduction decreased by increasing horizontal keyboard distance. In the current research, the results of ROM showed that the abduction decreased by increasing horizontal keyboard distance [17]. In the present study, the internal rotation decreased by placing the keyboard further away and increasing the monitor angle to 15 and 30 degrees [17].

As given in Table 3, the highest and lowest values of shoulder muscle forces were obtained in setups T3 and T4, respectively. In setup T3 with the monitor at 30° and the keyboard at the edge of the desk, most of the shoulder complex muscles (DELT3, INFSP, SUBSC, TMAJ, PECM1, PECM2, LAT1, LAT2, and LAT3) were subjected to high forces, and therefore, high risk of MSDs.

For setup T4, in which the monitor was at zero angles in front of the participants, and the keyboard was at 8 cm, the lowest forces (low risk of MSDs) were imposed on muscles DELT1, DELT3, SUPSP, INFSP, TMIN, PECM1, LAT1, LAT2, and LAT3. Moreover, in T7, many muscles (DELT2, SUPSP, TMIN, PECM3, and CORB) were subjected to a maximum force (high risk of MSDs) due to the 15-cm keyboard distance from the edge of the desk. Findings of muscle forces were similar to those of the study by Gustafsson [18].

This can be explained by the fact that the neutral shoulder posture results in lower muscle activity. In the current study, the shoulder flexion-extension moment was enhanced by increasing the monitor angles and the keyboard distance in nine setups. The highest significant difference was observed between T7, T8, or T9 and T1 or T2 (*P*-value<0.05) as also reported by Harari et al, [19].

One potential factor that describes the differences in the shoulder moments is the lever arm between the shoulders and the keyboard, which is the horizontal distance between the hand and the glenohumeral joint. The shoulder angle was also small in some studied setups, which may partially explain the reduction in peak moments in these setups [20].

According to the results, the lowest adduction-abduction moments at the right shoulder were recorded when the monitor angle was zero, and the keyboard was 8 cm away from the edge of the desk (*P*-value<0.05). The shoulder adduction-abduction moment trend line decreases smoothly across the nine studied setups that this pattern is similar for both glenohumeral joints.

In the current study, the lowest internal-external rotation moment at the right shoulder was observed when the monitor angle was zero, and the keyboard was at 8 cm (*P*-value<0.05). The trend line of the right shoulder internal-external rotation moment decreases smoothly across the nine studied setups. The trend line of the internal-external rotation moment at the left shoulder has a steeper slope as neutral shoulder posture produces lower muscle activity and decreases the glenohumeral joint moment, resulting in lower variability in kinematics, muscle activity, and shoulder load [12].

The joint reaction force components include vertical reaction as a compression force, and in the anteroposterior and mediolateral directions as shear forces [21].

In Figure 5 (Fx), the right glenohumeral joint contact force (Fx: anteroposterior force) is shown for the nine setups. The trend line of the right glenohumeral joint contact force increases for the nine setups. The keyboard distance affected the joint contact force, and the peak joint contact force was recorded for T7; however, the lowest joint contact force was recorded (*P*-value<0.05) in T4 with the monitor at zero angles and the keyboard at 8 cm.

Figure 5 (Fz) illustrates the right glenohumeral joint contact force (Fz: mediolateral force) that the trend line smoothly increases. For the mediolateral force, both monitor angle and keyboard distance were effective variables; accordingly, the lowest and highest mediolateral joint contact forces (high risk of MSDs) were observed in extreme setups such as T1, T2, T8, and T9 (P-value<0.05). For the intermediate setups (T3, T4, T5, and T6), the joint contact forces were close to each other (low risk of MSDs).

The right glenohumeral joint contact force (Fy: vertical force) for the nine setups is shown in Figure 5 (Fy), i.e., the trend line smoothly increases. In setup T7, the highest vertical contact force can increase the risk of MSDs (P-value<0.05). For the keyboard at 8 cm from the edge of the desk, the vertical joint contact forces are stable, and the changes in monitor angle do not affect this parameter. The results showed compatibility between the joint contact forces in the vertical and antero-posterior directions as compression and shear forces, respectively.

The limitations of this study are as follows: 1) ignoring the left shoulder model in kinetics assessment and 2) studying just males. Considering both shoulder models and studying female participants can provide more detailed information in future studies.

Conclusion

The results of this study can help to properly select the placement of computer input devices, such as monitors and keyboards to minimize the glenohumeral joint contact forces, ROM, and shoulder repetitive motion, which are the risk factors for shoulder MSDs. The horizontal keyboard distance from the body and monitor angle has an essential role in glenohumeral joint contact forces. Additionally, the keyboard at 8 cm from the edge of the desk and the monitor at zero angles results in lower glenohumeral joint contact forces. A reduction in the glenohumeral joint contact forces can reduce the risk of MSDs.

Authors' Contribution

The acquisition, analysis and interpretation of data for the work, and written the manuscript was carried out by M. Gholami. Conceived the idea, introduction and manuscript of the paper was done by A. Choobineh. Design of the work, results and analysis was carried out by MT. Karimi. Results and statistical analysis was carried out by A. Dehghan. The method implementation and experimental studies was done by M. Abdoli- Eramaki. All the authors read, modified, and approved the final version of the manuscript.

Ethical Approval

Ethics approval was obtained through the Shiraz University of Medical Sciences Ethics Committee (IR.SUMS.REHAB.REC.1399.021).

Informed consent

All participants provided fully informed consent for participation in this study, and all methods were conducted in accordance with Helsinki approved guidelines and regulations.

Funding

This study was conducted at Shiraz University of Medical Sciences (SUMS) and financially supported by SUMS via grant No. 98-01-04-21320.

Conflict of Interest

None

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